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Master Thesis

A comparative, simulation supported study on the diffusion of battery electric vehicles in Norway and Sweden

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With this thesis, a wonderful journey comes to an end. This journey has included travelling from Italy to Norway, Portugal and the Netherlands. But more than the places, the wonders have been in the people I have met, and in the inspiration and life lessons that I have received from them all.

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Executive summary

We are living at a point in history where global cost dynamics and specific political choices may lead to an integral transformation of the mobility system as we know it. After a century where the internal combustion engine vehicle dominated the scene, the battery electric vehicle (BEV) is making its way into the market- and in giant steps. The world's transition to electricity and thereby a lower carbon future, depends heavily on electrifying road transportation. Norway and Sweden's different policies represent a natural experiment: They share high ambitions towards a fossil free transport sector, but BEV policies differ. While Sweden has a technologically neutral transportation strategy and so support policies loom wide, in Norway policy efforts are concentrated on BEV support. BEV adoption rates have consequently been significantly different. The present study develops a system dynamics model to represent and quantitatively analyse the interrelatedness between policy, consumer behaviour, social dynamics, competition forces and cost and performance developments.

The thesis develops a comparative study of the electric vehicle system in Norway and Sweden, looking in specific at light duty private vehicles in the time-frame 2000-2050. The study explores 6 policy options and 4 additional scenarios. It finds that neither country will achieve their 2050 zero emission goals, but rather that they will be stuck at 2/3 BEV fleet penetration rates irrespective of policies pursued. Sweden's focus on parallel low emission horses, if continued, will lead to a growing gap with the Norwegian BEV penetration for the next decades, before the gap closes as Norway approaches the 2/3 penetration saturation. The transition to electrification of the vehicle fleet shows much stronger inertia than desired and expected in other studies; the transition seems, however, inevitable, given the current system conditions.

Table of Contents

List of Abbreviations

AFV	Alternative Fuel Vehicle
BEV	Battery Electric Vehicle
EV	Electric Vehicle
ETO	Energy Transition Outlook
GHG	Greenhouse gas
ICEV	Internal Combustion Engine Vehicle
ROI	Return on Investment
SD	System Dynamics
TCO	Total Cost of Ownership
kWh	Kilowatt hour
INDC	Intended Nationally Determined Contributions

List of Figures

List of Tables

1 Introduction

1.1 Problem description

We are living at a point in history where global cost dynamics and specific political choices may lead to an integral transformation of the mobility system as we know it. After a century where the internal combustion engine vehicle (ICEV)[1] dominated the scene, the Battery Electric Vehicle (BEV)[2] is making its way into the market. Improvements in battery technology and cost reductions are making the BEV an attractive alternative. Governmental subsidies reduce the price differential between the two vehicle alternatives. Contemporarily, environmental regulations at local, national and global level are bringing rigid requirements on the energy and transportation sector's environmental impacts (International Energy Agency, 2016). In order to avoid an unsustainable increase in global temperatures, greenhouse gas (GHG) emissions need to be reduced considerably. In 2010, the transportation sector accounted for 6.7 Giga-tons of emitted CO_2, corresponding to 22% of the world's total emissions (International Energy Agency, 2015). This level has remained approximately constant since then despite the growth in the global vehicle fleet because of improvements in fuel efficiency (International Energy Agency, 2015). Efficiency improvements do not seem sufficient however: GHG emissions from the transportation system are expected to increase by 120% from 2000 to 2050 as a result of the projected 3-fold increase in the number of cars worldwide (International Energy Agency, 2015).

If adopted on a large scale, vehicle electrification is expected to substantially reduce the transportation system's environmental impacts and lead the way to a "greener" future (European Commission, 2011; Sperling, 2009).

Norway can currently pride itself of the largest BEV share worldwide, reaching 23% of new car sales in 2016 and a fleet of over 100 000 vehicles in 2016 (Norwegian Information Council

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[1] The present study defines internal combustion engine vehicles (ICEV) as an umbrella term for all vehicles using fully or partially the mechanism of internal combustion as powertrain: the ICEV category therefore includes: Petrol ICEV, diesel ICEV, liquefied petroleum gas (LPG) ICEV, compressed natural gas (CNG) ICEV, biodiesel ICEV, bioethanol ICEV, petrol HEV, diesel HEV, biodiesel HEV, bioethanol HEV, petrol PHEV, diesel PHEV, biodiesel PHEV, and bioethanol PHEV.

[2] A battery electric vehicle (BEV), battery-only electric vehicle (BOEV) or all-electric vehicle is a type of electric vehicle (EV) that uses chemical energy stored in rechargeable battery packs. BEVs use electric motors and motor controllers instead of internal combustion engines (ICEs) for propulsion. They derive all power from battery packs and thus have no internal combustion engine, fuel cell, or fuel tank. (from Wikipedia website, retrieved in date 19.03.2017)

for Road Traffic/ OFV, 2017). The Norwegian BEV policy program is overall considered very successful ((Bjerkan, Nørbech, & Nordtømme, 2016; Nykvist & Nilsson, 2016; Saxton, Levin, & Myhr, 2016). This policy strategy includes consistent purchase cost reductions that make the BEV financially competitive with the ICEV and implies several use benefits such as access to bus lane, free parking and exemption from road toll charges (Figenbaum, Assum, & Kolbenstvedt, 2015).

The neighboring country Sweden presents a very similar geography, climate and history to Norway. The two countries have a comparable first phase of BEV penetration but different policy packages (Nilsson and Nykvist, 2016). Sweden also has high targets for future BEV adoption (Saxton, Levin, & Myhr, 2016), but up to present, the share of BEVs is significantly lower than in Norway: there were only 7 700 BEVs on the Swedish streets in 2016 and sales represented only 7% of the total fleet (Saxton, Levin, & Myhr, 2016). The reasons behind such a marked difference in BEV market shares between two apparently very similar countries are not clearly defined (Saxton, Levin, & Myhr, 2016). Figure 1 illustrates the development over time of the Norwegian and Swedish BEV fleets and Figure 2 represents the sales share development. Understanding the drivers behind this difference can also support in understanding the challenges to BEV diffusion Sweden, as well as in other countries.
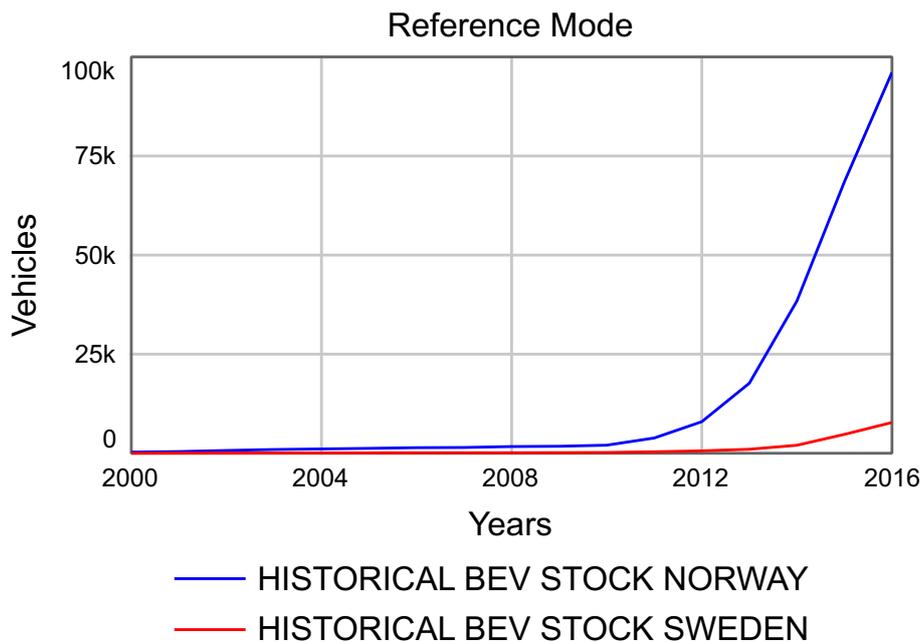
Figure 1. Reference mode for BEV stock in Norway and Sweden
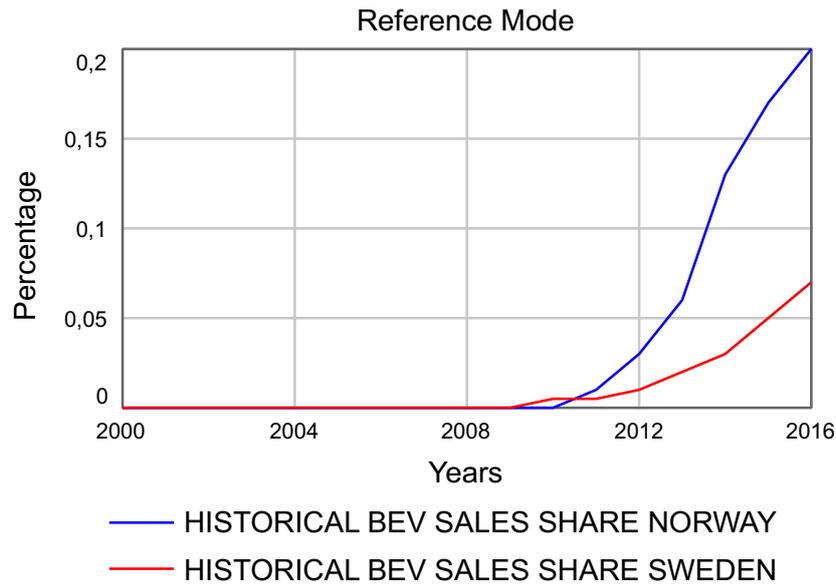
Figure 2. Reference mode for BEV sales share in Norway and Sweden

The marketing challenges of the BEV are large since there exist financial and practical risks associated to the purchase and use of BEVs (Bjerkan, Nørbech, & Nordtømme, 2016). The price is usually higher because the product is not part of a market of scale; the technological attributes may not outperform the market incumbent (Harrison & Thiel, 2017). It is difficult to predict the long-term outcome of the competition with the well-established ICEV, or how much customers do trust this new technology. In addition, incentives to BEV purchase and use represent a substantial financial cost for governments, and can only be temporarily sustained (Nyborg, Howarth, & Brekke, 2006). The determination of the "right" timing to interrupt incentives is a political choice that may determine the future of the BEV breakthrough (Ford, 1999; Struben and Sterman, 2008).

The diffusion of BEVs is a complex phenomenon (Struben & Sterman, 2006) and incentives only cover one role in the bigger picture (Figenbaum, Assum, & Kolbenstvedt, 2015; Bjerkan, Nørbech, & Nordtømme, 2016). It is no surprise that forecasts for the future of EVs diverge so broadly, from breakthroughs to disappearance (International Energy Agency, 2016; Nykvist & Nilsson, 2016; Pasaoglu, et al., 2015). A variety of mathematical models have been applied to describe and predict general EV diffusion (Massiani, 2010; Pasaoglu, et al., 2015; Struben & Sterman, 2006). The factors underlying in particular the Norwegian success have been studied by many authors in the transportation systems research field (Figenbaum & Kolbenstvedt, 2016; Bjerkan, Nørbech, & Nordtømme, 2016; Holtsmark & Skonhoft, 2014).

This research proposes to make a comparative study of the BEV system in Norway and Sweden, looking in specific at light duty private vehicles in the time-frame 2000 - 2050. The objective is to integrate knowledge contributions from a range of fields: system dynamics (SD) modeling, consumer choice theory, diffusion theory and macroeconomic theory. SD modeling has not been applied before to this Scandinavian context, bringing relevance to this research.

1.2 Research context and practical relevance

The project is conducted under request of the sustainability advisory and certification company DNV GL as part of the Energy Transition Outlook (ETO) directed by professor Bent Erik Bakken. The company is developing an integral SD model for the analysis of the future global energy supply and demand dynamics. One of the sectors of study is transportation. It is therefore of special interest for the company to develop understanding on the possible future developments of the vehicle fleet and from which energy source it will fuel. Two special cases in the European region, Norway and Sweden, are taken as case studies to improve our understanding on the possible transition patterns in the vehicle system.

The research is exploratory and practice-oriented, as it is believed that the study will provide practical utility to the company DNV GL. A simulation model calibrated to the specific context will be delivered with the capacity for possible future use.

The choice of the topic is also motivated by a large number of signals in both research and industry pointing to the high probability of a transition to electromobility. In the most recent BNEP Energy summit 2017, Michael Liebreich considered electric vehicles as one of the major drivers of the energy market developments, in synergy with the development of the renewable energies market and technology (Liebreich, 2017). Falling costs of batteries and rising costs of emissions are driving the industry and society to look for cleaner alternatives (IEA, 2016). Forecasts on the EV market have increased in optimism over the years: for example, in 2017 the EIA forecasted a 2025 EV market in the US of ten times the size of what had been predicted in 2014 (U.S. Energy Information Administration, 2017); (U.S. Energy Information Administration , 2014). Forecasts are relevant for the industry and governmental bodies since energy infrastructure requires long term investments. Hence, this research proposes to look at a topic with a contemporary and future relevance for both industry and society.

1.3 Research objective

The research proposes to apply the SD modeling methodology to analyze the structure and behavior of the BEV system for the context of Norway and Sweden. The objective is to provide

special insight, through a systems-thinking approach and the development of a system dynamics model, into the drivers and barriers to BEV diffusion in Norway and Sweden. The analysis hopes to bring broader understanding to why BEV adoption rates differ so broadly in Norway and Sweden. In particular, the role and effectiveness of governmental instruments directed to BEV adoption will be evaluated.

The research will have an *explanatory* focus: the analysis of the system will aim at identifying which factors explain the dynamic behavior of the phenomenon.

1.4   Theoretical relevance

Hopefully the research will bring a theoretical contribution to the broader field of System Dynamics modelling and the study of technology transitions, considering the vehicle sector as a case study. Firstly, technology transition is a complex topic, and system mapping can increase the understanding of the elements of the system and of the interrelations among these. Secondly, the method applied aims at developing an endogenous causal description, which is absent in most existing diffusion theories. The understanding will also be supported by simulation, which allows to test hypotheses and explore what-if scenarios.

A theoretical value in the research is seen for the larger field also by taking a critical look at the present knowledge and running a validation process through simulation. The method will be applied to a novel and contemporary transition context where little research has been done. EVs were introduced to the broader consumer market only in the last decade, hence there exists little research using empirical data to analyse factors behind adoption. Fridstrøm, Østli and Johansen (2016), Figenbaum et al. (2015) and Sierzchula et al. (2014) use different sample populations, and to date there has not been, to the knowledge of the author, a critical cross-comparison between the research institutions' results. Sample validation is one of the challenges of mere statistical studies. This research tries to do resolve this challenge by using a new approach, which will be described in depth in the next chapter.

1.5   Research questions

1.5.1   Central Question

In order to pursue the aims of the research, the following research question will be answered:

Based on the experiences in Norway and Sweden from 2000 to 2017, what are the country-specific drivers of BEV diffusion?

1.5.2   Subquestions

1. What factors define BEV attractiveness for potential buyers?

2. How do purchase policies influence the cost attractiveness of BEVs?

3. Based on the experiences from 2000 to 2017, what was the effectiveness of BEV policies in Norway as compared to Sweden?

4. What policies are determinant for a sustained BEV adoption?

5. When will cost parity be reached in Norway, and when in Sweden?

6. When will performance parity be reached in Norway, and when in Sweden?

1.6   Thesis outline

In this first introductory chapter, the research objective and the context from which this objective arose have been presented, followed by the theoretical and practical value of the research. The research questions that want to be answered in order to achieve the objective have been listed.

In the next chapter (Chapter 2) the research strategy chosen to answer the research questions is defended(2.2): the choice of the System Dynamics modelling method (2.1), the data collection method (2.2.3) and the model validation procedure (2.2.2). Limitations in the research are outlined at the end of the chapter (2.3). Chapter 3 presents the theoretical background on which the model is based: from a broader discussion on technological transitions (3.1) to a description of all the elements of the vehicle ecosystem: vehicle technology and infrastructure (3.6), purchase price and operational costs (3.5), driver habits and preferences (3.4) and governmental regulations (3.2). In the same chapter, the Norwegian and Swedish contexts are also described in detail (3.7, 3.8). The chapter ends with an outline of the dynamic hypotheses derived from a qualitative analysis of the system (3.9). In Chapter 4 the system dynamics model is described in all its components: first from an aggregate and qualitative perspective through a conceptual model (4.1), then sector by sector (4.2). The contextualization to the Norwegian and Swedish contexts is explained in section 4.4. In Chapter 5, the results of the model simulation are discussed and an answer is sought to the research questions; the validity of the model is considered, presenting the validation process (6.3). The limitations of the study are discussed (6.4), concluding with suggestions for further research (6.5). Chapter 7 concludes the text.

An Appendix is annexed to the thesis where it is possible to find details on model equations (A), model validation (B), and a brief final discussion on the carbon footprint of BEVs (C).

2 Methodology

2.1 Analysis of diffusion trends

The diffusion of innovations (such as the BEV) has been studied extensively with both quantitative and qualitative methods, as will be presented in detail in Chapter 3.1. This research draws on qualitative and quantitative studies and models and tries to address the limitations of these. Most transportation literature found is based on survey studies and statistical regression models. Regression models risk describing correlations instead of causality (European Commission, 2011); (Figenbaum, Assum, & Kolbenstvedt, 2015); (International Energy Agency, 2015). Statistics based on samples shows inevitable limitations related to sample size. Use of surveys is not always robust because of the presence of the responders' bias and the challenges in choosing a significant sample. In the case of EV policies, survey responders may give skewed responses because of vested interests, for example, not to lose the incentives (Bjerkan, Nørbech, & Nordtømme, 2016); (Figenbaum & Kolbenstvedt, 2016).

Consumers adopt electric vehicles for technical, financial, environmental and social reasons; most of these dimensions are disregarded by traditional methods (Nykvist & Nilsson, 2016). Technology transitions are highly complex, requiring research on the topic to take a systems perspective (Nykvist & Nilsson, 2016).

2.1.1 The System Dynamics approach

System dynamics is a method to enhance understanding in complex dynamic systems. It is a perspective, by providing the analyst with a system lens to the problem; it is also a set of rigorous tools that lead to the construction of a mathematical model (Sterman, 2000, s. 4). By creating a model, the structure and behaviour of a complex system can be analysed. The model can be qualitative by graphically describing the cause-effect relations between the system components, and functions therefore as a map for better understanding. A model can also be quantified, by specifying mathematically how the cause-effect relation looks like: this can be positive, negative, linear or non-linear. Equations are inserted in the respective computer software and the model can then be simulated to conduct experiments by numerical methods. Through experimentation, the system can be explored, the root of the problem can be detected, and better solutions can be discovered (Ford, 2010, ss. 5-12); (Sterman, 2000, ss. 37-39).

The vehicle system can be described as an ecosystem involving different actors (Geels, Technological transitions and system innovations: a co-evolutionary and socio-technical analysis., 2005): users, manufacturers, authorities and infrastructure suppliers. Each of these actors considers own decision rules when impacting the system, and interests may not be aligned or coordinated. Yet, the actions of all actors are tightly related and often dependent. To fully understand the dynamics of the vehicle fleet, a systems view is necessary. Using system dynamics implies the aggregation of agent classes to represent average levels. At the same time, different agents can be modelled, together with the specific decision rules that govern their behaviour. This is also done in other SD studies such as Struben and Sterman (2006) and Pasaoglu (2015). Pasaoglu's work develops a representation of EU powertrain technology transition with a market agent perspective. Struben and Sterman explore the challenges that Alternative Fuel Vehicles (AFV) are facing considering the interaction of drivers, automakers and politicians' decision making behaviour.

A simulation-based comparison between the Norwegian and Swedish BEV system has not been implemented so far, and it can support in better understanding the leverage strength of policies, the potential knock-off effects and unintended consequences. Also, simulation makes hypotheses testable, which is most often not possible in real-life (De Gooyert, 2016).

2.1.2 Simulation modelling

The SD software Stella Architect, version 1.3 from Isee Systems Inc., is used to build and simulate the model and quantitatively analyse the system.

The software allows to build at the same time graphical and mathematical representations of the system by having a user-friendly graphical user interface and a wide range of mathematical functions applicable. The representation is based on a simple set of concepts: stocks, flows, feedback loops and time delays. Stock is the term for any entity that accumulates or depletes over time; it is represented as a rectangle. Flows represent the rate of change of stocks and are represented as valves entering or exiting stocks. In addition to stocks and flows (which correspond to integral and differential equations), any type of mathematical variable can be included in the model, and is represented by a circle. Causal relations between the model variables are illustrated by arrows starting at the cause and pointing to the effect. Causal relations can cause loops when the effect influences, directly or indirectly, the original cause. This "feedback" effect is delayed in time and can be a matter of seconds or many centuries; the delay effect is usually represented by double stripes across a causal link. These four components are illustrated in Figure 3 next.
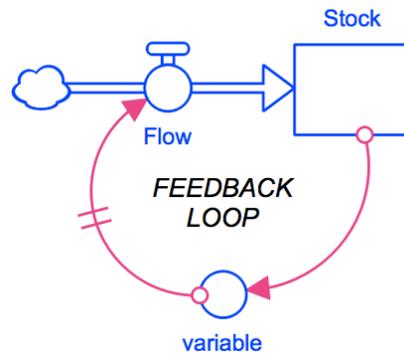
Figure 3. Basic ingredients of a system dynamics model

Mathematically, this corresponds to a system of differential equations causally relating the variables. Since the vehicle system is large and complex, the system will include more than a hundred equations, and a graphical, simplified representation of the causal relations is therefore very functional. In the present thesis, both graphical and equation representations will be used to describe the model.

2.1.3   Comment on the role of modelling in simulating the future

The SD model that has been constructed is simulated over the time period 2000 – 2050. However, care must be taken not to consider a simulation model as a horoscope: SD is not for "point prediction" of future values (Forrester, 1961, ss. 123-128). System dynamics is a method to explore the cause and effect relationships between components of an interdisciplinary system, looking in particular for feedback effects and delays that can have unexpected impacts on the system. The complexity of most systems requires the modeller to define a boundary of analysis and apply simplicity more often than precision. Hence, while the accuracy of the model estimates may not be as strong as a detailed and specific economic or mechanical model, the benefit of a SD model is that all dimensions of the problem are considered, often surfacing causal relations that are not manifest in the isolated sectorial perspective that traditional modelling applies. Nevertheless, SD models are like any other models: "always wrong" (Sterman, 2000, ss. 846-852), being based on subjective mental models of reality and specific assumptions. Hopefully, the models are useful (Sterman, 2000, ss. 846-852) to the client in improving understanding and strengthening decision making. In the present case, the model is built first of all to map the system, taking into consideration a range of cross-sectoral aspects, and then to run a series of simulations that can answer to "what-if" assessments, and explore the causal interrelations within the system. The model simulations shall therefore not be used as predictions but as projections into likely futures, given certain assumptions. In addition, the further ahead we move in the future, the larger the uncertainty: simulation model running

towards 2050 has therefore very low predictive value. Integral modal shifts may happen in the meanwhile- in the transportation system, in the economy, in the environment and the political environment.

2.2   Research strategy

The first section of this chapter has outlined the role and utility of modeling in the chosen problem context. The chosen research strategy is therefore to run a SD model-based case study, hence an inductive research approach that relies heavily on computer model simulation as theory-validation. The modelling approach is thus quantitative. Following the system dynamics guidelines, (Sterman, 2000, ss. 83-105), the following modelling steps have been followed:

1. *Problem definition*, including: choice of topic, identification of key variables, choice of time horizon, definition of reference mode
2. *Formulation of dynamic hypotheses and system mapping*
3. *Formulation of simulation model*, including specification of structure, decision rules, parameters and initial conditions
4. *Model testing* (see section 2.2.2)
5. *Policy analysis*

The first stage of the research process has been the definition of the research problem. The knowledge basis of the research and of the model built has been derived from a broad literature review including: past research on the BEV and its system; theories on innovation diffusion, consumer behaviour, governmental policies; information on vehicle attributes such as performance, price and cost components; statistics on consumer behaviour, fleet and infrastructure development; past modeling studies. A qualitative analysis of the literature has supported the determination of the dynamic hypotheses and a mapping of the principal causal relations. The qualitative analysis has successively been quantified and simulated, and a validation procedure has been performed. Scenarios have been developed to explore the system in simulation, and the resulting analysis has supported in answering to the research questions. The scenario analysis approach is chosen in line with the approach taken by two similar SD modelling studies on vehicle technologies, in context of the European region: Pasaoglu et al. (2015) and Harrison & Thiel (2017).

Next some details of the research strategy will be discussed more in depth: the choice of the simulation time, the validation process, and the data collection.

2.2.1 Choice of the simulation time

Historical data will be used since the year 2000, which is when the BEV diffusion in Norway started its first growth phase. The diffusion of BEVs in Sweden started a decade later, but for comparison purposes the same time range will be applied. In both countries, environmental policies directed to private vehicle transportation started being introduced already in the 1990s. The end-time of the simulation time is set to 2050. This medium-term view is considered a reasonable trade-off between the long-term perspective advocated by SD and the intrinsic shifting nature of the system under study: beyond 2030 both European policies and landscape drivers globally (energy markets, climate regimes, technology breakthroughs) can shift in fundamental ways. A set of policy scenarios will therefore be developed to explore different future outcomes. On the other hand, the slow turnover in vehicle fleet and the even longer lifespan of infrastructure imply that sales in the present will influence the vehicle fleet of 20-30 years from now. A key question in the research is at what speed the new technology can penetrate the entire car fleet. From an environmental perspective, this is important in order to assess at what speed it is possible to lower the transportation sector's CO_2 emission rate: the GHG atmospheric concentration in 2050 will depend on governance choices made in the next decade (IPCC, 2014). In addition, the chosen end-time is in line with the scenarios developed in the Energy Transition Outlook produced by the company DNV GL. Finally, the futures studies regarding BEV diffusion chosen for comparison in this research also develop forecasts up to the year 2050, and hence this time range is functional for triangulation.

2.2.2 Model validation

The model validation process is run following the main SD frameworks: Barlas, 1996, Forrester and Senge 1980 and Sterman, 2000 (chapter 21).

As the purpose of the model is to explore how the interactions between the vehicle fleet, consumer behaviour, infrastructure development and costs dynamics can impact the diffusion of the BEV, the model successfully serves as a dynamic hypothesis to achieve this purpose. When building a model, a balanced selection of all existing factors must be done, evaluating, prioritizing, aggregating. When comparing the model behaviour with historical data, it must be expected that details will be lost and full precision is limited.

Making a simulation model resemble reality is a challenge that can maybe not be surpassed. A model is a simplified representation of reality, and the causal relations that are drawn and described with equations are hypotheses on how the world may work. Sterman states that no model can ever be truly verified or validated because "all models are wrong" (Sterman, 2000); it therefore seems justified to focus more on verifying the purpose of the model and the process

used in building the model to gain confidence in how well the model structure represents its counterpart in the real-world, rather than "point prediction" of the real system (Forrester, 1961). Sterman has outlined twelve different groups of assessment tests that can be used to evaluate the validity and sensitivity of a model, among which there are the causal analysis of system dynamics, comparison with reference mode, dimensional consistency, extreme condition tests, boundary adequacy, and model specification tests. Chapters 4.3 and 6.1 compare a qualitative and a quantitative analysis of the causal relations in the model, prior and after simulation. In chapter 5.1 the model output is compared to historical data; in the Appendix (chapter B) a set of procedures for model validation are presented. The validation process is summarized in the discussion chapter (6.3).

The development of scenarios, policy analysis and sensitivity analysis have been performed to address the main uncertainties in past and future parameter values and in the causal structure of the model.

The validation of a system dynamics model may be limited by the absence of objective measures for all variables. The sizes considered are aggregate and average values, and hence there is an intrinsic limit to the accuracy of each variable. in that case, also semi-formal and objective means can be used to validate the structure (Barlas 1996): this can still give support to the judgement of the model's usefulness with respect to its purpose. The final discussion takes this aspect in consideration as well.

2.2.3   Data collection

Both qualitative and quantitative data will be collected through literature review and online research. The platforms RUQuest and Google Scholar have been used to search academic articles. Content analysis (Luna-Reyes & Andersen, 2003) served as a method for data collection; the Snowball search method was applied from key articles to find further information. Even though the phenomenon is on-going, there exist empirical data for the period 2000- 2016 that can be used for theory validation (Norwegian Information Council for Road Traffic/ OFV, 2017; Lovin & Andersson, 2017). The data gathered is specifically for light duty private vehicles in Norway and Sweden. Sources of knowledge have been academic books, publications from journals, official reports from national statistical entities, the Ministry of Energy, Transportation and Environment, and from scientific research bodies. For example, Sierzchula et al. (2014) perform linear regression analysis of empirical data to validate the influence of financial incentives on electric vehicle adoption; this, and similar studies, will be used as knowledge sources for the present study. Triangulation has been applied to validate the data.

The main data sources for the Norwegian context are: the national statistics bureau (Statistisk Sentralbyrå/SSB), the governmental webpages (regeringen.se), the Transportation Department webistes (Statens vegvesen), the independent transport research institute (Transportøkonomisk Institutt/TØI) and websites on alternative fuel vehicles in Norway (primarily nobil.no).

More than one source needed to be retrieved to find all values for the historical BEV market size in Norway. For the period 2000-2003, no values were found, so linear interpolation is applied. For the period 2003-2008, the Wikipedia page on plug-in EVs in Norway was used (where a webpage from gronnbil.no is used as source, but this page does not exist any more).

Historical values from 2008 are retrieved from the International Energy Agency's Global EV Outlook (2016) p. 34, statistical annex (Table 6). Since the table provides overall EVs (BEVs and hybrids), the BEV proportion has been calculated. Up to 2013, only BEVs were sold. In 2014, 7% of EVs was PHEVs, so that 7% was subtracted from the total value in IEA 2013. For 2015, 23% of the EVs new sales were PHEV, so the same operation was done with this value. Value for 2016 retrieved in date 28.3.2017 from (Frydenlund, 2016).

As for the size of the total vehicle fleet, SSB was the main source. The retrieved statistics for light vehicles represent both private vehicles and cargo vehicles. It is assumed that the proportion of private to total (private and cargo) is 85%, as was found for 2011.

Only data in the period 2003-2015 could be found, so for the earlier years 2000-2002 and year 2016, a linear approximation has been created from the historical trend.

The main data sources for the Swedish context are: the national statistical bureau (Statistiska centralbyrån/ SCB), the governmental webpages (regeringen.se), the Transportation Department websites (Transportstyrelsen.se), the independent transport research institute Trafikanalys and websites on alternative fuel vehicles in Sweden (as miljofordon.se).

2.3 Limitations

The study is based on secondary data, accounting for the reliability of this. This includes statistics over consumer preferences, which may contain biases and mistakes.

The researcher acknowledges the intrinsic limitations of the study due a number of elements: the model boundaries, limited time and resources (Denscombe, 2012, s. 129). The definition of the model boundary, as will be discussed in section 4.1.1, defines certain factors to be endogenous, others to be exogenous. Concerning resources, model variables have been quantified on the basis of previous studies, including statistics that themselves show limitations,

limitations that consequently may be carried over to this study. On the other hand, one of the objectives of this study is to address these limitations by cross-comparison and critical analysis. No historical data could be found on the historical discard rate for BEVs for the two contexts. This has limited the possibility to check the reliability of the historical data found. In system dynamics terms, considering the total number of vehicles as a stock implies that annual sales represent an inflow, and scrappings represent an outflow. The equations for inflow, stock and outflow are mutually related in a way that, if two variables are known, the third can be derived. In the present case, historical stock and inflow are documented, but not the outflow. The outflow can then be derived at any point in time by the following formula:

$$Outflow_t = Stock_{t-1} - Stock_t + Inflow_t$$

By doing this with the historical data, it could be seen that discards are not solely a function of the stock size and vehicle lifetime (as defined by the model), but also by other parameters which are not included in the model.

3 Theoretical background

In this chapter, the relevant theory for the research is described. Numerous theories have been developed to explain technological transitions in general and the diffusion of alternative fuel vehicles in particular; but the knowledge basis for this research needs to be even broader. Modern car-based transportation can be described as a socio-technical ecosystem (Geels, 2005). This ecosystem consists of a large variety of components, going far beyond the vehicle artefact: technology, regulation, user practices, cultural meaning, infrastructure, maintenance and supply networks. Different actors control each of these components, each following own decision rules. Transformations in this system are characterised by a considerable inertia since each component follows its own time of responsiveness. Consumer habits may change over days, regulations may be defined over months, infrastructure may be developed over years. Transformation requires parallel alignment across components.

In the next sections the components of the vehicle "ecosystem" are therefore discussed (sections 3.2 through 3.6). A description of the Norwegian and Swedish vehicle landscapes follows in section 3.7 and 3.8. At the end of the chapter, the dynamic hypotheses derived from the literature review are presented. The SD model, which will be presented in the next chapter, will be used to test these hypotheses. But first, the topic of technological transitions will be explored, including theories and related empirical research.

3.1 Technological transitions

At the turn of the 19th century, many large cities in the United States moved from horse drawn carriages to vehicles (Schiffer, Butts, & et al., 1994). The first models in the streets were electric vehicles and steam-engine vehicles. The electric vehicles, in particular, received enthusiastic reviews from scientists and the media because of their speed records (in 1899 an EV set the world speed record of 61 mph (Flink, 1970)), their silence and cleanness (Kirsch, 2000). Yet, in a few years the sales of internal combustion vehicles surpassed those of electric vehicles, becoming the dominant mode of transport and shaping the standards of driving for the next century. Since then, internal combustion and oil have defined our world economically, environmentally and socially.

Today, in response to the increasing environmental concerns, a transition away from fossil-powered ICE vehicles is proposed (European Commission, 2012; International Energy Agency, 2015). Dethroning the ICEV is however difficult: repeated attempts to reintroduce the EV as well as other AFVs have failed: in the US, in Italy, New Zealand and Canada (Filho & Kotter, 2015). Transition programs are seen to stagnate soon after ending of subsidies (Schiffer, Butts, & et al., 1994; Flink, 1970).

A common explanation is that vehicle costs are too high and that the technology is not mature. Looking to the history of ICEV diffusion however, it is see that this was not initially the case. Being the "first mover" was not a sufficient advantage either. One major determinant for the vehicle choice of consumers at that time was the function of the vehicle: society developed a taste for touring in the outskirts of the city. This required a car with a long travel range or a well-developed network of charging points. The electric vehicle of that time had neither of these. Therefore, even if the performance of the EV was higher than the ICEV's on certain criteria, consumer preferences drove the popularity of the ICEV.

Sterman and Struben (2006) argument that the relative higher costs and lower performance of AFVs have an endogenous nature: these are consequences of a coevolution between the internal combustion technology, the petroleum industry, transport networks, settlement patterns and regulations. A sustained adoption of AFVs would therefore not only require strict cost and performance parity, but an alignment of the whole ecosystem (Struben & Sterman, 2006). Technology transitions require the formation of a self-sustaining market through alignment of consumers' interests, producers' capabilities, infrastructure development and regulations. Complementary resources play a key role in the transition: each vehicle requires compatible infrastructure, fuel, repair services and standards (Struben & Sterman, 2006). Without prospects of a big market however, investors and society will show reluctance to take a risky decision. Since a complete alignment of all system components is necessary for success, transition to a new platform meets large obstacles, leaving the system locked in the old equilibrium.

In the past, the numbers have not quite lived up with the hype around different AFVs. Worldwide, electric vehicles (full-electric and hybrid) represent approximately 0,1% of the global vehicle stock (International Energy Agency, 2016); in Europe, less than 1% of new car registrations are BEV, and slightly higher for hybrids. This is not significant enough to bring a radical change in fuel consumption and GHG emissions (International Energy Agency, 2016). Grauers et al. (Grauers, Sanden, Sarasini, & Arnas, 2013) talk about a "deeper green transition" when considering the challenges of EV adoption: achieving electromobility depends on solving significant challenges related to technology, but also to complex social change. This includes

behavioural shifts, changes in city structures and new transport models. Plötz (2014) highlight the importance that research and policy makers do not only consider economic factors as cost dynamics: the socio-technical dimension is key to identify governance and policy requirements. Another theory in the transition sciences is the Multi-Level Perspective (MLP). MLP is a heuristic model used to understand changes in socio-technical systems. Transitions are multi-dimensional, as technology is only one aspect; it is applied to fulfil a societal function through infrastructure, markets and distribution. In the MLP model a transition is said to happen at an incremental scale: from niche to regime to landscape level. Niches are "safe ports" for technologies to develop free from market pressures; an example can be the military and aircraft technology or local scales. Regime is the denomination for socio-technical networks: user practices, infrastructure, policy, research and culture; these are mainly at national level. For a technology to scale up from niche to regime, regime components need to shift in parallel, which is neither automatic nor rapid: change is slow and incremental (Geels & Schot, 2007). The landscape level involves the macro-dynamics, often international: economic pressures, social trends, wars, environmental issues. MLP is often used to understand a policy within the socio-technical levels, and how it can create the pressure that innovations need to ascend. Nykvist and Nillson (2015) and (2016) and van Sloten (2015) use MLP to study the diffusion of EVs in Sweden. Their research brings relevant knowledge to the present study. In the modelling process however, the focus will be on the national level in order to better compare the Swedish and Norwegian contexts.

Quantitative studies have also been performed on the topic. Examples of general innovation diffusion models include Norton and Bass (1987), Mahajan et al. (1995), Rogers (1976), (2010) and Maier (1998). Urban (1996) develops innovation diffusion models applied to the auto industry. Pasaoglu et al. (2015) develop a SD model to simulate future vehicle transportation transitions based on different powertrain technologies. The conclusion of this study is that a shift to AFVs will not occur unless two conditions are satisfied: these vehicles are made available by the manufacturers and users want them. The challenge is identified as aligning supply and demand, as incentivizing both drivers and manufacturers. This is in line with the most recent study on electromobility conducted by McKinsey & Company (Knupfer, et al., 2017). Simulation of scenarios in Pasaoglu's work (2015) suggests that favourable "macro" market conditions such as high oil prices and strong GDP growth will not be sufficient to enable a technological transition. Two kinds of policies are needed: policies that incentivize manufacturers to lower emissions and policies that increase the attractiveness of low emission powertrains among consumers.

Fridstrøm et al. (2016) develop a stock-flow cohort model of the Norwegian passenger fleet. The model has a high granularity in specifying 22 vehicle types and 31 age classes; vehicle flows include new registrations, vehicle aging, scrapping, imports and exports. New car registrations follow from a disaggregate discrete choice model based on sales data. Specific time lags are included to represent the inertia of the system.

The challenge with technological innovations is that these often bring challenges to the early adopters (Sierzchula, Bakker, Maat, & can Wee, 2014). Electric vehicles are "eco-innovations" (Brown, 2001): they provide a lower environmental impact than the conventional vehicle and thus bring utility to society; but prices do not incorporate societal benefits. Firms, in a capitalist system, are therefore not incentivized to invest in research and development of new technologies (Arrow, 1962); hence the product development stagnates, and adaptation as well. In addition, the inevitable spill-over of technological knowledge between competitors slows down the relative rate of technological development of innovations (Struben & Sterman, 2006). Following neoclassical economics, government policies should be employed to help correct for such situations (Rennings, 2000). In the next section, literature and opinions on the role of policies in the adoption of BEVs are presented.

3.2 BEV policies

Arthur Pigou developed the concept of economic externalities in "The Economics of Welfare" (Pigou, 1920); from this work derives the denomination of Pigouvian taxes and subsidies as any governmental regulation that acts on market activities generating negative externalities. In the case of EVs, policies can be considered as a compensation for the positive externalities of the BEV as opposed to the ICEV. This compensation can be monetary- compensating for the price and cost differential- or practical- compensating, through practical benefits, for the loss in performance. Anxiety from the high level of uncertainty early in the development phase of a product is natural and observed in a range of products (Abernathy & Utterback, 1978). Consumer subsidies are considered as necessary in the early commercialization period of EVs to reach a mass market (Hidrue & et al., 2011; International Energy Agency, 2015).

There exist many ways in which governments can try to influence the EV adoption: purchase premiums, tax exemptions, investments in Research & Development (R&D), information campaigns, restriction imposition, and so on. Policy strategies can be classified in a variety of ways, depending on the perspective. Van der Steen et al. (Filho & Kotter, 2015, ss. 27-51) describes EV policies on the basis of where, across the vehicle value chain, policies are directed: to R&D, to production, services or customers. Bjerkan et al. (2016) consider three classes:

policies that reduce fixed costs, that reduce use costs and the policy of bus lane access. The classification of EV policies done by EAFO with geographical mapping is illustrated in Figure 4. We can see that all European countries apply different strategies.
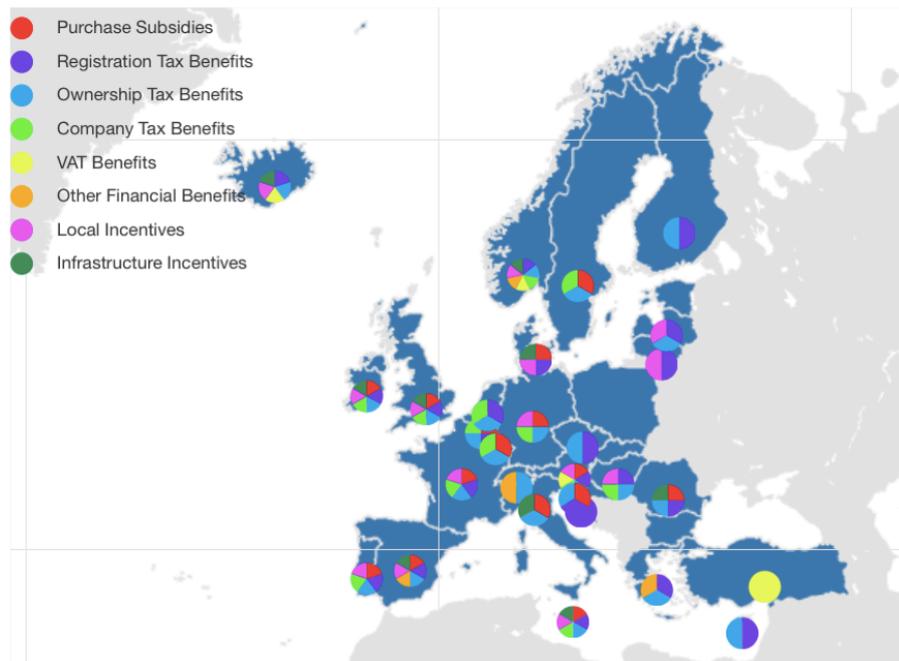
Figure 4. Map of EV policies in Europe in place in 2016[3]

There is naturally no golden rule on which policy is most efficient in EV diffusion, and it is Bjerkan (2016), Holstmark and Skonhoft (2014), Sierzchula (2014) and van der Steen's (2015) main research questions what policies are critical for BEV adoption. The result of each research group is different. Based on surveys from nearly 3400 BEV owners in Norway, Bjerkan concludes that reduction of fixed costs is critical for over 80% of respondents; to another substantial group however, exemption from road tolls and bus lane access are the only decisive factors. Sierzchula, on the other side, concludes that financial incentives and charging infrastructure are statistically significant factors, but that the strong uncertainty component associated to BEV ownership may not be compensated by financial incentives to a sufficient extent to motivate uptake. Holstmark and Skonhoft's research defends the arguments that incentives are ineffective, have several unintended consequences and are counterproductive to BEV diffusion. Research has therefore not reached a unified opinion on the best strategy to achieve the declared EV targets.

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[3] From the European Alternative Fuel Observatory (http://www.eafo.eu) Retrieved 20/03/2017.

Each type of regulation has its limitations: command and control policies are not tailored to the context and may therefore lose cost efficiency. Economic incentives bring high expenses or losses in revenues to governments. Bus lane access to EVs has been observed to cause higher congestion in the long run (Holstmark and Skonhoft 2014). Hence it is a challenge for policy makers to determine which instruments to adopt- and at what costs.

From the perspective of neoclassical economics, financial incentives will stimulate agents to learn and improve their performance; governments will act as rational arbitrageurs in moving prices to the appropriate values. Kampmann and Sterman (2014) show however, through a series of experiments and through comparison of empirical time series with model simulations, that this does not happen in reality. Sub-optimal choices are mostly observed, independently on the individual's level of education. His research rests on, and corroborates, a behavioural theory of market agents that diverges broadly from neoclassical economic theory, and therefore questions the value of incentives. Market institutions may improve the performance of systems, but the benefits are not automatic: they depend on the feedback properties created by the system and the market institution. The effects of public policies are not instantaneous and cannot compensate for the misbeliefs and miscalculations of people.

Yet, it is in the interest of this research to dive into the mechanisms of policies directed to BEVs. It is believed that SD, offering a systems perspective and an integration of economic, technical and social factors, can bring light to this complex topic.

In this research, a classification of policies, alternative to the ones already existing, will be applied. This is based on the stages in vehicle ownership: first the consumer must take the purchase of a BEV into consideration, then comes the purchase, then comes the use of the vehicle over the vehicle's lifetime. It can be useful to map the ownership by stages because each policy instrument targets a specific stage in the ownership phase, and a related barrier to the adoption. For example, at the stage of consideration, the main barrier for a potential adopter may be the lack of knowledge or of trust for the alternative. Information campaigns can therefore "educate" the consumer to the real attributes of the BEV. After consideration, an additional barrier for the potential adopter may be the price: if the relative difference in prices is not affordable, motivation to buy will not be sufficient. Premiums on purchase or tax exemptions can help to reduce the price differential. Throughout use, the BEV ownership may still present challenges, for example in relation to charging availability. Investments in infrastructure development can generate more favourable conditions, and practical benefits such as access to bus lanes and free parking can be strong drivers of attractiveness.

Table 1 maps the three stages and the respective barriers and policies. This mapping is functional to motivate the structure of the simulation model, which will be presented in the next chapter. However, the model will not include all the policy instruments listed due to the model boundary definition, as will be presented in chapter 4.

Table 1. The BEV ownership story

Stage	1: Considering	2: Purchasing	3: Using
Barrier to adoption	Low awareness, Low trust, Low social attractiveness	High price, Lack of offer	Range limit, Lack of charging facilities, payment of high road tax, of road tolls, no parking, congestion
Policy instrument	Information campaign, Marketing, Advertisement, Media coverage, Consumer surveys, Research	Subsidies, Tax exemption, Vehicle leasing opportunity[4], BuyBack programs[5], Upgrading of market offer	Free charging, Infrastructure development, Exemption from road tax, from road tolling Free parking, Access to bus lane

3.3 Theory on competition

Neoclassical economic theory supports a Darwinian market view: competitive selection will efficiently lead to the "survival of the fittest" (Spencer, 1851). Market systems behave however not always in this optimal fashion, as discussed in the section above (Kampmann & Sterman, 2014): in the end of the 19th century, the ICEV won the competition against the BEV, which had, at that time, higher performance in speed and silence. There are many examples of harmful technological lock-ins, where a poor or inferior solution obtains the market share because a better solution arrived later or was side-lined by other reasons- as in the case of the Dvorak keyboard, which is claimed to be more time-efficient than the standard Qwerty layout (Arthur, 1989). Struben and Sterman (2006) also describe technological lock-in as one of the main challenges in technology transitions. This study aims to incorporate behavioural elements in the determination of the BEV market share.

The following market setting is being modelled: the competition between two vehicle alternatives: a market incumbent, the ICEV, and a market entrant, the BEV. Even though the ICEV is an umbrella term for both traditional gasoline, diesel, and newer biofuel-driven and

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[4] **Vehicle leasing** is the use of a motor vehicle for a fixed period of time at an agreed amount of money. It is commonly offered by dealers as an alternative to vehicle.

[5] **BuyBack programs** involve the driver being paid for turning in his/her working old car for scrapping. It is a program designed to take old, polluting vehicles off the road

hybrid electric cars, the present research considers this whole class as the actor currently controlling the market. The market entrant is the BEV, representing the technological innovation and the competition challenge to the ICEV. The market incumbent is considered to have reached near to technological maturity and to be well established and stable in the market. Sterman (2000, ss. 349-406) analyses a series of battles for dominance between market alternatives where the appeal of the product depends on the present market penetration and on the availability of complementary resources. Competition is seen to drive a strongly path dependent behaviour: reinforcing forces can become so strong that "the chance that any random shocks or policies might reverse the outcome is vanishingly small" (s. 402). The setting described here is slightly different since the ICEV and its complementary resources (gas stations, reparation services, technical knowledge) are well-established, while the BEV needs to build its base. Characteristics such as relative price and performance will therefore be more important to determine which vehicle alternative would take over the market. The specifications of the current research will be described further in the next chapters.

Another behavioural economic theory can support in understanding how people choose between options that involve risk: Prospect theory (Kahneman & Tversky, 1979). The theory states that people make decisions based on the probable value of losses and gains rather than the final outcome. In addition, losses and gains are not evaluated objectively, as Utility theory would describe: in this evaluation, people apply certain heuristics that deform the objective value. In particular, people have a tendency to be loss averse, and are hence more risk prone in cases of gains than in case of losses. The value of gains and losses is therefore a non-linear function. This theory has been applied to the contexts of stock markets, gambling (Barberis & Haung, 2006) and other contexts which have been found difficult to reconcile with traditional economic theory. This theory will be applied in the present study when considering the value of vehicle costs and performance.

Plötz (2014) argues that successful market strategies and policies for technological innovations depend on knowledge about the characteristics and needs of early adopters. In the next section, it is argued why knowledge about all adopter groups is important for understanding BEV diffusion, and not just early adopters.

3.4 BEV adopters

Who is the typical BEV adopter? Research mapping the profiles of BEV adopters has only been able to reflect real decision making in the most recent years (Figenbaum & Kolbenstvedt, 2016; Knupfer, et al., 2017; Lovin & Andersson, 2017) since the market started growing to a significant extent in the last decade, and empirical data could then be collected for the first time. Contemporarily, study on earlier diffusions of technologies has resulted in theories on innovation adopters, among which Rogers' Diffusion of Innovations theory (1976). The discussion on BEV adopters will start with the presentation of this theory.

Rogers' theory seeks to explain how, why and at what rate new ideas and technology spread. Rogers defined diffusion as a process where an innovation is communicated over time through certain channels among the members of a social system. To become self-sustained, the adoption rate must reach a so-called critical mass. A similar concept is discussed in Struben and Sterman (2006): a critical threshold. In Rogers' theory, this threshold is 50% of the total market share. Rogers defines a chronological sequence of adopters:

1. Innovators
2. Early adopters
3. Early majority
4. Late majority
5. Laggards

Figure 5 shows the classification of successive consumer groups adopting the new technology (shown in blue). Its market share (yellow) will eventually reach the saturation level. The adoption follows an S-curve when plotted over time. In mathematics, the yellow curve is known as the logistic function.
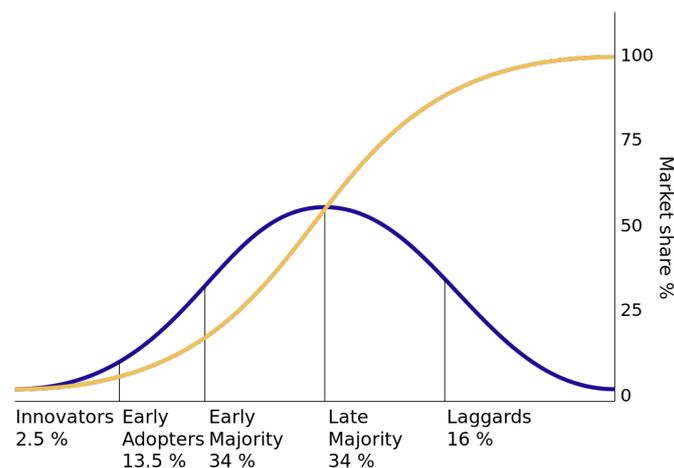
Figure 5. Rogers' Diffusion of Innovations theory

Each category has traits that influence their likelihood to adopt the innovation. The first share of adopters is more open to adjust, in the desire to adopt the innovation. This adjustment can be in the behaviour, in the price paid, or in the comfort. The motivation to adjust can derive from the symbolic value of the innovation (e.g. environmentally friendly, high class) or from the fact that the risk taken is not that high for these individuals (this may be the case for multi-vehicle households, wealthy individuals or for urban drivers). As larger market shares are conquered, consumers with a higher aversion to risk face the choice of adoption. Adoption will not take place unless specific criteria are met, which can range from cost to performance parity or to social acceptability. Table 2 lists in detail the characteristics of Rogers' adopter categories (Rogers, 1976, s. 283).

Table 2. Adopter categories

Adopter category	Definition
Innovators	Innovators are willing to take risks, have the highest social status, have financial liquidity, are social and have closest contact to scientific sources and interaction with other innovators. Their risk tolerance allows them to adopt technologies that may ultimately fail. Financial resources help absorb these failures.
Early adopters	These individuals have the highest degree of opinion leadership among the adopter categories. They use judicious choice of adoption to help them maintain a central communication position. Early adopters have a higher social status, financial liquidity, advanced education and are more socially forward than late adopters. They are more discreet in adoption choices than innovators.
Early Majority	They adopt an innovation after a varying degree of time that is significantly longer than the innovators and early adopters. Early Majority have above average social status, contact with early adopters and seldom hold positions of opinion leadership in a system.
Late Majority	They adopt an innovation after the average participant. These individuals approach an innovation with a high degree of scepticism and after the majority of society has adopted the innovation. Late Majority typically have below average social status, little financial liquidity, in contact with others in early majority and little opinion leadership.
Laggards	They are the last to adopt an innovation. Unlike some of the previous categories, individuals in this category show little to no opinion leadership. These individuals typically have an aversion to change-agents. Laggards typically tend to be focused on "traditions", lowest social status, lowest financial liquidity, oldest among adopters, and in contact with only family and close friends.

The results of empirical data collection on BEV adoption (Figenbaum & Kolbenstvedt, 2016; Knupfer, et al., 2017; Lovin & Andersson, 2017) bring valence to the theory. The global BEV market sales share reached 3.7% in 2016. Following Rogers' theory, this implies that the next target for the future BEV sales are the Early Adopters category. The study by Figenbaum and Kolbenstvedt, analyzing surveys from 3111 Norwegian BEV drivers, reports that 71% of BEV owners are multi-vehicle households and live in urban areas. Very few drivers report issues with charging availability, since the majority enjoys good access to private parking and

charging facilities at home. This can be the case for many households with high income and living in low-density areas.

The most commonly stated reasons to buy a BEV were: the environmental performance, owning a future-proof technology, economy of use and exemption from road tolls. The first two stated reasons reflect the eco-friendly mindset of Innovators, as classified by Rogers. The last two reasons- economy of use and exemption from road tolls- show that purchase price was not a barrier for these adopters, while they seem to consider the Total Cost of Ownership (TCO) more than the purchase price. Since the BEV battery has not reached technological maturity, the vehicle lifetime is uncertain. Considering the total cost of ownership therefore requires taking a gamble, and financial liquidity is required. This corresponds to the first adopter category described by Rogers.

The driver characteristics of Innovators reported in empirical data studies as the ones described above are not representative for the society at large. The challenge of data sampling is indeed to include both potential and actual adopters so that the whole society's opinion is documented. Potential adopters are in fact the richest source of information regarding the barriers to diffusion. In addition, the opinion of adopters is often skewed by heuristics such as the attitude-action gap (Lane and Potter, 2007). This is an example of a frontier where theory can be applied to empirical contexts. Following Rogers' theory, the next horizon of BEV adopters is going to be individuals with a high social status and a strong opinion leadership. For the BEV to surpass the critical threshold of adoption, sales efforts must be addressed to individuals who are more budget-focused and satisfying their requirements in performance parity on most criteria: range, lifetime, charging availability, and model diversity (Knupfer, et al., 2017).

Based on driver behaviour studies from the Swedish context, Lovin and Andersson (2017) describes two categories of disadvantages related to BEVs:

1. Cost-related, which may be related to three aspects:
   a. Purchase price
   b. Operational Costs
   c. Depreciation and related 2nd hand value

2. Related to vehicle attributes, e.g.
   a. Travel range
   b. Lifetime
   c. Unavailability of specific vehicle model
   d. Comfort

e. Safety

In addition to cost and performance disadvantages, research points to other possible obstacles to diffusion. McKinsey's empirical studies from the US, China, Norway and Germany (Knupfer, et al., 2017) show that consumers have misconceptions about EV maintenance costs, reliability and driving performance: the maintenance and operational costs are misconceived to be much higher than they are. The review of driver behaviour studies done by Lovin and Andersson (2017) also points to the existence of many urban legends and little knowledge on AFVs. Drivers' opinion is that information and marketing campaigns are difficult to understand, and therefore to trust. Misconceptions about costs are an especially challenging topic which will be discussed further in section 3.5.

The research also shows that there exists a large gap between expected and experienced barriers and benefits. Approximately 50% of drivers are yet not familiar with EVs and related technology. In Germany, 30% of drivers consider purchasing a BEV, but only 3% end up doing it. One of the reasons pointed out is that consumers tend to prefer and trust traditional brands; hence, even if Tesla is an exciting and popular topic, when it comes to the purchase decision, most consumers will pick a familiar brand. Struben and Sterman (2006) and Pasaoglu (2015) (based on Struben and Sterman's work) talk about "willingness to consider" as an action involving both obtaining information, understanding and gaining emotional attachment. Figenbaum and Kolbenstvedt (2016) argue that peer-to-peer contact is the main source of information leading to purchase, as this oral contact creates trust and reliability. The study calculates that the average BEV owner influences about 1.2 persons to buy and 1.2 persons to consider buying a BEV. In presenting the modelling of innovation diffusion, Sterman (2000, p. 323-346) presents the word of mouth reinforcing feedback as one of the strongest loops driving the diffusion. For the specific context of vehicles, Struben and Sterman (2006) also present word of mouth and related network effects as the major drivers. Thus, self-sustaining sales of BEVs seem to be supported by peer-to-peer contact, at least if the valence is positive: the speaker's opinion on BEVs needs to be positive in order to increase the popularity.

Based on the presented literature, this study considers awareness, confidence and willingness as important factors behind the diffusion of BEVs.

In economics, a consumer's satisfaction for a good or a service is measured by its *utility*. Utility can be defined objectively and subjectively. In system dynamics, a concept similar to subjective utility is called *attractiveness*. Being a system dynamics study, the concept of BEV attractiveness will be discussed from now. BEV attractiveness can be defined as the degree to which the purchase of a BEV instead of a conventional vehicle is a more appealing option. The

attractiveness is defined in both monetary and non-monetary terms. In the present study, two aspects of attractiveness are defined, based on the reviewed literature: objective attractiveness and awareness. The objective attractiveness is itself composed of two main categories: costs and performance. In the next two sections, these categories will be discussed in depth.

3.5 Costs

The ownership of a vehicle implies expenses both at purchase and throughout use. Depending on the vehicle type, these expenses may differ considerably, as this depends on production costs, on fuel price, on maintenance costs, on vehicle lifetime and other factors. These factors can differ significantly between the two vehicle alternatives, which does not make the price of purchase alone a representative indicator in the comparison between vehicle types. We need to look at the entire ownership lifetime of a vehicle. In the 2017 McKinsey study (Knupfer, et al., 2017) it is argued that, in order to make BEVs into a profitable business, automakers need to shift their economic balance from purchase price to TCO: this, they argue, is the only way to overcome the cost barriers at production and increase profitability. A new business model, the argument continues, is needed where the automaker is involved throughout the vehicle lifetime. In the same way, the consumer needs to move the focus from purchase price to operational costs. That is where the large benefits of BEVs lie, compared to the ICEV (Knupfer, et al., 2017). Drivers seem to misconceive operational and maintenance costs of BEVs: drivers may save money on fuel and maintenance over the long term, but a higher initial price at purchase remains intimidating (Knupfer, et al., 2017). This reflects consumers' bounded rationality: behavioural economics demonstrates that consumers do not maximize individual utility: they make inaccurate evaluations, use heuristics and rules of thumb, often follow a social, instead of individual, utility (Kampmann & Sterman, 2014).

It seems important to take into consideration the value of the total cost of ownership, even if consumers do not do this instinctively. The present research will explore BEV attractiveness by considering a combination of the two.

3.5.1 Purchase price

At purchase, the price paid includes a start price of the vehicle, as delivered from the automakers, and taxes set by the government. The purchase price of a BEV before eventual tax exemptions and subsidies is to date on average higher than a comparable ICEV, creating a barrier to diffusion (Knupfer, et al., 2017); in other words, "mass-market cars need mass-market prices" (Randall, 2016).

The main price component of the BEV is the battery pack (Wikipedia, 2017). The actual costs of battery packs and the development of the price in the future are much discussed and speculated upon. There are many drivers behind the development of battery costs, first of all investments in R&D. Economy of scale and efficiency in manufacturing can also speed up the rate of batteries' technological development.

A study published in February 2016 by Bloomberg New Energy Finance (BNEF) observes that battery prices fell by 65% since 2010, and by 35% just in 2015, reaching US$350 per kWh in 2016 (Randall, Bloomberg L.P., 2016). The study concludes that this trend will allow price parity between the BEV and the ICEV by 2022 without government subsidies. By 2040, long-range electric cars are projected to cost less than US$22,000 expressed in 2016 dollars. BNEF expects electric car battery costs to be well below US$120 per kWh by 2030, and to fall further thereafter as new chemistries become available (BNEF 25/2/2016).

McKinsey estimated that the cost of battery packs will not be competitive before 2030, when it will reach $100/kWh, and expects pack costs to be $190/kWh by 2020 (Knupfer, et al., 2017). The automaker Tesla, on the other hand, claims to be below $190/kWh since the beginning of 2016 (Lambert, 2016).

The second important component in the price are government subsidies and vehicle taxes. As discussed in section 3.2, there exist many types of policy instruments that can target the consumer at the stage of purchase: tax exemptions on BEVs, emission taxes on ICEVs, purchase subsidies, leasing and payback programmes. All these policies are meant to lower the gap between the ICEV and the BEV's price.

As a consequence of technological development and market of scale, the purchase price of BEVs has the potential to converge towards that of the ICEV, also without subsidies (Dodge, 2014). The production costs of the BEV, once the challenge of the battery is surpassed, may even be lower than those of the ICEV because of simpler technology (Fridstrøm & Østli, 2017).

3.5.2 Operational costs

Operational costs are calculated over an annual basis and include among others refuelling/recharging costs, road tolling, circulation tax, the cost of travel time, parking expenses, costs of maintenance and repairs.

The refuelling costs for the ICEV depend on the price of fuel and on fuel efficiency. Being an umbrella term, ICEV fuel will include gasoline, diesel, biofuels, liquefied petroleum gas and compressed natural gas. The price development of each of these fuels over the next decades is highly uncertain, as well as the use share of each. The forecasts used in the ETO model are adopted in the present study (DNV GL, 2017). The average fossil fuel prices are expected to

decrease over time starting in 2020 as a result of improvements in production effectiveness resulting from digitalization. Fuel efficiency is also assumed to improve over time. Historical values have been applied to the Study's context based on IEA's Fuel Economy study (2015, s. 118), and for future values it is assumed that the decaying trend is followed, but at a slower rate.

Similarly, the price of recharging depends on power prices, battery efficiency and charging behaviour. Due to rapid development and cost reduction of renewable energies such as solar and wind power, the sustainable production of electricity is expected to grow in capacity and availability and electricity to become cheaper over time. The power distributor then regulates the price to the consumer. The power supplied to households is often priced differently than in public spaces. Fast charging stations provide a higher power transmission speed and are therefore more costly than slow-charging facilities. Vehicle charging can also be free of charge in special cases: an example is Norwegian public parking and charging locations in urban areas, which are subsidized by the government. Hence, depending on whether the driver uses mostly fast charging, slow charging, home or public connections, the price may differ considerably.

When considering the cost of travel time, theory from transportation economics can be applied to convert the time lost or saved into monetary terms. Driving a BEV may cause time loss because of the longer time to charge the vehicle. On the other hand, there are many contexts where BEVs are given access to bus lane or to areas with limited traffic, therefore avoiding congested lanes and saving time. The cost of travel is an important determinant of vehicle attractiveness among consumers, but not as much as vehicle price (Sierzchula, Bakker, Maat, & can Wee, 2014; Bjerkan, Nørbech, & Nordtømme, 2016).

One important component in vehicle operational costs are toll charges. This toll is increasing in many cities as a measure to reduce vehicles in high-traffic areas and thus reduce air and noise pollution (Flamig & Wolff, 2016). As the emission levels of new vehicles are lower and as low-emission vehicles are entering the market, road tolling is becoming vehicle-specific. The "polluter pays" principle is applied in many cases. Markets are also experimenting space-and time-specific road tolling, also called "dynamic" road pricing: based on GPS data, the system charges the driver based not only on the vehicle type but also on where and when he/she drives (Norwegian Department of Transportation, 2017; De Borger & Glazer, 2017).

Vehicle maintenance is also a considerable cost in the ownership of a vehicle. Depending on the technology, reparations can be quite costly. A market of vehicle parts and a diffused technical knowledge about the technology are prerequisites for the vehicle maintenance.

3.6   Vehicle performance

A second component of BEV attractiveness can be considered the vehicle's performance. A vehicle has many attributes: travel range, lifetime, design, horsepower, the fitness of the vehicle model to the needs, emission level, comfort, safety, speed limit, speed of acceleration, and more. The present study's main objective is to compare the ICEV and the BEV's attractiveness for the average consumer on a simplified set of criteria. The following five attributes are therefore selected:

1. Range
2. Recharging density
3. Lifetime
4. Diversity of BEV market offer
5. Emission level

3.6.1   Travel range

BEVs and ICEVs have not yet reached range parity. The limited range of BEVs is considered one of its major caveats (Thiel, Alemanno, Scarcella, Zubaryeva, & Pasaoglu, 2012), and is indeed the performance attribute that made the BEV lose the competition with the ICEV at the rise of the vehicle history in the US, at the end of the 19th century (see chapter 3.1). Extensive research is ongoing to eliminate this imparity and boost BEV attractiveness (Liebreich, 2017; International Energy Agency, 2016). To present, only the Tesla S, with a 100 kWh battery, has reached a travel range of 500 kilometres, close to that of a typical ICEV (between 500 and 1000 kms).

The BEV's travel range depends on a number of factors: the battery capacity (in other words, the energy storage), the weight and type of vehicle, and also weather conditions, terrain and driver performance. Under very low temperatures, batteries exhibit a weakened capacity, hence reducing the vehicle travel range.

The importance of travel range varies among consumer profiles: urban settlers will not require a high range on a daily basis, as their travelling pattern includes the distances home-work or home-shop, and these can be covered by the current BEV models. For people living in rural areas on the other hand, or in regions with a high frequency of extreme temperatures, travel range is a key performance requirement (Thiel, Alemanno, Scarcella, Zubaryeva, & Pasaoglu, 2012).

3.6.2 Recharging density

One of the main obstacles for the diffusion of an AFV is the lack of complementary infrastructure, such as charging stations for the BEV (Harrison & Thiel, 2017; Struben & Sterman, 2006). This topic is therefore considered in this study as a main attribute defining BEV performance. If the density of charging stations is too low, the performance of this vehicle alternative will be considered low. The European Clean Power for Transport directive recommends that there should be one publicly available charging point every 10 EVs by 2020, (without specification of transmission type). If we consider the forecast of over 200 thousand vehicles in Norway in 2020 (Fridstrøm & Østli, 2017), a total of 20 thousand charging points would need to be installed, which is three times the present number (9088 as of 19.05.2017. retrieved in the same date from nobil.no).

BEV batteries must be periodically recharged with a frequency that depends on the battery capacity and on the kilometers travelled. The travel range has been shorter than the ICEV's up to present. On the other hand, most BEV owners recharge their vehicle overnight on slow-charging home-connectors, or while they are at work or at the mall, while the car is parked. The refuelling patterns are therefore considerably different than the ICEV's, and may change over time.

The driving behaviour is also an important determinant of what type of charging infrastructure that is needed. Driver behaviour studies conducted by the Norwegian Transport Economic Institute (Figenbaum & Kolbenstvedt, 2016) report that Norwegian BEV owners charge mainly at home; only 10% of BEV users make use of public chargers on minimum a weekly basis. Public chargers are used mainly in case of bad planning, and in case of longer trips. Long trips with private vehicles make traditionally only 2% of total trips (Norwegian Statistics Central Boureau, 2017). This can contribute to explain why public chargers are so rarely used. In addition, these public fast chargers are used at a cost, while most park-and-charge facilities are free of charge (Sierzchula, Bakker, Maat, & can Wee, 2014). On the other hand, as the BEV travel range increases, the travel habits may change and BEVs may be used for longer trips as well (Sierzchula, Bakker, Maat, & can Wee, 2014).

Charging points can be differentiated on the basis of many characteristics: location (home, roadway, city road, near shops, work), charging effect (slow, medium or fast), price of charging, popularity. This study defines a classification of charging points based primarily on the function of the charging point: some charging stations are built in a similar way to gas stations, while other are connected to a parking solution. In nowadays' congested cities, parking space is a

valuable resource for car travellers (Norwegian Department of Transportation, 2017): a vehicle is parked for approximately 90% of the day. Reduction of parking space is one of many instruments through which governments can control traffic volumes (Norwegian Department of Transportation, 2017). In many cases, BEV drivers enjoy free and secured parking spots in the city connected to charging infrastructure (Amsterdam Round Tables and McKinsey & Company, 2014); this is a way in which governments increase the attractiveness of BEVs. These charging points can both be slow and fast, and they can be located in streetways, in front of shops, at the workplace or in the household's parking space.

There are also charging stations which resemble very much the classical ICEV's gas station. These are often along roadways, primarily outside of the city centre, and especially on intra-urban connections, and offer predominantly fast charging.

There is more than one barrier to the construction of charging stations: costs, fitness of local grid, and likely returns on investment. Depending on the location, the costs can be very high if an extension or upgrading of the electricity grid is required (Norwegian Ministry of Watercourses and Energy/ NVE, 2016). These costs may not be attractive if there is no certainty of a strong business model. Hence the installation of charging stations for BEV is halted by both technical, economic and psychological factors.

3.6.3 Vehicle lifetime

The lifetime of a vehicle is an important parameter determining user satisfaction: the average ICEV has a lifetime of 18 years, and the purchase of a vehicle is therefore considered a long-term investment. Due to a poor battery technology and to the high speed of technological development, BEV models have a shorter lifetime than their competitors up to date. This is however improving over time, and forecasts predict that the BEV will have a higher lifetime than the ICEV in the long term (Knupfer, et al., 2017).

3.6.4 Car type diversity

Pasaoglu et al. (2015), Knupfer et al. (2017) and Struben & Sterman (2006) point to market offer as a main driver of BEV diffusion. Due to the low performance and high production costs, automakers (apart from Tesla) have not included many BEV models in their portfolio. The first models that came to the market were targeting specific niches, such as consumers of luxury vehicles (as in the case of the Tesla S) and environmentally minded, urban settlers (as in the case of the Think City). The Nissan Leaf was one of the first models targeting average households, and is today the EV market leader in compact cars. To conquer more niches, a

higher diversity of models must be offered on the market. In 2018, more than 50 EV models across all vehicle types are expected to come on the market as a result of the increased optimism towards BEVs both in the automotive industry and among consumers (Liebreich, 2017).

3.6.5 Emission factor

BEVs have zero tailpipe-emissions and are therefore advocated as the best alternative to the ICEV to solve the problem of air pollution in the cities and CO2 levels in the global atmosphere (Prud'homme & Koning, 2012). It must be noted that global warming emissions need to be considered from an integral lifecycle perspective, hence not only considering the moment of driving, but also the manufacturing and the end disposal. The carbon footprint of the BEV is highly dependent on how electricity is produced (Wikipedia, 2017): If deriving from hydropower, wind or nuclear, 99% of emissions can be reduced, compared to an average new 2014 car. Electricity generated from solar and geothermal offers a reduction of 92% in emissions, while natural gas offers 51% reduction. Electricity produced from oil or coal generate a zero reduction.

All ICEVs emit exhaust gases, which are composed for the largest part of nitrogen, water vapour and carbon dioxide; these are not toxic or noxious, although carbon dioxide is a greenhouse gas that contributes to global warming. A relatively small part of combustion gas is undesirable or toxic substances, such as carbon monoxide, hydrocarbons from unburnt fuel, nitrogen oxides (NO_x), and particulate matter (mostly soot). The introduction of biofuels can reduce life cycle GHG emissions by 19-48% depending on the source of energy used during fuel production (U.S. Dep. of Energy., 2017).

The five attributes described above are considered the most important elements in the definition of the relative BEV performance compared to the ICEV. Before that, relative costs and consumer awareness were described. But there is one more aspect which is very important to define the diffusion of BEVs, and that is the context. Since the present research proposes to compare the Norwegian and Swedish BEV systems, the final part of this chapter will present the two countries' contexts in relation to the BEV.

3.7 The Norwegian context

Norway has a population of 5.2 million people (Norwegian Statistics Central Boureau, 2017) and 94 000 kilometers of roadways over a land coverage of nearly 400 000 square kilometers (CIA, 2013). The population density is low and the nature is "hard", as much of the country is

dominated by mountainous terrain: therefore, the development of public transport in rural areas has been low, and many people depend on private vehicles for travelling (Wikipedia, 2017). Norwegians show among the highest GDP per capita worldwide, with a 2016 average of $70 655 (2017 $) (International Monetary Fund, 2017). The country is rich in hydropower, and 99% of the electricity produced in the country is from renewable sources- of which 98% is hydropower. The state has large ownerships in the industry (Wikipedia, 2017).

The country does not have a large automotive industry, but the vehicle density over the population is high, with a historical average of 0.4^6 vehicles per person for the period 2000-2017. The car fleet was composed of 1.6 million vehicles in 2000 and grew to 2.7 million vehicles in 2016 (Norwegian Information Council for Road Traffic/ OFV, 2017). The sales rate has grown substantially over this period, from a low of 88 000 vehicles in 2002 to a high of nearly 155 000 in 2015 (Norwegian Information Council for Road Traffic/ OFV, 2017). Following the method applied in the ETO model (DNV GL, 2017), the growth in the car fleet is assumed to be correlated to the development of the GDP per capita. The Norwegian Statistics Central Boureau (SSB) assumes an approximately linear growth in the population over the next decades, reaching 5.6 million people in 2026, 6.2 million in 2040 and 6.6 million in 2050 (2017). The highest population growth is expected in and around the largest cities: by 2040, Oslo and Akershus are expected to see a 30% growth in population (Norwegian Department of Transportation, 2017). The ETO model (DNV GL, 2017) derives forecasts of GDP per capita for the European region, which is expected to have a strong linear growth over the whole simulation period. Being amongst the highest ranked countries, Norway's range of improvement is narrower than economically developing countries. Hence the GDP per capita is expected to grow more moderately than the European average. Vehicle density is therefore also expected to grow moderately over the considered period up to 2050.

In December 2015, in Paris, countries across the globe adopted an international climate agreement at the U.N. Framework Convention on Climate Change Conference of the Parties. In anticipation of this moment, countries publicly outlined the intended climate actions post-2020, known as their Intended Nationally Determined Contributions (INDCs). Norway has set the target of reducing GHG emissions by 40% by 2030 compared to 1990 levels (Norwegian Department of Transportation, 2017). In the Transport plan 2019-2028 outlined by the Transportation Department in 2017, the targets for the transition to fossil-free transportation are

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[6] calculated from demographic and vehicle fleet data (Norwegian Statistics Central Boureau, 2017)

set. The Norwegian government has established its intention to become a carbon neutral society by 2050- starting with no new ICEV sales after 2025. A coalition of political parties has favoured the introduction of incentive programs to zero- and low-emission vehicles since 1990. The abundant and cheap access to zero-emission hydroelectric power allows the possibility to offer free charging at many public charging stations without large costs, compared to other countries.

The Norwegian government has defined high taxations on vehicles, so that the retailer vehicle price only constitutes approximately 50% of the total price paid by the private individual (this and next values are retrieved from (Norwegian Tax Agency, 2017): the Value Added Tax (VAT) adds 25% of the original price, while the purchase fee can add up to 70% of the base price depending on vehicle weight, CO_2 and NOx emissions; further minor taxes and fees apply. Therefore, tax exemptions are a very attractive tool to increase BEV attractiveness relative to the ICEV: since 2001, the choice of a BEV can halve the vehicle price.

The list of policies directed to EVs is presented next in Table 3, by year of issue:

Table 3. Norwegian BEV policy history

Year	EV policy
1990	No purchase/import fee
1996	Low annual road tax
1999	Free municipal parking
2000	50% reduction on company car tax
2001	Exemption from 25% VAT on purchase
2005	Access to bus lanes
2009	No charges on road tolls or ferries
2015	Exemption from VAT on leasing contracts

In addition, a governmental program is in place to finance the establishment of at least two multi-standard fast charging stations every 50 kilometres over all main roads by 2017.

Today, Norway has the highest per capita number of BEVs in the world: more than 100 000 vehicles at the beginning of 2017, in a country of 5.2 million people (Wikipedia, 2017). The high rate of adoption has allowed the country to be the first to reach the European emission targets for the new sales vehicles of 85 g CO2/km in 2017- 3 years ahead of the stated target (by 2020). The Norwegian BEV strategy follows the "polluter pays" principle, not through bans, but through economic compensation for the differential and through practical benefits,

such as access to bus lanes and free parking (Norwegian Department of Transportation, 2017). In Figure 4, the type of policies adopted by each European country is outlined. It reveals that Norway has the largest portfolio of policies. Differently from most European countries (including Sweden), Norway does not use purchase subsidies.

The Norwegian incentive program will be revised in 2020 and adjusted in parallel with the BEV market development (Norwegian Department of Transportation, 2017). From 2018, the local authorities will decide on the local policies such as access to bus lanes and free municipal parking (Norwegian Department of Transportation, 2017). Free toll roads will be replaced with a dynamic pricing system in 2018 based on CO_2 and NO_x emissions and on the time and place of travel; the price will however never surpass 50% of the price paid by ICEVs (Norwegian Department of Transportation, 2017).

Following the historical demographic trend and its correlation with the vehicle fleet size, one could assume that the vehicle fleet will double in size by 2050. However, in the ambition to become a fossil free society and maintain high environmental standards, the government has also set the target of a zero-growth in the vehicle fleet in all major cities (Norwegian Department of Transportation, 2017). Demographic growth will concentrate in and around the city areas, and the additional demand in mobility will need to be covered by public transport, walking and biking. Large investments are dedicated to the development of these modes of mobility. Consequently, the natural growth of the vehicle fleet will be weakened.

The passenger transportation by light vehicles is envisioned to become emission free by 2040. Being a member of the EEA, Norway has signed to achieve a 10% share of renewables in the transportation system already by 2020. Electric vehicles, biofuels, gas and hydrogen vehicles are all considered renewable sources and can be possible strategies to achieve the goal.

The BEV is the primary long-term strategy for Norway, while hybrids and biofuels are considered important platforms in the short-term transition phase; hydrogen is considered a feasible strategy only starting from 2025, when the technology will be more advanced (Norwegian Department of Transportation, 2017). Norway must in addition comply with European regulations on fuels, implying that fuel emissions per energy unit must be reduced by 6% by 2020 compared to the EU average level in 2010. This can be achieved, among others, with broad use of biofuels. Some incentives and regulations have therefore been introduced to diffuse the use of biofuels. However, the Norwegian strategy is unilateral on BEVs, and biofuels and hybrids do not obtain the same financial and practical benefits as the BEV (Norwegian Department of Transportation, 2017).

In addition to the regulations and subsidy programs, the government founded in 2001 the company Enova SF, with the role of supporting in the restructuring of the energy system. The company disposes of public sums to invest in projects and research for development of low emission technologies. Enova has had a leading role over the years in supporting BEV marketing and awareness campaigns, charging infrastructure development and research (enova.no).

An important factor in the diffusion of BEVs is the charging infrastructure. With an increasing sales market share (22% in 2015), there could be up to 250 000 EVs in Norway by 2020. Following the European Clean Power for Transport directive, this fleet size would require 25000 publicly available charging points; today (June 2017) there are less than 9 000 points, so much work is still required. Of these charging points, 54% are on public roads, 12% in car parks and 12% outside shops. Most charging points use standard connectors (76%) while 11% are accelerated and 13% are fast charging.

There is large optimism over the future of BEVs in Norway. The installation of charging points is becoming a business opportunity, as reports Defa CEO (DN, 2017). The Norwegian EV Association voices that the Norwegian system works because it is constructed to make the least polluting cars the most attractive. In addition, incentives need to stay in place long enough to change the way people think about transportation; - otherwise the trend will fade away as a fashion. This argument is in line with system dynamics theory (Sterman, 2000) and with Geels (Geels, 2005), who states that the shift in values, belief systems, ideologies and public opinion are the core of every transition process.

3.8   The Swedish context

Sweden has a population of 10 million people and 580 000 kilometers of roadway over 450 square kilometers of landscape. Sweden consequently has a low population density and rich natural resources, primarily forests. Sweden is ranked high (17th) in GDP per capita: $49 836 (International Monetary Fund, 2017). Timber, hydropower and iron are the main resources of its export-oriented economy, and the industry is mainly privately owned. Sweden is also the largest European biofuel producer thanks to its abundant forests. Sweden held historically an important export-based automotive industry, with the automakers Volvo and Saab. To present, these companies are owned by foreign entities.

The production of electricity derives from a mix of sources: 44% from hydropower, 47% from nuclear, 9% from biofuels and 1% from wind (Wikipedia, 2017). The government has declared its intention to phase-out nuclear power. The country intends to become one of the world's first

fossil-free societies; for the transportation sector, the objective is to achieve fossil fuel independence by 2030 (Saxton, Levin, & Myhr, 2016). The outlined strategy is to transit fossil to a share of biofuels and electric-driven vehicles; biofuels will play an important role in the short-term, while BEVs will take a more important role once price and performance parity is reached on an international scale (Swedish Government, 2013, s. 39). The expected market shares for the BEV are 20% in 2030, 40% in 2040 and 50% in 2050. Sweden also delivered its INDC in 2015 stating the objective to reduce total GHG emissions by 40% by 2040, compared to 1990 levels.

Over the last decade, many policies have been put in place to help the transition to greener vehicles, in particular to biofuels. Being part of the EU, European regulations and targets are followed, but strategies are designed at country level. The government has stated technological neutrality and supports all fuel vehicle types with low environmental impact: biofuels, electricity-driven, gas, hydrogen and fuel-efficient internal combustion engines (Swedish Government, 2017). The underlying principle of the designed policies has been that vehicles with high emissions pay a tax that compensates for the negative effect that emissions cause, or conversely, that prize low emission vehicles: a "polluter pays" principle, also called "bonus-malus"; the intention is to reinforce this principle from 2018 (Andersson, 2017). This is in line with the theory on environmental policies (section 3.2) and is similar to the Norwegian policy strategy. Differently from Norway though, vehicle taxes only represent approximately 25% of the purchase price (as opposed to 50% in Norway). Hence, the marginal change in price after tax exemption is smaller in Sweden compared to Norway.

To achieve its targets in light vehicle transportation Sweden has implemented both direct subsidy programs, tax exemptions and diverse practical benefits, for example free parking. Table 4 shows the timeline of policies for greener transportation.

Table 4. Timeline of Swedish policies for light vehicles

Year	Policy
2000	Subsidies to infrastructure of biogas vehicles
2002	Generic tax exemption for biofuels (ethanol and biogas)
2002 – 2011	Reduced benefit taxation to biofuels and el-hybrid vehicles
2006	The Pump Act for biofuels
2007	Financial contribution to biofuel pumps

2007 – 2009	*Miljobil*[7] premium
2007- 2009	Exemption from congestion tax to biofuels and el-hybrid vehicles
2009	5-year tax exemption to all *miljobilar*
2012	Lower tax benefit to all *miljobilar*
2012	premium to *supermiljobil*[8]
2013	Differentiated vehicle tax to all fuel-efficient vehicles

As can be seen in Table 4, Sweden has invested primarily in biofuels: from 2000 to 2012, economic incentives have been given to increase biofuel sales. In addition, all fuels from renewable sources such as ethanol, methane, biofuels, peat and waste are exempted from CO_2 taxes. This has allowed a large expansion of the use of biomass in transport, heating and the industry. The results in the transportation system are manifest: there were nearly 230 000 ethanol-driven vehicles in the streets in 2015. Emissions from new vehicles have fallen since 2006 and the total fleet emissions have sunken as well, despite the growth in the fleet.

However, it has been observed that the use of ethanol is highly volatile: since most vehicles do not need motor modifications to be fuelled both with petrol and with E85 (the most diffused ethanol based biofuel), the driver will choose which fuel to use based on price. In addition, as the fuel efficiency is lower, the same full tank of E85 does not give the same mileage as the tank with diesel or gasoline. Very few drivers choose to pay more for the fuel at the benefit of being environmentally friendly.

From 2012 biofuels have lost some of their benefits, while the *Supermiljobilspremium* for EVs was introduced. The government declared the objective of having 600 000 electric vehicles (all-electric and hybrid) in the streets by the year 2020. This has created a competitive alternative

[7] The term *miljobil* is used in Sweden to classify vehicles with a low environmental impact. The definition has evolved over time, as technology developed, and also to be aligned with European standards. Nowadays, a vehicle can be classified as miljobil if certain requirements on vehicle emissions, vehicle weight and alignment with the European emission classes are satisfied. The definition is not limited to biofuels and electricity-driven vehicles, but also to highly energy efficient and low emitting internal combustion driven vehicles. A miljobil is subject to lower taxes, exemption from congestion pricing and it receives parking facilitations, access to bus lanes and to limited-traffic zones in some municipalities.

[8] From 2012 the definition of *supermiljobil* has been introduced: this includes vehicles of the class EU 5 and 6 with kilometer emissions lower than 50 g CO_2. This includes in principle only EVs (BEV and hybrids). The premium to supermiljobilar consists of 40 000 SEK to BEVs and 20 000 SEK to hybrids, plus the exemption from vehicle tax for the first five years.

to biofuels, but has not produced similar results: while the biofuel fleet has stabilized in size over the last 4 years and the hybrid fleet counted 43 000 vehicles in 2016, the BEV fleet counted only 7 700 vehicles.

In the most recent declaration on climate strategies in the transportation sector (Andersson, 2017), the Swedish government has declared that the Supermijobilspremium will be kept in place until 2019; also, the bonus-malus system is intended to be reinforced, by increasing gradually carbon taxes and maintaining financial benefits to *miljobilar*. In addition, road and ferry tolls shall not be paid by EVs. The timeline of this strategy is not defined in the document.

Being part of the European Union, Swedish policy making follows European directives; among these, there is the directive on charging infrastructure which gives as a target to all member states to build one charging point every 10 electric vehicles (European Commission Press Release, 2014). As Enova in Norway, Sweden has a public financing and consulting institution for environmental innovation technologies: the public agency Vinnova. Electric vehicle alternatives are one of the fields addressed (vinnova.se, 2016). Enova and Vinnova also have collaboration programs.

7% of the national fleet is *miljobil*, but less than 1% of this portion is BEV. The Swedish experience over the last two decades shows a highly competitive environment among different AFVs. Nykvist & Nilsson (2015) criticize the governmental neutrality towards technologies for causing a weak signal and high confusion to both industry and consumers.

Finally, the attractiveness of EVs is weakened by the low density of charging facilities: in March 2017, 1010 charging stations were counted over the whole country.

Sweden and Norway have equally high ambitions for the emission targets of the national vehicle fleet, and the strategies followed by the two countries up to 2017 and planned for after 2017 are very different: while Sweden applies a large portfolio of alternative fuels, Norway focuses on one technology.

3.9   Dynamic hypotheses

This chapter has presented the research context and the theory on which the SD model is based. To help in answering the research questions, the SD model will be used to test a series of dynamic hypotheses which are derived from the literature or from the researcher's preliminary conjectures:

- *H1: Through the continued use of current BEV policies, the Norwegian BEV fleet will reach 1.5 million units in 2030* (Norwegian Ministry of Watercourses and Energy/ NVE, 2016)

- *H2: The Swedish BEV fleet will also reach 1.5 million units by 2030*

- *H3: If current BEV incentives are reduced in Norway by 2020, the BEV system will not be able to maintain a self-sustaining growth* (Figenbaum, et al., 2015)

- *H4: If current BEV incentives are reduced in Sweden by 2025, the BEV system will not be able to maintain a self-sustaining growth*

- *The main driver of difference in BEV adoption between the Norwegian and Swedish system is:*

  - *H5: the BEV policy strategy* (Figenbaum, Assum, & Kolbenstvedt, 2015)

  - *H6: Geographic and demographic characteristics of each country*

  - *H7: "it's just a matter of time": Norway started earlier with policy action*

- *H8: Cost parity between ICEV and BEV will be reached in 2030* (Liebreich, 2017)

4 Model description

In this chapter, the model built to answer the research questions will be presented. A general model will be presented first in conceptual and extensive form (sections 4.1 and 4.2), without contextualizing to the Norwegian or the Swedish systems. The contextualization will be discussed in section 4.4.

In order to present the model, some specifications on the topic of research are necessary. Furthermore, since a quantified model is built, a high precision is required in the definition of the variables, so that the model outcomes can be compared correctly with empirical data. The main variable considered is the number of battery electric vehicles registered in the country (Norway or Sweden). Only light-duty passenger vehicles are considered, being defined as motor vehicles having at least four wheels and for the carriage of passengers. This corresponds to the Category M as defined by the European Commission (Directive 2006/126/EC of 20 December 2006).

There exist two types of vehicle consumers: private individuals and actors operating entire fleets (companies, car rental agencies, public entities). It is assumed that the decision-making process behind purchase of vehicle is the same for the two groups. The study focuses on the first group, since it represents the majority and the model accordingly does not include eventual policies targeting fleet operators.

The following market setting is being modelled: the competition between the market incumbent and a market entrant. The market incumbent is the internal combustion engine vehicle (ICEV). Even though the ICEV is an umbrella term for both traditional gasoline, diesel, and newer biofuel-driven and hybrid electric cars, the present research considers this whole class as the actor currently controlling the market. The market entrant is the BEV, representing the technological innovation and the competition challenge to the ICEV. The market incumbent is considered to have reached near to technological maturity, and to be well established and stable in the market. Hence ICEV characteristics as the vehicle's lifetime, travel range and fuel station density are assumed to remain constant and for the market entrant to represent goal values that need to be achieved in order to become sufficiently competitive. The model structure of the two vehicle alternatives is therefore not fully symmetrical: there is no need, for example, to define

the structure for the development of gas stations, as these are already installed in sufficiency, and the number has remained constant over time.

4.1   Conceptual Model

A conceptual model illustrates a simplified version of the SD model to avoid excessive details in the first presentation of the mapping approach (Figure 6). The Stock and Flow Diagramming technique, a SD mapping procedure which is subsequently quantified and allows simulation, is chosen here because it successfully illustrates cumulative behavior and feedback processes with time delays involved (Sterman, 2000, s. 102). The model will be presented by first discussing the model boundary and the model components, and secondly by describing the main relations across model sectors.
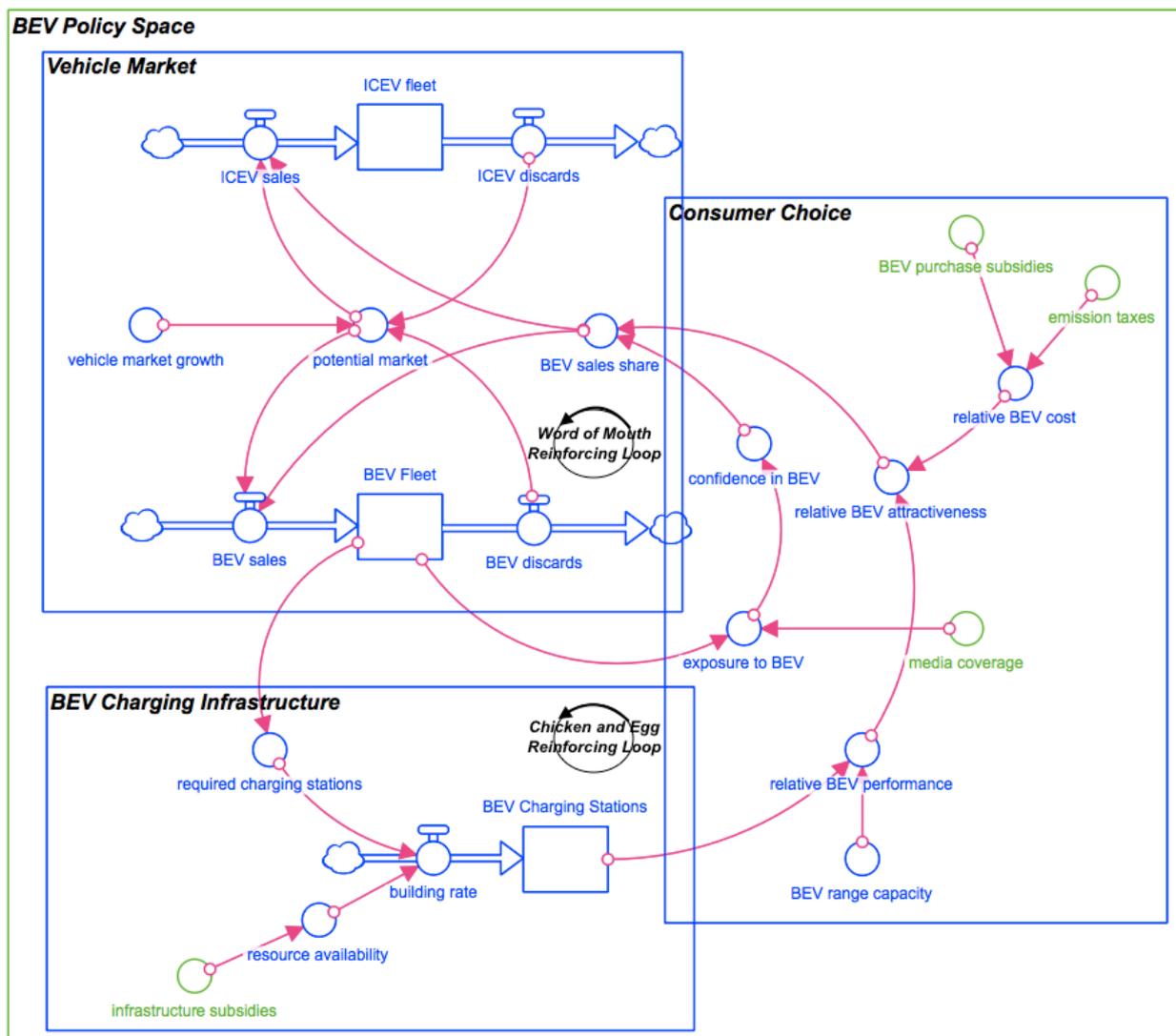
Figure 6. Conceptual model

4.1.1 Model boundary

Diffusion of the BEV vehicle is driven by both local, national and international factors, as discussed in the theory chapter. A national perspective is chosen to best compare the Norwegian and Swedish context. This perspective drives the definition of the model boundary and the distinction between endogenous (meaning defined by other variables in the model) and exogenous (meaning defined by external sources) variables. Within the defined boundary, all major agents and their decision rules will be mapped.

A BEV Policy Space is outlined in green in Figure 6, inside which the government has the potential to influence parameters through regulations (such as laws, taxations, incentives, marketing campaigns, investments). Outside of this boundary, governmental forces do not have influence. Oil prices (excluding taxes), rate of technological development and vehicle supply are for example not part of the national policy space, and are defined exogenously. Cost and performance attributes are defined by both national and supra-national dynamics.

Regulations in the model are exogenously defined parameters to allow policy analysis. For historical time values, the existing data has been used; for future time values, a set of most-likely values are assigned in order to describe a most-likely future. Alternative scenarios will be explored in later sections to test different parameter assumptions and conduct policy analysis (section 5.3 and 5.3). A number of other exogenous variables such as oil and power prices and technological development rate will also be used to create alternative scenarios. This approach is similar to what has been done in Pasaoglu et al. (2015) and Harrison and Thiel (2017).

As introduced in the theory chapter, the model has been built in accordance with the stages of vehicle ownership: there is a section focusing on the consumer choice stage, where the individual calibrates each vehicle's attributes against each other, and expresses a preference; there is a vehicle market in which the purchase happens, and that determines the balance of vehicle types in the national fleet; finally, there is the utilization stage of the vehicle, of which the complementary infrastructure makes an important component: hence, a sector on charging infrastructure has been developed.

4.1.2 Main feedback loops

System dynamics modelling is well suited for understanding the nonlinear behaviour of complex systems over time by explicitly identifying feedback mechanisms and time delays that are important drivers of system behaviour. Feedback loops are circular causal relations between variables that can generate divergent or convergent behaviour, including vicious or virtuous cycles (Sterman, 2000, p. 137). In the model presentation given in this chapter, these elements are described in detail, sector by sector. Three main components have been identified inside the

policy space: Vehicle Market, Consumer Choice and BEV Charging Infrastructure. These components are causally related and compose a set of reinforcing or balancing feedback loops. There are two reinforcing feedback processes which causally relate two or more system sectors. The first one is denoted in Figure 6 "Word of Mouth Reinforcing Loop". This loop represents how the social exposure to a certain type of vehicles increases its attractiveness: the more BEVs are observed in the streets, the more people can get acquainted with this vehicle type and its characteristics, conversations will more often fall on this topic, and the vehicle type becomes more popular and attractive. Media coverage and marketing can increase exposure and awareness among consumers. Note that this reinforcing mechanism can also constitute a vicious cycle if the exposure decreases or if the relative BEV attractiveness falls. Hence, the vehicle market and policies influence the consumer choice, and consumer choice determines the development of the vehicle market. This feedback process is delayed by some perception time, which will be discussed more in detail in section 4.2.2.

There is another important dynamic in the system, the so-called Chicken-and-Egg loop. This causal connection relates vehicles and the necessary charging infrastructure. Both internal combustion and electric vehicles are highly dependent on refuelling periodically. While there exists a high density of gas stations, electric vehicles are not yet supplied with a good network. This low density decreases also the attractiveness to buy a BEV, in the fear to remain without power. On the other hand, installing and running a charging station requires expenses that need to be compensated with future incomes. Hence, if the BEV fleet is very small, there will be a low attractiveness to invest, as the return on investment (ROI) is low, and the pay-back time is far in the future. This investor scepticism is reinforced by the high uncertainty related to the future of the BEV market.

The same reinforcing mechanism can also work in the positive direction: the more charging stations, the more attractive and safe is the alternative of driving a BEV; the increased attractiveness drives sales; sales drive investor optimism to build charging stations; and so on, this motivates even more drivers to switch. Whether the presence of charging stations or of vehicles is the initial driver of the reinforcing mechanism, is however unclear. The feedback loop mechanism is called chicken and egg because of the similar unclear cause-effect sequence as in the folklore saying: whether the chicken (the BEV) or the egg (the charging station) came first, is, at least in the saying, a mystery (Sterman 2000, p. 13). In addition to market mechanisms among investors, policies can intervene to support a balanced development of vehicle and infrastructure supply. In the Chicken-and-Egg loop, all system sectors are causally related in a feedback process. Therefore, multiple delays act during the process: the time to

build infrastructure, the time to see the fleet grow, and the time consumers use to perceive a change in vehicle performance.

Balancing processes will also determine the behaviour of the system. Competition between the two vehicle fleets can weaken the diffusion of BEVs, depending on relative costs and performance. The BEV fleet, as the whole fleet, can only grow up to a carrying capacity, which is context dependent and endogenously determined. This carrying capacity is not constant but determined by the growth (or decay) of the vehicle market. This mechanism will be described more in detail in the vehicle sector description.

4.2   Sector conceptualization

As mentioned above, three components have been identified for the present model: Vehicle Market, BEV Charging Infrastructure and Consumer Choice. Even though the vehicle system can be described as a vast "ecosystem" (as discussed in chapter 2.1), a national perspective is taken in the present research, and hence only actors that behave within the national environment are extensively mapped. Manufacturers are consequently not included in the present case. Only national authorities, infrastructure suppliers and users are included. The agents considered and their main interactions are described in the next section. Subsequent sections will explore in detail the actors' decision rules and specific interactions, and each module will be described in detail. Sector-specific feedback loops will be presented.

Note that the figures below represent isolated modules or model details, without always representing all interactions with other modules. The system is complex and the causal relations are many and intricate, and a full representation of all would limit the visual clarity.

4.2.1   Modelling the vehicle market

At the core of the model, there is the stock-flow aging chain structure for each of the vehicle alternatives, see Figure 7. The unit of simulation is *vehicles*, which is specified to be battery-electric or internal combustion driven.[9]

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[9] Diffusion models generally measure the phenomenon in units of adopters, hence people. The choice in this study of vehicles as units is driven by a number of factors: first, the number of BEV(/ICEV) vehicles directly reflects the number of BEV(/ICEV) owners; second, this choice is consistent with the available data; third, we are interested in the diffusion of BEVs first of all for environmental reasons, and each vehicle corresponds to a certain contribution to GHG emissions; fourth, individuals can own zero, one or multiple vehicles (possibly of different types); fifth; the aging flow is driven by a tangible variable, namely the vehicle lifetime.

Applying an aging chain to the vehicle market is very functional because of the inherent development of the fleet over time: new car registrations "flow in", the vehicles pass from one life stage to another, and are scrapped at the end of their lifetime, "flowing out" of the system. The structure and the concepts are very similar to demographic models, where individuals, instead of cars, are born or immigrate ("flowing into" the population), and after a certain period, "flow out". The factors determining how many vehicles will flow in and flow out will be described below.

Two age classes are defined for vehicles in the model: "young" and "mature". Young vehicles include newest vehicle sales and following cohorts up to the vehicles which have covered 1/3 of their lifetime. Mature vehicles are all other vehicles, up to scrapping time.

The lifetime of BEVs and ICEVs is different. For ICEV, the value 17 years is used, which is the average of values from Fridstrøm, Østli and Johansen (2016) figure 6. For BEVs, the lifetime is endogenously defined by the model and the formulation will be presented in the section on Performance.
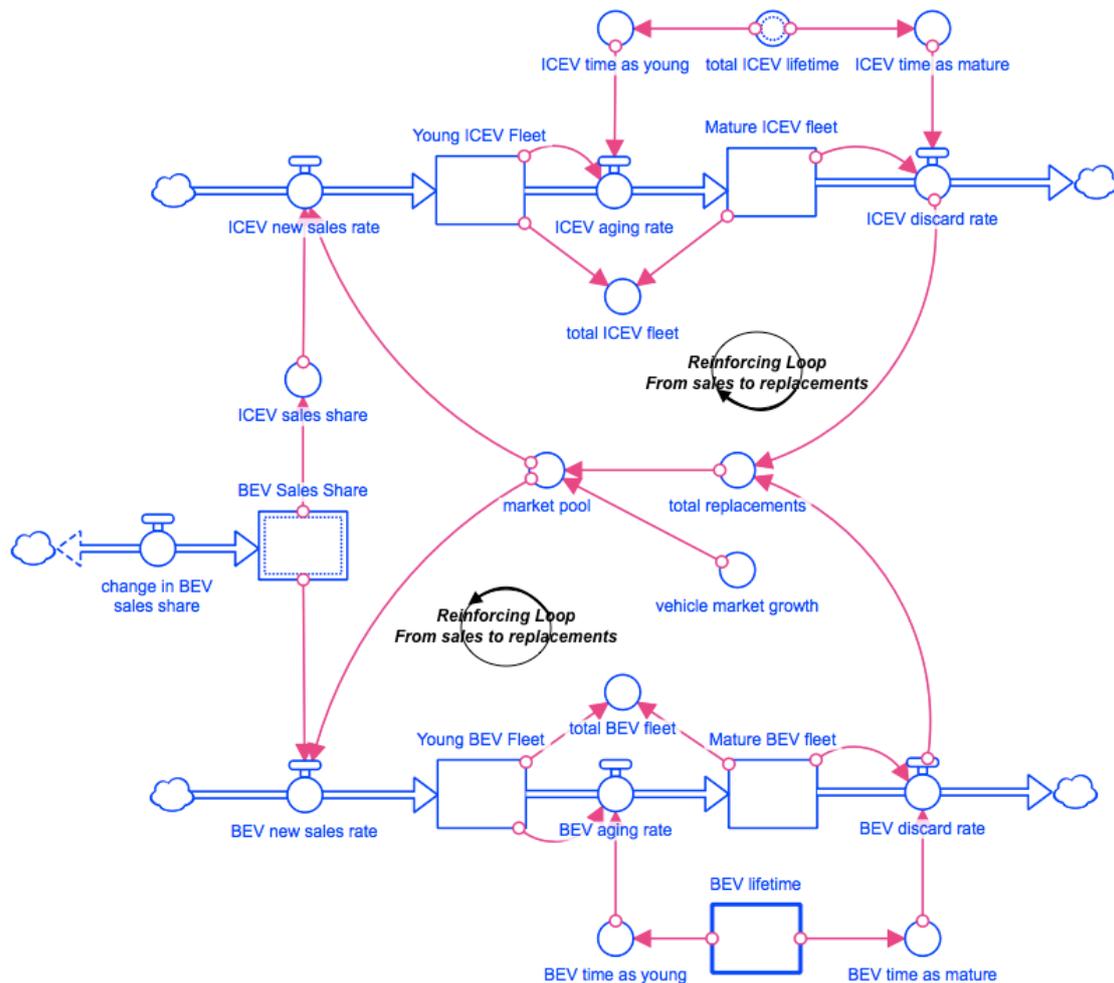
Figure 7. Vehicle system module

The stocks are initialized with historical data for each of the two contexts (Norway and Sweden), considering respective age classes.

The model simulates the competition between two vehicle alternatives: the ICEV vehicle and the all-electric. The competitive dynamic is modelled by defining a common market pool from which sales are allocated to one vehicle alternative or the other. This allocation depends on sales market share, which is endogenously defined. How the BEV market share is determined will be discussed in the next section. As we assume that ICEV ad BEV cover the whole market, the market share for ICEV will necessarily equal 1 minus the market share of BEV:

Equation 1) ICEV_sales_share = 1 - BEV_Sales_Share

The market share is combined with the size of the potential market (the market pool) to define next year's sales:

*Equation 2) new_sales_rate = market_pool * Sales_Share*

The equation applies to both ICEV and BEV sales and shares. The sales rate can increase both with the growth of the market share and with the size of the market pool. The market pool represents the total number of private light vehicles that will be sold next year, not specifying the fuel type. The size of the market pool is determined by the market growth and by the necessary replacements from latest discards.

Equation 3) market_pool = total_replacements + vehicle market growth

Total replacements are defined by the combination of ICEV and BEV discards, as we assume that every vehicle which has been scrapped will be substituted with a new one[10]:

Equation 4) total_replacements = ICEV_discards + BEV_discards

In Figure 7 the reinforcing loop "From sales to replacements" is illustrated. This feedback structure is symmetric for both ICEVs and BEVs and reflects the effect of the cohort structure: the more vehicles flow into the vehicle stock in the form of sales, the more vehicles will flow out (hence be discarded) by the end of their lifetime. Each discard translates into a necessary replacement, and hence sales increase; at the end of the vehicle lifetime, this contributes to more discards. BEV lifetime, as will be discussed in section 4.2.4, is lower than the ICEV's until 2030, after which it is expected to be higher. Hence the turn-over rate of the BEV platform is

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[10] This is necessarily not the case if the total market is shrinking. In periods of severe economic down-turn, or within cultural and transport-modal changes, households may choose not to replace their old vehicle with a new one, but for example shift to other transport types as bikes, public transport, motorbike. The present definition is therefore simplifying reality.

different from that of the ICEV, and it changes over time (ICEV lifetime is assumed to stay constant). As long as BEV lifetime is relatively lower, the turn-over will be faster. This causes a faster depletion of the stock compared to the ICEV; and hence the growth of the BEV fleet is delayed. This mechanism is turned after 2030, when ICEV lifetime is lower than BEV lifetime.

In addition to these larger loops, minor loops are present: both aging rate and discard rate are defined as functions of the stocks they originate from. Hence, the larger the stock, the greater the outflow; but the larger the outflow, the quicker the stock is depleted. Hence there are multiple minor balancing loops in the vehicle system.

The vehicle market growth is assumed to be driven by the population size and an indicated vehicle density, measured in vehicles per person. The most important determinant of vehicle density is GDP per capita (Wu, Zhao, & Ou, 2014), but also the stability of the national economy (hence the consumer's confidence in investing) and the transportation culture and requirements. These are not considered in the present model, and instead an exogenously defined vehicle density is used, dependent on the context. This is because of two main reasons: first, it is not the aim of this research to derive a detailed quantification of the vehicle market growth- the focus is on the sales share allocated to BEVs as opposed to ICEVs; secondly, the discard rate is not modelled with a similar precision[11], and hence the stock size would show a more volatile behaviour than what happens in reality.

An indicated fleet size is determined by comparing the indicated vehicle density with the total population size. This indicative value is compared with the current fleet, and the market growth equals the gap between the current fleet size and an indicated size. The system shows therefore goal seeking behaviour towards the indicated fleet size, which is a dynamic size. The respective model structure, in simplified form, can be seen in Figure 8, together with the balancing loops.

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[11] The discard rate is simply defined as a function of the vehicle stock and of the vehicle lifetime as mature: *discards = Mature_Fleet / time_as_mature*. In reality, vehicle owners may choose to discard their vehicle earlier because of the attractiveness to shift to another vehicle type (for example because of PayBack programs); or later, if they cannot afford yet buying a new one.
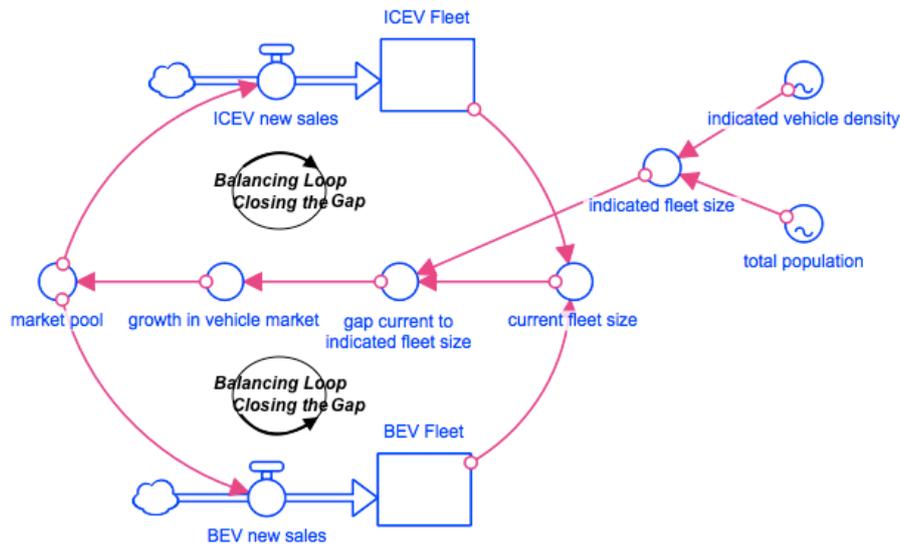
Figure 8. Determination of the vehicle market growth

Next, the model structure behind the determination of BEV market share will be presented.

4.2.2 Modelling consumer choice

The complete model structure defining sales share can be seen in Figure 9. In order to derive the equation for the BEV sales share, one needs to take a few steps back.

As discussed in the previous chapter on theory (Chapter 3), BEV sales share is defined based on two elements: its objective attractiveness and customers' awareness around this alternative. Objective attractiveness will be discussed first.

Objective attractiveness is determined by the attributes costs and performance. It is defined in relative terms, meaning that the variable entails the evaluation of BEV attributes relative to ICEV levels. The definition in relative terms is necessary in order to combine the comparison on costs with the comparison on performance and obtain the level of attractiveness, independently from monetary units, years of lifetime or grams of CO_2 per kilometer. The variable can cover values on the interval [0, n] where n is a positive number smaller than infinite. If relative attractiveness equals 1, then the BEV and the ICEV are equally attractive for the attribute considered. Considering price, for example, a relative value of 1.2 means that the BEV is 20% more expensive than the ICEV over an average of all vehicle types. Considering for example emission performance, a value of 0.1 means that a BEV emits only 10% of the CO_2 an ICEV emits.
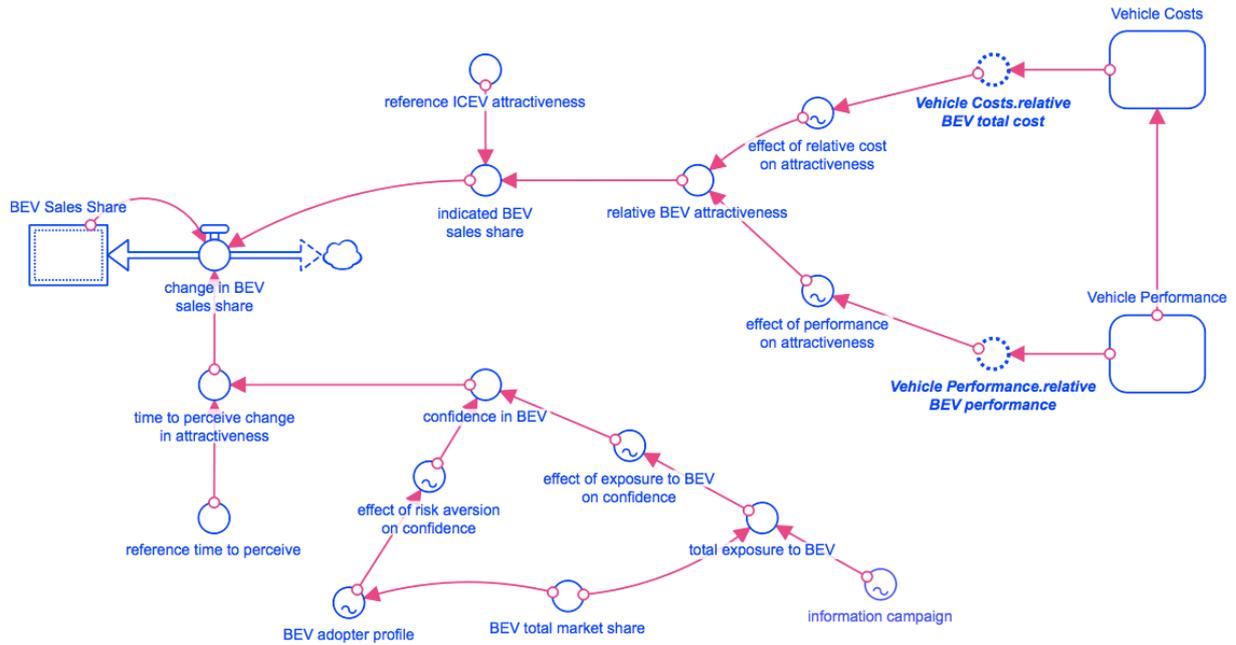
Figure 9. Drivers of BEV attractiveness

The definition of relative BEV attractiveness is based on Sterman (2000, p. 392-395, in particular eq. 10-5):

Equation 5)   relative_BEV_attractiveness =
effect_of_performance_on_attractiveness*effect_of_relative_cost_on_attractiveness

The effect of relative cost and relative performance are combined to determine the relative BEV attractiveness. This value determines the indicated BEV sales share, based on the comparison with a reference ICEV attractiveness.

The model calculates relative cost and relative performance, as will be discussed below; but in the expression above the *effect* of these quantities determines the attractiveness. The definition of the effect functions is based on Prospect Theory to represent that a saturation is reached at high or low levels of the relative attribute. In Sterman (Sterman, 2000, ss. 392-396), alternative definitions of effect functions are described, and in particular the application of the exponential function. The definitions by Sterman are not chosen in the present context mainly due to two reasons. Firstly, the exponential function does not reflect saturation, but instead brings attractiveness to increase more and more for each unit added. Secondly, the context modelled in Sterman describes a situation where both competitors can lose complementary resources and are mutually exclusive. In the context of this thesis, the BEV and the ICEV are not considered to be mutually exclusive, but instead a coexistence is assumed possible.

The effect is defined as a s-shaped graphical function, as can be seen in Figure 10 for cost and performance to the left and right respectively. The formulation of the effect function is based

on Prospect Theory, which is discussed in the theoretical background chapter. What here is called effect represents the value of the attribute (relative cost or performance), so that a value function can be drawn, for different values of the relative attribute. The value function has certain characteristics: there exist a point of indifference where the BEV and the ICEV are equally attractive: therefore, the curve will always pass through the point (1, 1). The s-shape describes the fact that consumers are highly sensitive to a marginal change from the indifference point; but after large added benefits or added losses, the change in value will not be so strong. In addition, the curve is asymmetrical. Negative effects hit more strongly than positive effects, and hence the lower tail is heavier than the upper tail. The shape is convex for losses, concave for gains. The maximum and minimum values are assumed to be equal for relative cost and performance: 1.8 in the case of a gain, 0.05 in the case of a loss. But while relative cost can range from near to zero to three times as large, the relative performance spans the range [0, 2]. These values are chosen to allow the relative BEV attractiveness, which is defined by the multiplication of the two effects, to have a value between 0 and 3.24.
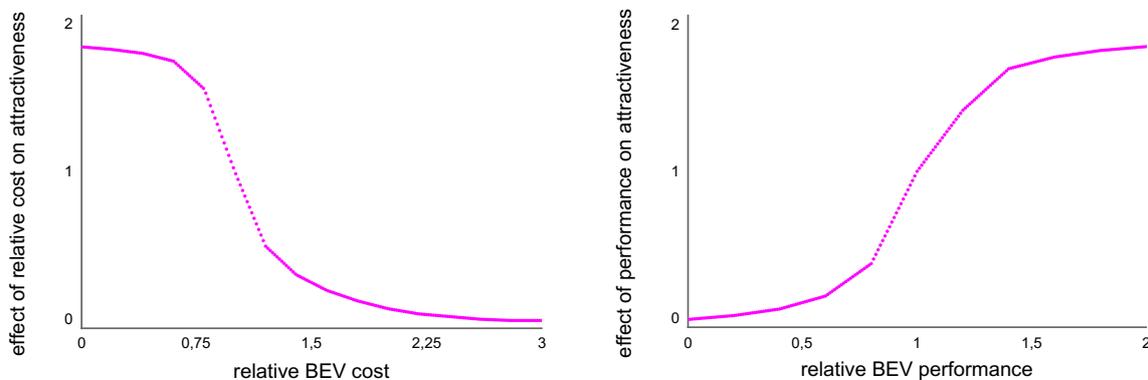
Figure 10. Graphical functions for the Effect of relative cost (left) and performance (right) on attractiveness

The determination of relative costs and relative performance results from the consideration of many attributes. Modules for costs and for performance attributes have therefore been defined, which will be discussed in the next sections. Before that, we consider how the relative BEV attractiveness determines the sales share. As can be seen in Figure 9, the relative BEV attractiveness does not directly define the sales share, but only an indicated share.

Equation 6)   indicated_BEV_sales_share = relative_BEV_attractiveness /
(relative_BEV_attractiveness + reference_ICEV_attractiveness)

The formulation is derived from Sterman (Sterman, 2000, s. 392). Hence in this model it is assumed that the drivers of BEV sales share are the BEV's relative performance and relative TCO. The reference ICEV attractiveness is equal to 1. This implies that if the attractiveness of

the BEV is double as high as the ICEV's, the indicated market share of the BEV is 66%, while if the attractiveness is half that of the ICEV, a 33% market share can be achieved. As discussed above, the relative BEV attractiveness can cover values in the range [0, 3.24]. This will in turn give a range of possible indicated BEV sales shares between 0 and 75%, by applying Equation 7. This can be considered as a conservative assumption, since the model does not allow for the sales share to become 100% at any times. On the other hand, the BEV and its complementary infrastructure does not exclude the possibility that the ICEV exists at the same time. Sensitivity analysis will be applied to test the determination of different definitions of the effect functions.

The model assumes that indicated market share for BEV becomes reality only after some "thinking process" from the side of the users, as discussed in section 3.4: there exists some inertia in switching from the traditional platform to a technological innovation, no matter the cost-benefit analysis and relative attractiveness. There exists a gap between expectations and experience, which delays the building of trust. This thinking process is concretized in the model as the time to perceive a change in attractiveness. This delay time variable entails a number of psychological aspects: Struben and Sterman (Struben & Sterman, 2006) talk about the "willingness to consider" as the process of learning, considering and creating an emotional connection to the product. Trafikanalys (Saxton, Levin, & Myhr, 2016) and McKinsey (Knupfer, et al., 2017) report consumers' delay in perceiving the actual cost and performance attributes, and consumers' attachment to traditional brands and traditional vehicle types. It is therefore reasonable to assume that the choice to change to a different vehicle type involves a considerable inertia. This structure is naturally not required for the symmetric ICEV market share, since this is the market incumbent and its image is well-established.

It is assumed in the model that it takes 10 years for the market to learn about the whole spectre of cost and performance attributes of a new product launch, trust it and be convinced to move over to the better alternative. Given a reference perception time of 10 years, the confidence in the product impacts the time it takes to perceive changes in objective BEV attractiveness. If the confidence is low, it will take more time to perceive improvements. Hence the inverse of the confidence value is applied:

Equation 7)   time_to_perceive_change_in_attractiveness =

reference_time_to_perceive / confidence_in_BEV

The confidence in the BEV is defined as follows:

Equation 8)   confidence_in_BEV =
effect_of_exposure_to_BEV_on_confidence*effect_of_risk_aversion_on_confidence

The variable represents the drivers' confidence to BEVs. The confidence is defined as the product of the effects of two factors: the level of risk aversion to innovations and the exposure to the BEV platform. Confidence increases with exposure to the new vehicle, while it decreases with risk aversion.

A parenthesis on the variable values as defined in the model follows. The variable confidence can have a value in the range [0+, 5], which is guaranteed by the ranges of the two effects and by the sensitivity value. The effect of risk covers the range [0, 1] while the effect of exposure covers the range [0, 5]. This range is functional because of the way confidence can define the time to perceive change in attractiveness: this time can be magnified if confidence is low (smaller than 1), or it can be shortened if confidence is very high (larger than 1). Since the reference time to perceive is equal to 10, the lowest possible time to perceive is 2.5 years when confidence is at its maximum (5). For a confidence level of value 1, the time to perceive will equal to the reference time.

The effect of risk aversion will be described first. The graphical function is shown in Figure 12 (left). Since the BEV is a market entrant, adopters may be optimistic or sceptic to this innovative product. Rogers' Diffusion of Innovations Theory defines five categories of adopters, where the BEV adopter profile is a function of the total BEV market share (see 3.4 for the graphical representation and further theory). The adopter profile reflects a certain level of risk aversion. This can be reinterpreted as a reference level of confidence of the potential adopter to the product.

According to consumer theory, the earliest adopters have a more optimist and risk prone attitude, plus they are better prepared to handle eventual malfunctions with the earliest product versions. In other words, they show higher confidence. Hence the effect of risk aversion on confidence is near to neutral (the value 1) for the early adopters.

As the market share grows, the potential adopter pool is composed of consumers with a more sceptic and risk averse profile. Hence the level of risk aversion grows with the market share; this growth is modelled to grow proportionally with the shift to a new adopter profile.

The lowest value defined is 0.6 for the laggards. The level of risk aversion of this class of consumers nearly halves the confidence in BEVs. This mechanism introduces a balancing effect in the diffusion of the BEV which was not discussed in section 4.1.2, and which is illustrated in Figure 11. A Causal Loop Diagram is used here to illustrate the causal relations. In this type of diagram, variables are interlinked by arrows representing cause-effect relations which are

denoted with a plus (+) or minus (-) sign. The plus sign indicates that the effect is directly proportional to the cause; the minus indicates that the proportionality is inverse.

The "Risk Aversion Balancing Loop" illustrates how the mechanism described above works: the higher market penetration, the more risk averse are potential adopters, and hence confidence is lower, and sales share is reduced (if BEV attractiveness is constant).
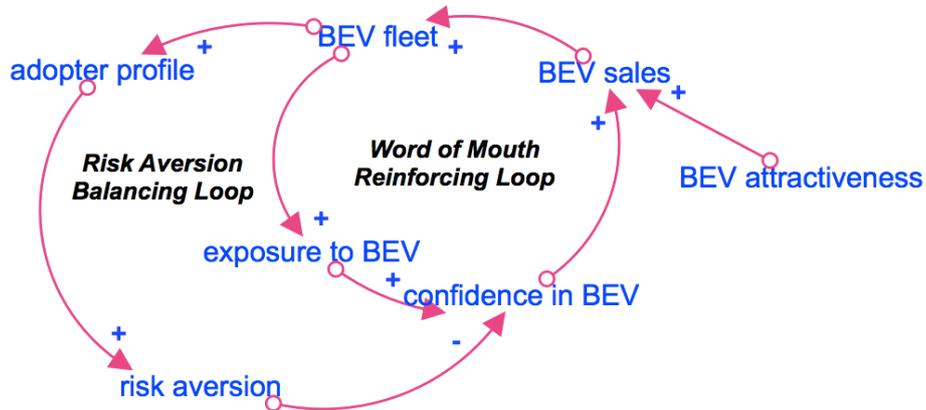
Figure 11. Causal loop diagram for confidence in the BEV

The effect of risk aversion combines to the effect of total exposure. Total exposure is given by the combined effects of two elements:

$$\text{Equation 9)} \quad total\_exposure\_to\_BEV = BEV\_total\_market\_share + information\_campaign$$

The total exposure to BEVs is a combined effect of the proportion of vehicles observed in the streets that are BEVs and the effort of information campaign and similar channels, such as marketing and media coverage. These two factors are in the ranges [0, 1] and are summed to give the total exposure. The variable is an indicator of how much exposure society gets to BEVs. Hence the value is chosen arbitrarily in this research to be on a scale [0, 2]. Low/high values correspond to a low/high exposure; the threshold for a positive effect is 0.2.

The effect of total exposure is defined by a concave, monotonically increasing graphical function of total exposure (Figure 12 right). The function can take values from 0 to 5. This range is chosen to provide convenient input to the variable confidence. The effect has neutral value, hence the value 1, when the total exposure is 0,2. Below this exposure level, the effect on confidence is negative, while above 0,2 there is a positive effect of exposure on confidence.
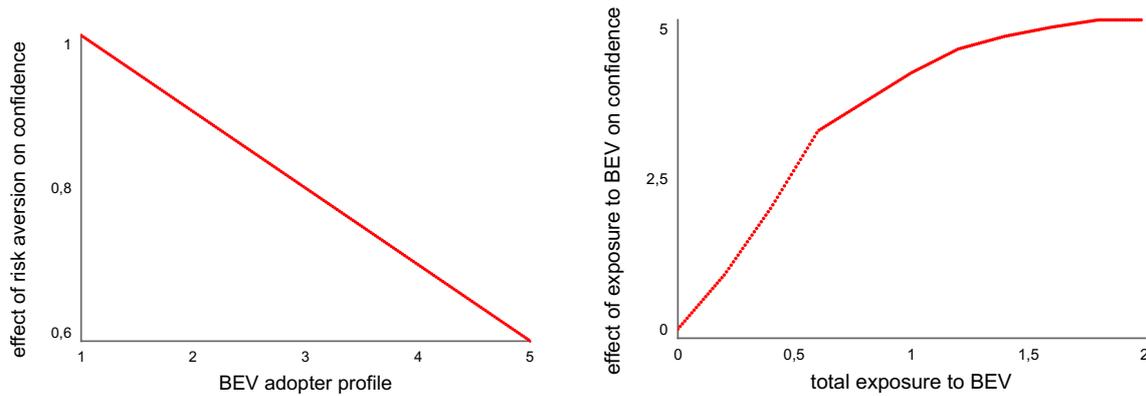
Figure 12. Graphical function for the Effect of adopter profile (left) and the Effect of exposure on confidence (right)

The effect that is being modelled here is also called in the literature word-of-mouth or peer-to-peer contact. It was already discussed in the theory chapter (section 3.4) how important this contact is in the diffusion of innovations. This mechanism is part of the reinforcing loop depicted in Figure 11 above.

The BEV market share is used as a proximate indicator of exposure. This also allows for comparison across contexts with very different fleet sizes. In the case of Norway and Sweden, Norway has a fleet approximately half the size of Sweden, so that basing the level of exposure on a given number of vehicles would not provide the right information.

The information campaign effort is defined as a graphical function and is context-dependent, hence it is not represented in this section. It expresses the effort made by governments, manufacturers and retailers to advertise and merchandise the BEV, as well as the media coverage in television, newspapers and online. This parameter affects the visibility of the BEV and if high enough, magnifies the size of the BEV fleet to appear larger than it actually is.

In reality, the variable is endogenously defined by market mechanisms: it may be correlated to sales rate or to political priorities. In the present model, information campaign effort is defined exogenously. The definition of the variable is not based on empirical data, but on subjective evaluation of the level of media coverage on the topic. This is derived, for example, by the frequency of newspaper articles over a certain period. Considering the fading nature of topics in the media, we assume that information campaigns are high only for a short period, 4 to 10 years (Sterman 2000, p. 339).

The Word of Mouth reinforcing loop and the risk aversion balancing loop act in opposite directions on confidence: the first increases it, the second reduces it. The joint effect of the two forces is determined by the strength of the effect of each force on confidence. Looking back at Figure 12 illustrating the effect functions of risk aversion and exposure to the left and right respectively, it can be seen that the effect of exposure is stronger than that of risk aversion on confidence, for the same market shares. Hence the balancing loop Risk Aversion slows down, but does not necessarily halt, the growth in sales share from market share. In other words, risk aversion of adopters brings a delay effect in the transition to BEVs.

The determination of the BEV market share can now be presented. Being defined as a stock, the value is updated by the following flow equation:

$$Equation\ 10)\quad change\_in\_BEV\_sales\_share =$$
$$(indicated\_BEV\_sales\_share\text{-}BEV\_Sales\_Share)$$
$$/time\_to\_perceive\_change\_in\_attractiveness$$

The formula for this bi-flow simply substitutes the old value with the new, scaled by a delay time. The sales share converges towards the indicated sales share at a rate defined by the time it takes to perceive the change in attractiveness. This definition implies that the real sales share can never surpass the indicated value, which is in turn defined by the relative attractiveness. When confidence is high, convergence to the indicated sales share is faster than before, but the value of the sales share is not increased by high confidence. This definition can be judged as conservative as it does not include the reinforcing effect of word-of-mouth mechanisms on consumer choice: in the long run, it is relative performance and costs that determine the sales share, and not the exposure to one product versus another.

In the next sections, the attributes behind relative attractiveness will be discussed: costs and performance.

4.2.3 The cost module

Figure 13 illustrates the structure of the module on costs per vehicle. As can be seen, this is the part of the model with the highest number of policy instruments directed to BEVs (in green). The policies illustrated are either or both for the Norwegian and Swedish context, and section 4.4 will specify the policies that are in place in each country.

Monetary costs are measured in this model with the unit *kroner*, which is the currency in both Norway and Sweden (Norwegian and Swedish krone respectively). The change between currencies is at present minimal (in date 26.05.2017 1 NOK = 1.033 SEK), hence for simplicity

the model assumes that kroner is the same monetary unit for both contexts. The values are normalized to the level of the krone in 2015, so that inflation is not included.

The values assigned to vehicle prices and operational costs are only indicative for the average vehicle, as two aggregate classes are considered. There exists a large variation among vehicle classes, engine types and among users. In particular, the ICEV umbrella term encapsulates diesel, petrol, biofuels, hybrids and more, and the costs and attributes of each can vary considerably; "green" ICEVs as hybrids and biofuels can in cases receive the same cost reductions and benefits as the BEV. On the other hand, the cost reductions and benefits are offered as a compensation measure because of a higher purchase price or lower performance. These policies are in addition introduced in the early market introduction phase, while the "green" fleet is still very small. Hence, the change in costs and price applies to a very little share of ICEVs and is considered negligible in this study. The value for the ICEV's cost and price is therefore kept as a constant reference for comparison.
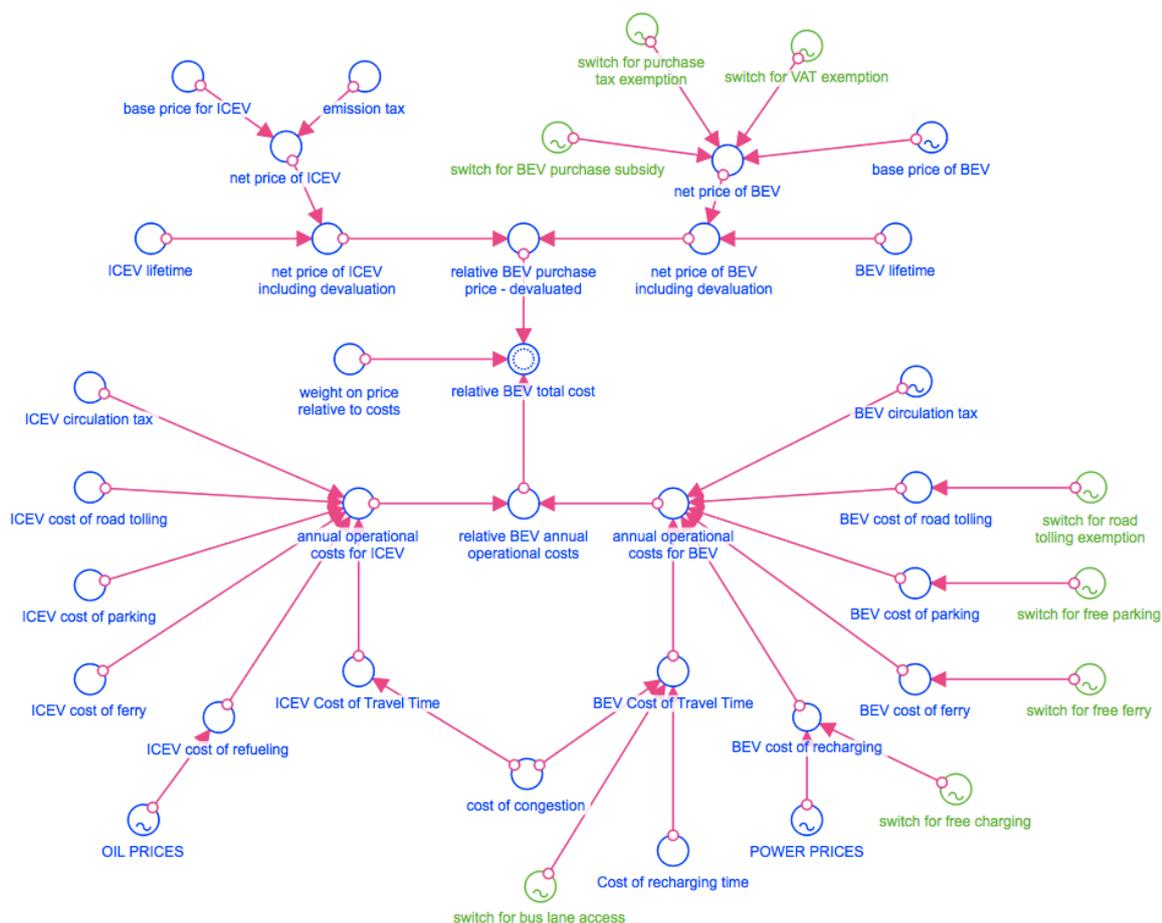
Figure 13. Costs module

The main output variable of the module is the relative BEV total cost. This variable is defined by a weighted average between relative purchase price and operational costs, to represent the Total Cost of Ownership discussed in section 3.5. The equation is as follows:

*Equation 11) relative_BEV_total_cost =
relative_BEV_purchase_price*weight_on_price_relative_to_costs + (1-
weight_on_price_relative_to_costs) * relative_annual_operational_costs*

The relative BEV cost can take values in the range [0+, n], where the value 1 indicates that BEV and ICEV have cost parity. A value larger than 1 means that BEVs are more expensive than ICEVs. If smaller than 1, BEVs are cheaper than ICEVs.

Total costs are defined in the model by two elements: price at purchase and annual operational costs. The equation formulation includes a weight on price relative to costs. As discussed in the theory chapter, the value of the weight is uncertain, it depends on the user and it may change over time. It may not be fully correct to assume that price and costs have equal weights since the consumer may not be able to make a correct evaluation of costs and benefits when many dimensions are involved, as in this case. Larger weight may be on the purchase price. Sensitivity analysis will be applied to handle this uncertainty (section B 6). The basic structure is represented in Figure 14.
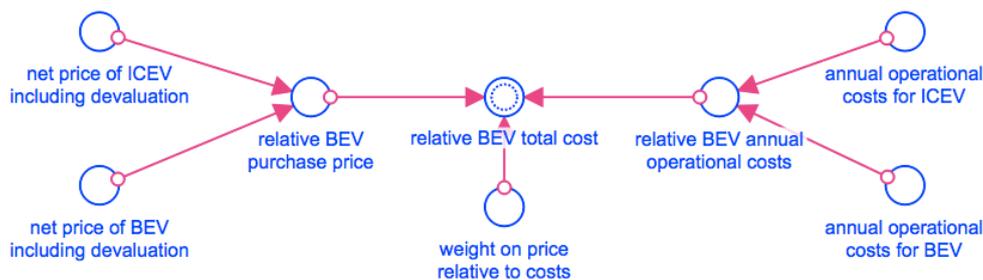
Figure 14. Simplified structure for derivation of relative BEV cost

Relative purchase price will be presented first. The relative BEV purchase price is derived from comparing BEV and ICEV purchase price. The base price of the BEV changes over time as battery prices fall and market of scale dynamics come into action. The price of the BEV is set to be 3 times that of an average ICEV in year 2000. The price is assumed to fall below the price of the ICEV by 20% by the year 2050, in accordance with the arguments presented in section 3.5.1: hence a goal-seeking behaviour. Figure 15 illustrates the model structure describing this behaviour: the base price as a stock, with an outflow representing price reduction. The base price is specified for each context in section 4.4. In both cases, the simulated data fit well with the historical price development, reported among others in Figenbaum et al. (2015, s. 33).
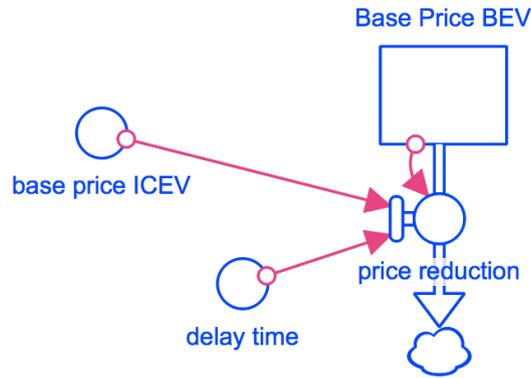
Figure 15. Model structure for BEV base price

The price paid by the consumer is also based on emission taxes, eventual tax exemptions and subsidies, depending on the national context. Emission taxes are defined contextually. However, as will be seen in the next section, the effect of emission taxes on the vehicle price is not so significant: thanks to rapid technological development and spill-over effects, the ICEV is reducing its emission levels rapidly. Emission policies are therefore defined as dynamic by defining stricter and stricter requirements. A scaling factor is included in the model to represent this.

The price comparison also includes the effect of the vehicle's lifetime on the devaluation of the product: if the lifetime of the BEV is relatively lower, the price will be perceived as relatively higher than if the lifetimes were the same. The value of the ICEV base price is considered to be a reference and therefore kept constant; the initial value for BEV base price is assumed to be 2.5 times the ICEV base price.

This module includes the modelling of many of the governmental policies targeting BEVs. Policies bringing practical benefits are also included in the model. Switch variables are defined to control whether a policy is "active" or not, and for what time period.

The relative operational costs are obtained by comparing BEV and ICEV operational costs. Operational costs are defined over a year of use and include:

1. Refueling/recharging
2. Cost of travel time
3. Road tolling
4. Parking expenses
5. Use of ferry
6. Annual road tax

The definition does not include minor additional costs or maintenance costs, since there exists little data on the topic for the BEV.

1. Refueling/recharging costs

For simplicity, one uses the term "refuel" for ICEVs and "recharge" for BEVs. The cost of recharging depends on the price of power and on the average amount of kWhs (kilowatt hour) consumed per BEV driver per year. Historical values have been retrieved, and from 2018, the price of power is assumed to decrease over time as a consequence of increased renewable energy production on large scale. Recharging costs may be subsidized by the government or other entities. This is often the case in Norway, since free charging is a policy to increase BEV attractiveness and where power is relatively cheap and abundant. Hence a switch is applied which "turns on or off" these costs depending on existing policies. The amount of kWhs consumed per year is a function of BEV energy efficiency. The cost of power development and BEV energy efficiency are illustrated in Figure 16 below.
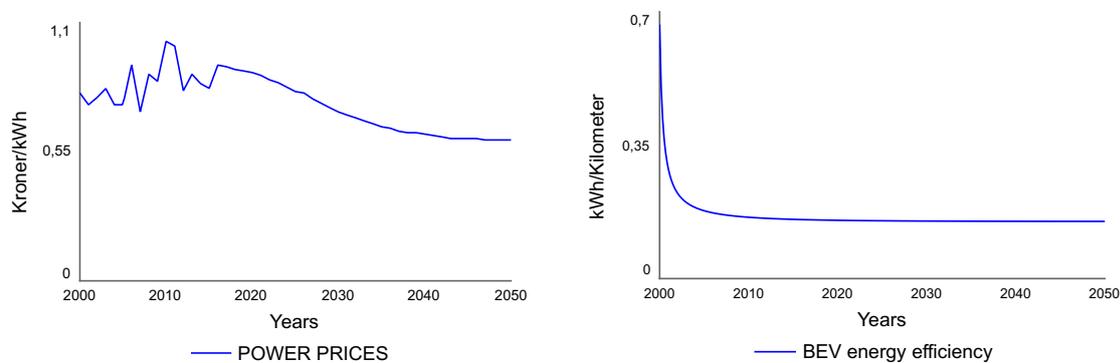
Figure 16. Development over time of power price (left) and BEV energy efficiency (right)

Since ICEV fuel is an umbrella term for both gasoline, diesel, biofuels, etc. (based on the aggregate definition of ICEV), the refuelling costs of each fuel must be taken into consideration. A simplified approach is however chosen here: one fuel price is defined, based on an average between diesel and gasoline prices. It can be argued that biofuels have a different price per litre and that hybrid vehicles drive half on the time on electricity, and hence the price of electricity must be considered. However, following the forecasts used in the ETO model (DNV GL, 2017), the share of hybrids and biofuels is assumed to be low for all future times. Hence the price of gasoline and diesel fuel is considered as representative for ICEV fuel prices; the historical and forecasted price development is illustrated in Figure 17 (left). The number of liters consumed per year depends on the ICEV fuel efficiency. This is approximately equal in Norway and

Sweden (International Energy Agency, 2015, s. 118) and is assumed to fall over time as illustrated in Figure 17 (right).
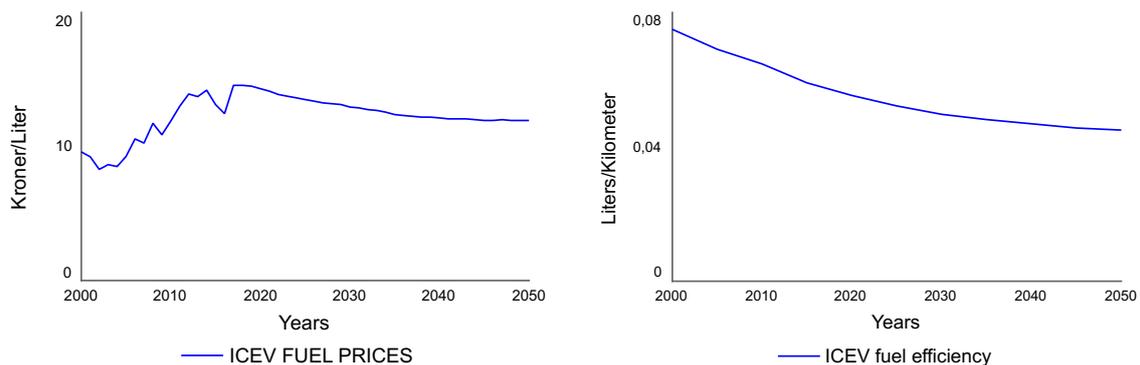
Figure 17. Development over time of ICEV fuel price (left) and fuel efficiency (right)

2. Cost of travel time

The most significant travel costs differentials for ICEV and BEV are defined as the time spent in traffic and the time to charge the car. BEVs can at times benefit from access to bus lanes, which reduces the time spent in traffic. On the other hand, it takes to date more time to charge a BEV than to fuel an ICEV, which implies higher travel costs for the BEV. The charging time changes over time however, therefore it is interesting to observe the development of travel costs over time for each vehicle platform.

From Transportation Economics theory, loss and savings of time are converted in monetary terms. Annual costs of congestion and a monetary value of time lost in charging the car are included. The model does not consider the costs from charging time for plug-in hybrids, assuming that the share is so small that this will not impact on the difference. Congestion from normal traffic lanes is assigned a monetary cost of 500 Kroner per year.

3. 4. 5. 6.

Symbolic values are given to the annual cost of ferry use, road tolling and parking to allow for a comparison between ICEV and BEV. The values are assumed to be equal for Norway and Sweden. Not everyone uses ferries, so an average value between the spending of those using it and of those not is defined. The value of the annual road tax is specified by the context, since it is equal for all vehicles in Sweden while it is lower for BEVs in Norway.

4.2.4   The performance module

The main output of this module is the relative BEV performance, but also other variables derived here are important in the rest of the model, as BEV battery capacity and recharging

time. As discussed in the theory chapter, there are many factors determining the performance of a vehicle. In the present model, a selection of the most important attributes is done based on the literature. Performance is defined by five attributes:

1. Relative range
2. Relative lifetime
3. Relative emission level
4. Diversity of BEV market offer
5. Charging availability

The relative performance is defined as follows:

Equation 12)   relative_BEV_performance =
effect_of_relative_range_capacity_on_BEV_performance*weight_vector_for_perform
ance_attributes[travel_range]+ effect_of_relative_lifetime_on_BEV_performance*
weight_vector_for_performance_attributes[lifetime] +
effect_of_charging_availability_on_BEV_performance*weight_vector_for_performan
ce_attributes[CS_density] +
effect_of_relative_emission_level_on_BEV_performance*weight_vector_for_perform
ance_attributes[emissions]
+likelihood_of_meeting_desired_market_diversity*weight_vector_for_performance_a
ttributes[diversity]

The equation is a weighted average of attribute effects, weighted by their perceived importance. The core representation of this formulation is depicted in Figure 18.
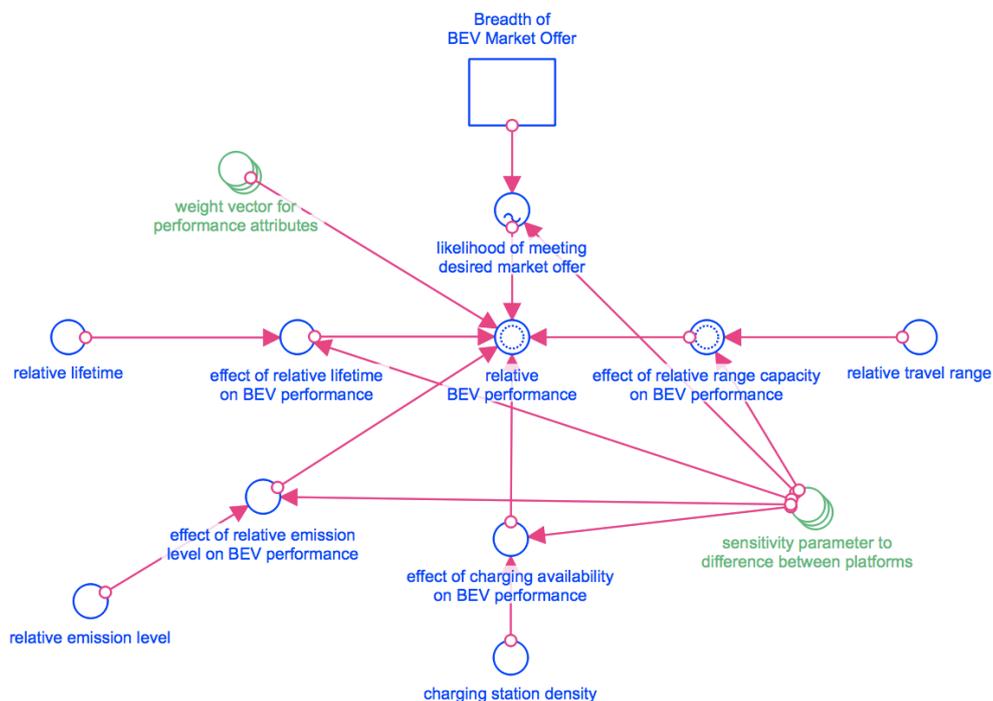
Figure 18. Core structure defining relative performance

73

The weights are introduced to express consumers' priorities when considering vehicle performance. Based on surveys and research discussed in the theory section (Figenbaum & Kolbenstvedt, 2016; Knupfer, et al., 2017; Lovin & Andersson, 2017), we define the following ranking for the attributes' importance. The weights are defined based on this ranking but are subjectively chosen. The weights sum up to 1.

Table 5. Ranking of performance attributes and assigned weights

Ranking	Attribute	Weight
1	Charging availability	0.4
2	Travel range	0.3
3	Lifetime	0.15
4	Diversity	0.1
5	Emission level	0.05

BEV performance is defined relative to ICEV performance. Being an umbrella term, the performance of difference vehicle types with internal combustion needs to be taken into account. This performance will therefore change over time; in the model however, the ICEV performance is taken as a reference point for comparison and therefore kept constant. Only in the case of relative emission levels the roles switch: while the BEV has a constant emission level near to zero, ICEV emissions falls following fuel efficiency. The value 1 indicates that ICEV and BEV have performance parity.

Relative performance is:

   - directly proportional to range capacity, since a larger range means higher performance

   - directly proportional to charging station density, since a higher density means higher performance

   - directly proportional to relative lifetime, since the nearer BEV lifetime is to the reference ICEV lifetime, the higher the BEV performance

   - directly proportional to the likelihood of meeting the desired market offer

   - inversely proportional to the relative emission factor, since the BEV performance is boosted by a relatively lower emission level, compared to the ICEV.

When comparing ICEV and BEV in a series of attributes, it is often not the crude ratio or the precise difference in values that is significant for the consumer, but some function of this. In addition, the importance of this difference may change over time because of habit creation or

behaviour transformations. Sensitivity parameters help us to express how sensitive the decision maker is to a marginal change in some attribute value.

In the present model, the square root function is applied in a number of cases. This function suits well when applied to variables near to the value 1, for example in the range [0, 2]. The square root function causes values in the range [0, 1] to increase towards 1 and values in [1, 2] to decrease towards 1. Hence, when considering relative differences in attribute values, this function may be good to express low sensitivity of consumers to marginal changes from the mean.

Next, the model formulation of the five attributes of performance will be discussed.

1. Relative range

The model structure defining relative range is illustrated in Figure 19. Travel range is measured in kilometers. The travel range of the BEV is an endogenously defined variable which increases over time, based on a rate of technological development. The initial value for year 2000 is 30 kilometers, which is approximately the travel range of the much-diffused Think City model at that time (the EV market leader in mini-segment vehicles).
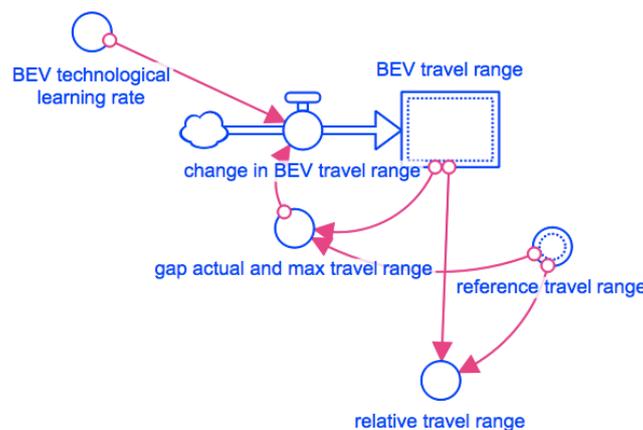
Figure 19. Model structure of relative travel range

The ratio of BEV to ICEV travel range is considered to define relative range. Hence, if the travel range is the same, the value of the variable is 1. If BEV has a lower travel range than the ICEV, the value is lower than one and equal to the relative difference. Hence, if the ICEV has a travel range of 800 and the BEV of 400, the value of the variable will be 1/2.

In the present model, the BEV's travel range will not surpass the range of the ICEV. Hence this value will always cover the range [0, 1]. In reality, the ICEV travel range may also improve over time; in the model however, a constant reference value is assumed for simplicity, and also since the focus is on the comparison BEV to ICEV.

The relative difference between ICEV and BEV travel range is scaled by a sensitivity parameter, which in this case is a square root function. The relative travel range is a value between 0 and 1, but the effect on total performance does not need to be always negative. Consumers may find it acceptable if the relative difference is smaller than a margin. Hence the square root function is applied to the relative difference to smoothen this negative effect. If the BEV has half the travel range of the ICEV, the effect on total performance will be SQRT(0.5) = 0.7, which has a lower negative impact than 0.5.

2. Relative lifetime

The lifetime of the BEV is an endogenously defined variable which increases at a constant rate over time, until a maximum lifetime has been reached. The rate of change is defined in such a way that the initial value is 5 years and the relative lifetime is equal to 1 in 2030; after 2030, the BEV lifetime is assumed to continue growing, in accordance to the discussion in section 3.6.3. The equation for the change in lifetime is the following:

Equation 13)

Change in BEV lifetime = IF(gap in lifetime > 0) THEN 2/5 ELSE 0,

where the gap in lifetime is defined as the difference between maximum lifetime and BEV lifetime. The maximum lifetime is set to 50% above the lifetime of the ICEV.

Figure 20 illustrates to the left the model structure, and to the right the comparison between BEV and ICEV lifetime simulated over time. It can be seen that the growth is quite slow, and in 2050 the maximum value is not yet reached.
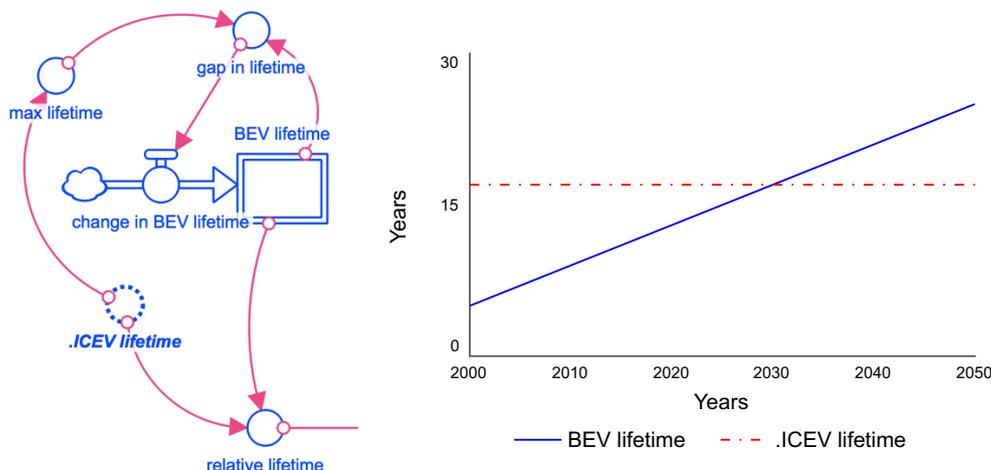
Figure 20. Left: Model structure for relative lifetime. Right: Development over time

The lifetime depends on technological development for a number of reasons: first, the battery technology is not matured, and is assumed to reach full maturity only in the next 20 years (Pasaoglu 2015). The rapid technological development causes vehicle models to become

obsolete in few years: the travel range of yesterday's model may be doubled in a few years. Finally, up to present there has been a lack of standards for charging systems across regions and inside the same region; this can cause models to become incompatible with the system.

As the model is a simplification of reality, early scrappings (meaning earlier than the expected lifetime), imports and exports are not included. The concept of lifetime as is used in this model is therefore related to both technological attributes and to the driver's consumption pattern.

The relative difference between ICEV and BEV lifetime is scaled by a sensitivity parameter, which in this case is a square root function. The relative lifetime is a value between 0 and 1, but the effect on total performance does not need to be always negative. Consumers may find it acceptable if the relative difference is smaller than a margin. Hence the square root function is applied to the relative difference to smoothen this negative effect. If the BEV has half the travel range of the ICEV, the effect on total performance will be SQRT(0,5) = 0,7, which has a lower negative impact than 0,5.

The ratio of BEV to ICEV lifetime is considered. Hence, if the lifetime is the same, the value of the variable is 1. If BEV has a lower lifetime than the ICEV, the value is lower than one and equal to the relative difference. Hence, if the ICEV has a lifetime of 15 and the BEV of 5, the value of the variable will be 1/3.

In the present model, the BEV's lifetime will not surpass the ICEV's. Hence this value will always cover the range [0, 1].

3. Relative emission level

The emission level is measured in grams of CO_2 emitted per kilometre, which is a standard way to measure a vehicle's emission level (International Energy Agency, 2015; Pasaoglu, et al., 2015). The BEV is considered a zero-emission vehicle, as there are no tailpipe emissions (and in fact no tailpipe!). However, the environmental footprint of this vehicle type must be considered from a well-to-wheel[12] perspective: the BEV's emissions are shifted to the location where the electricity is generated. As discussed in Chapter 3.6.5, Sweden and Norway use predominantly renewable energies to produce their electricity, and hence, also from a well-to-wheel perspective CO_2 emissions are low.

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[12] Well-to-wheel is the specific Life Cycle Assessment when considering transport fuels and vehicles. The first stage includes fuel production, processing and fuel delivery or energy transmission and is called the "upstream" stage, while the stage that deals with vehicle operation itself is sometimes called the "downstream" stage. The well-to-wheel analysis is commonly used to assess total energy consumption, emissions impact including their carbon footprint, and the fuels used in each of these transport modes ("Green Car Glossary: Well to wheel". Car Magazine. Archived from the original on 4 May 2011. Retrieved 28 February 2011).

Since ICEV is an umbrella term including gasoline, diesel, hybrids and biofuels, each fuel's emission level needs to be considered. Diesel has lower CO2 emissions than gasoline, but diesel has higher NOx emissions, hence its attractiveness in emission terms is not much higher than gasoline. As for biofuels, ongoing research is debating on whether these are bringing any improvements to air pollution or not. Ethanol is a particulate-free burning fuel source that combusts with oxygen to form carbon dioxide, carbon monoxide, water and aldehydes (Wikipedia, 2017); depending on the production process, the carbon intensity can be higher than diesel and gasoline (UK Department of Transport, 2013). Hybrid electric vehicles, on the other hand, are considered to contribute positively to the reduction of emissions, since on average 50% of the time they are driven on battery mode (Figenbaum & Kolbenstvedt, 2016). The emission level of ICEV is directly proportional to ICEV fuel efficiency, scaled by a conversion factor expressing how many grams of CO_2 there are in each liter of fuel. This value changes over time and is specific to each country, and Scandinavian values have been applied. It has also been assumed that the CO_2 concentration per litre decreases over time as a consequence of higher shares of biofuels in the fuel mix. The fuel efficiency (expressed in liters per kilometer) is assumed to improve over time base on IEA Fuel Economy studies (2015), and hence the emission level decreases as well. The simulation of the development of ICEV emissions is illustrated in Figure 21, in comparison to historical values. The simulation (in red) seems to represent the historical development (in blue) to a satisfactory degree.
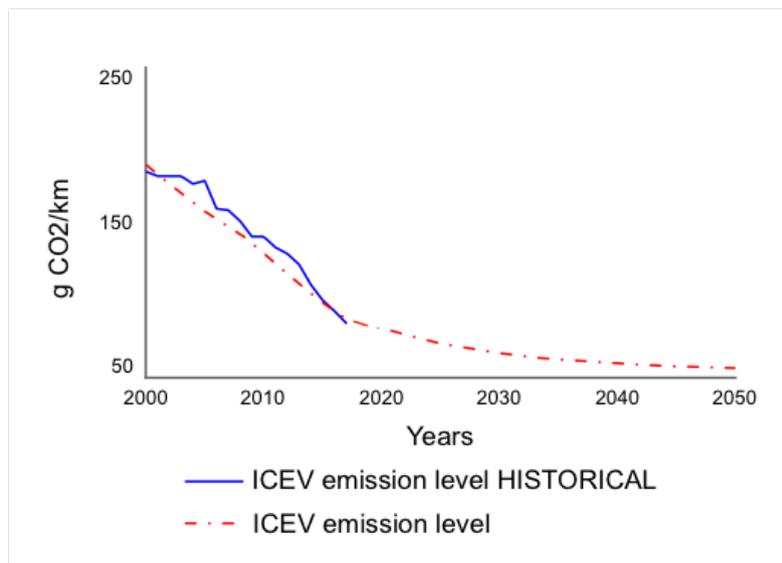
Figure 21. ICEV emission level, simulation versus historical

The relative BEV performance is higher the lower the BEV emissions are, compared to ICEVs. Therefore, a negative sensitivity parameter is applied to the relative emission level.

4. Diversity of BEV market offer

Light passenger vehicles include a large number of types: SUVs, sports-cars, vans, sedans, hatchbacks, runabouts and more. The offer of BEV models on the market has not yet reached a large diversity. In 2000, the market offer was nearly non-existent; measuring diversity in units of vehicle models, the initial value 1 is therefore chosen. According to Liebreich (2017), in 2018 the international market will see the offer of a large number of BEV models, covering most vehicle types. Still, the industry scepticism is high due to the uncertainty in investment (Knupfer, et al., 2017).

Since the model takes a national perspective, the diversity of the vehicle offer is primarily dependent on the offer given by the vehicle retailers; it is however in reality the international vehicle diversity that is determinant for the diversity that the retailer can offer. This will not be accounted for here.

The growth in diversity of the BEV market offer is modelled as a function of society's confidence in the BEV. The confidence is defined over the range [0, 5] and therefore a conversion function is defined to express a proportional rate of product development, measured in models per year. The rate parameter is used here as indicator of how much national vehicle retailers can and want to offer electric models. The higher the confidence, the stronger the rate of development of new models. In addition, we assume that the value is following a goal seeking behaviour, where the goal is a reference diversity of 100 models. The value of 100 is considered the reference diversity value for ICEVs. The model structure is illustrated in Figure 22.
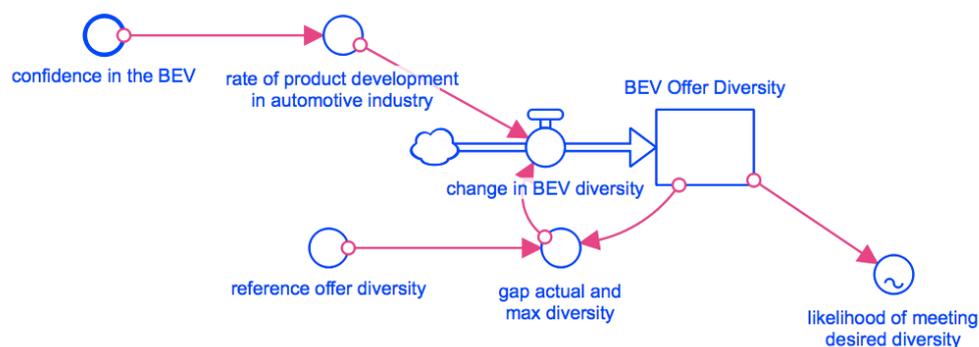
Figure 22. Model structure for BEV diversity

The likelihood of meeting the desired market offer as a potential BEV buyer is not linearly related to the number of models available on the market. In addition to the number, an important factor is the vehicle type. Most light private vehicles demanded are of medium size, while a smaller market segment looks for very small or very large cars. Hence, likelihood and model

number are causally related in a positive direction, but until a certain number is reached, the likelihood keeps low. We then assume that, after 50 models on the market, the likelihood is boosted, and that above 80 models, the likelihood is near to certainty. The graphical function in Figure 23 encases this behaviour.
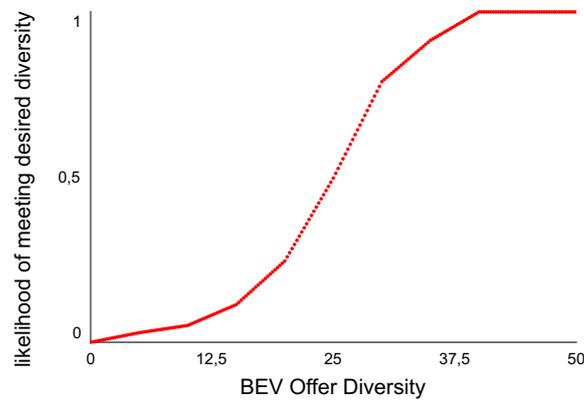
Figure 23. Effect of BEV Offer diversity on performance

The causal relation between confidence and BEV offer diversity creates yet another Chicken and Egg situation: if the offer diversity is high, relative attractiveness from performance is boosted, and from it sales, and the BEV stock; a large stock brings high confidence in a high ROI, so that retailers introduce more models in the market. On the other hand, if the diversity is low, BEV sales are curbed, and retailers cannot expect a high ROI, and are therefore not motivated to invest in the BEV market. In addition to this reinforcing mechanism, a balancing feedback is part of the process as the maximum offer diversity is reached. The two feedback loops are illustrated in Figure 24.
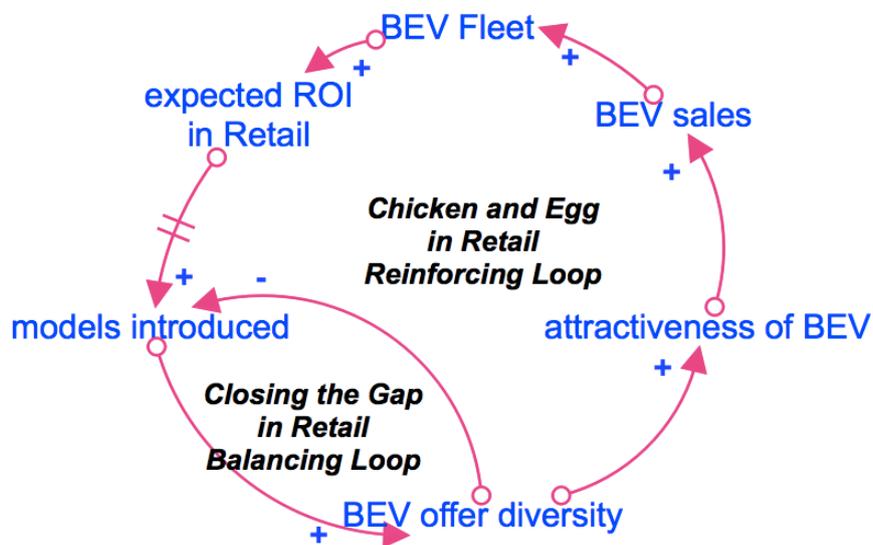
Figure 24. Casual loop diagram including Retail sector

5. Charging availability

The average charging station density represents the difference between the demand for charging stations and the existing supply. When considering the effect of this density on the overall performance level of BEVs, the density is scaled by a sensitivity factor in order to express the fact that the perception of this density is not linearly related to the difference itself. In the case of charging availability, the sensitivity has a value of 1/2: the square root function dampens the negative effect a low supply. If, for example, supply covers 50% of demand, attractiveness from charging station density will be only 30% lower than ICEV attractiveness, and not 50% lower. In addition, we include the factor "+0.1" to express that attractiveness is comparable to the ICEV's, even if the charging density is 10% less than desired. The equation for the effect is the following:

Equation 14)   effect_of_charging_availability_on_BEV_performance =
.average_charging_station_density^sensitivity_parameter_to_difference_between_plat
forms[CS_density] + 0,1

The determination of charging station supply and demand will be described in section 4.2.5.

The performance module derives the trend behaviour over time of two other attributes related to the electric vehicle: battery capacity and recharging time. These are inputs to the cost module. Battery capacity is an endogenously defined variable, dependent on the rate of technological development. The initial value is 20 kWh, and the value is assumed to increase to a maximum of 120 kWh over the simulation time. This estimate is based on the relation between battery capacity and travel range: since a range of 1000 kilometres is considered the desirable target, a battery of 120 kWh would satisfy this condition. This behaviour is obtained by introducing a goal variable ("estimated max battery capacity"), to which the stock converges (see Figure 25). A monotone decaying behaviour is assumed for the variable recharging time, defined as dependent on rate of technological development. The value is representative for the average BEV; hence it averages the vehicles that use fast charging, slow charging, vehicles with large and small batteries, and vehicles with different charging capacity. Much research is being done at present to develop faster charging solutions. Among the conceptualized and not fully developed ideas are battery swapping and charging by induction. These solutions can considerably increase the charging time efficiency. The initial value at year 2000 is defined as 300 minutes, and the model simulates in 2017 a charging time of less than 1 hour, and in 2050 only 6 minutes.

Finally, it is important to notice that the Cost and Performance modules are strongly related: vehicle performance drives in many cases its cost. For example, the BEV travel range and the battery capacity are drivers of recharging costs; the recharging time impacts the cost of travel time; the vehicle lifetime impacts its rate of devaluation; and the level of ICEV emissions determines the level of taxation it is subject to. Hence, not only public policies but also technological development drives the relative price between ICEV and BEV. This will be discussed in depth in the next chapter (6).

In Figure 25 the complete Performance module can be seen.
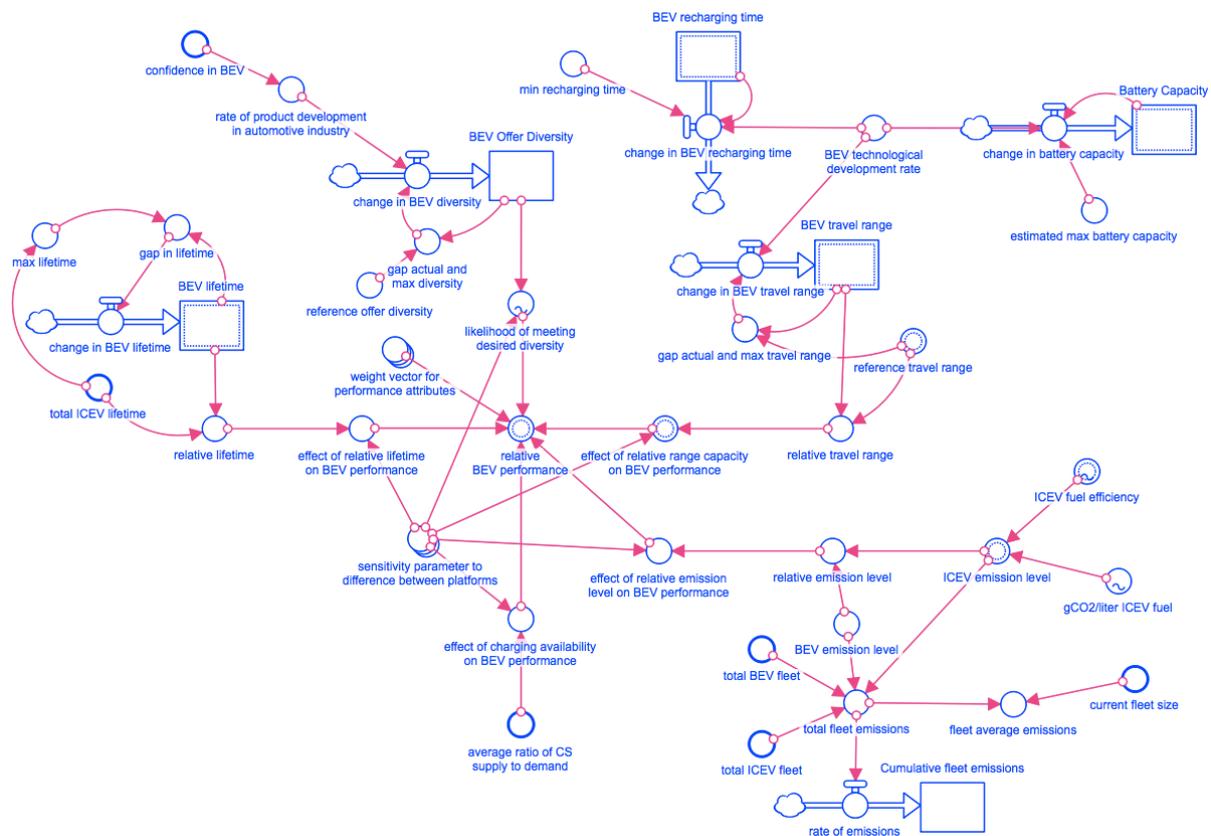
Figure 25. Performance module

The next section will take a closer look into the main performance attribute: the availability of charging infrastructure.

4.2.5 Modelling charging infrastructure development

The average charging station density, which is one of the five performance attributes, is calculated in a separate sector by the following equation:

> *Equation 15)   average_charging_station_density =*
> *(density_of_fast_charging_stations + density_of_park&charge_points)/2*

The average between the densities of two types of charging stations is taken: fast charging stations and park&charge points. This classification is explained in section 3.6.2 from the theory chapter. In Figure 26 the model sector is illustrated.
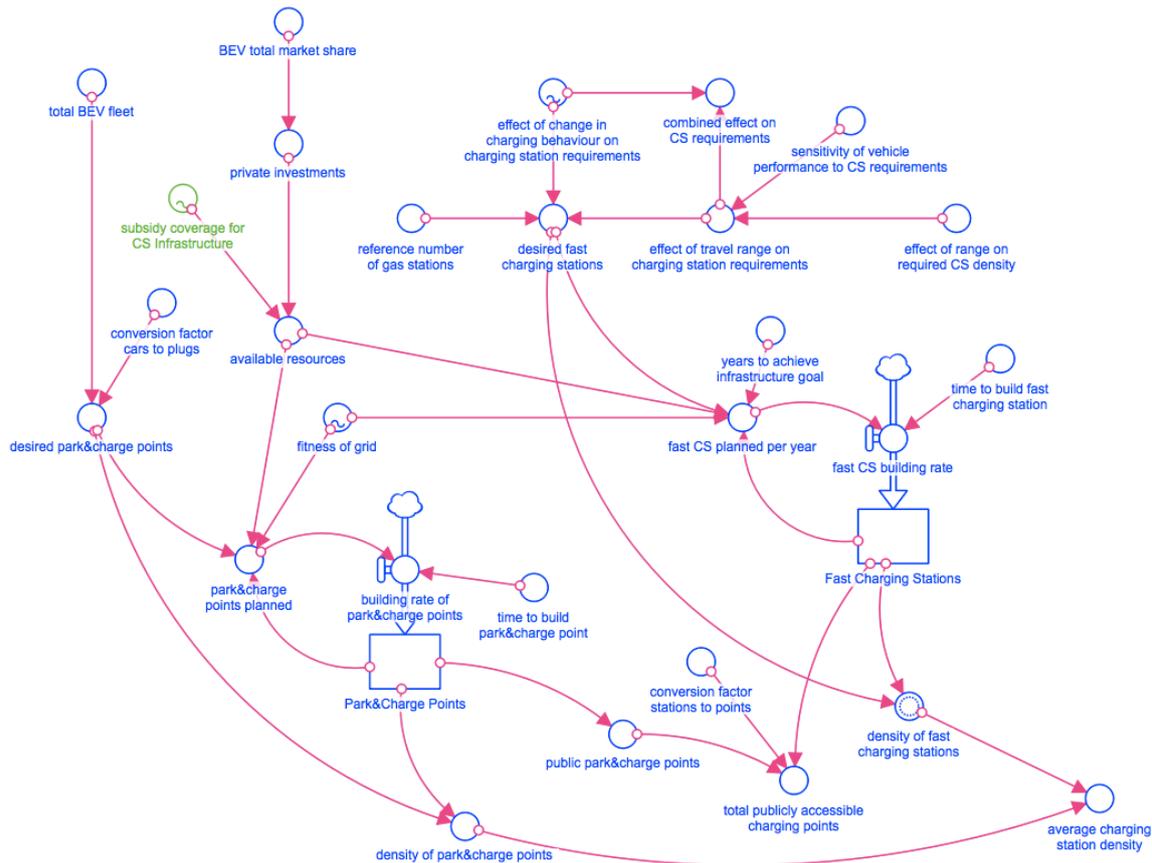
Figure 26. Charging infrastructure sector

As mentioned above, the density represents the difference between the demand for charging stations and the existing supply. More precisely, the equation is:

$$Equation\ 16)\quad density\_of\_fast\_charging\_stations = \\ Fast\_Charging\_Stations/desired\_fast\_charging\_stations$$

Supply is represented by the existing stations, while a desired level of charging stations is considered the demand. The ratio of supply to demand will have a value between 0 and 1, since the model does not include incentives to build more private charging stations than required. This sector describes the drivers of both demand and supply. To do that, the two charging point types will be considered separately.

Fast on-road charging stations

In order to estimate the required national number of public fast charging stations required by BEV drivers, we compare with the total number of petrol stations in the country. This should be an acceptable reference point since the use of fast charging stations and of gas stations is similar, in allowing short as well as long travels across the country.

Up to approximately 2022, the required number of fast charging stations for BEV drivers will be slightly higher than the number of gas stations because of the difference in travel range. After 2022, the number can be more or less the same. In addition, this variable only tells us something about the number of charging stations, and not the frequency of use. This will, however, change considerably: as long as the travel range is short, charging will be used very frequently. As the travel range increases with technology development, the use of these stations will decrease. We do not take the spacial distribution of charging stations into account.

Surveys document a change in driver habits: fast charging stations are not used as much as the "park&charge" possibilities- whether this is at home, at work or at shops (Figenbaum & Kolbenstvedt, 2016). This supports the belief that drivers will move towards more and more park&charge solutions and away from visits at charging stations.

BEV drivers are expressing a preference for this solution because of convenience with respect to time, money and correlated benefits such as a parking space. As the charging effect increases, the home charge will be quicker and allow for longer and longer trips, thus decreasing the need for fast charging stations on a large radius around the home. Fast charging stations are required for extra-ordinary trips, but not for daily use. At the same time, the short travel range has lowered the attractiveness to make long trips with the BEV; this may change as the travel range improves, and therefore reintroduce the importance of charging stations.

The effects discussed above are represented in the model and can be seen in Figure 27.
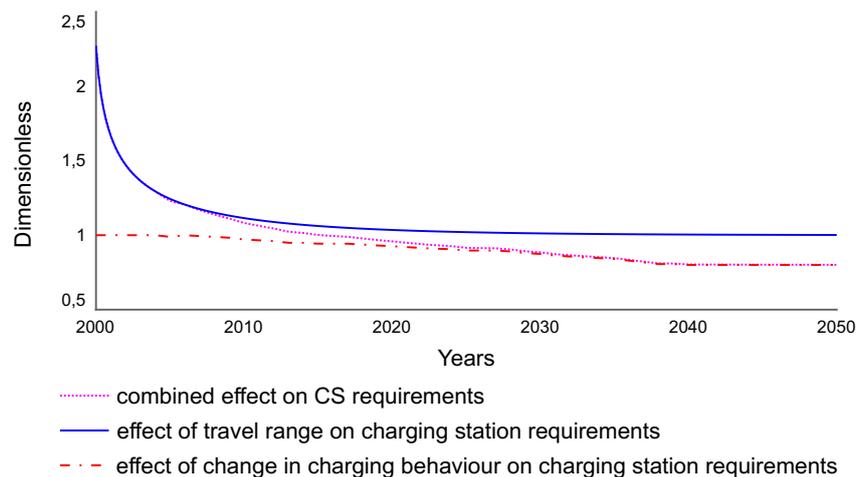
Figure 27. Effect functions on charging station requirements

The number of fast charging stations planned and built does not necessarily equal the desired number of fast charging stations: one will also need to take into consideration the available resources (here only assumed to come from subsidies), and the fitness of the grid to the installation of charging points.

Available resources for the construction of charging infrastructure derive from two sources: private actors, as for example grid operators, automakers, private enterprises, and public subsidy programmes, as the Enova program in Norway. Private investments in charging infrastructure are assumed to be driven by the prospect of profit. The total market share of BEVs is used as a proxy. Private actors are assumed not to drive proactive instalment of infrastructure, as public entities may be. Private actors are supposed to be responsive to the market dynamics.

The amount of charging stations planned is the gap between the supply and the demand in charging stations, scaled by the availability of resources and the fitness of the grid. The building rate is assumed to be driven by planning. The only limitation to "filling the gap" is the years set to achieve the goal. This defines indirectly how many stations can be built per year. This is a realistic assumption since infrastructure incentives may be delivered in instalments over a longer period of time.

The delay time to build a charging station is a personal assumption. This time depends not only on construction time but also on a range of uncertain factors such as planning time, availability of information about site of installation, time to receive permission to build, etc.

Park&charge points

Charging points include in the definition of the present model charging points in the household parking space, parking lots at work, in public streets and in front of shops. The desired level of park&charge points is directly related to the number of BEVs in the streets (the variable total_BEV_fleet). Most travels by car are those for moving between home and work, school and shops. We assume that every BEV will require, on an average travelling day, two charging points connected to parking space. These will be, in most cases, the household for the night and the workplace for the day. Other parking locations where BEV drivers can also benefit of charging are parking spots in public roads, in front of shops and of other facilities.

Parking space is a key aspect of vehicle ownership, as on average a car is parked for 90% of the day (Norwegian Department of Transportation, 2017).

The planning of building park&charge stations is driven by three elements:

- the assumption that each BEV owner should have access to 2 plugs on average (the required park&charge points)

- the present number of installed park&charge points

- the fitness of the grid, expressing in how many cases there is the possibility to actually install a plug.

The formulation is as follows:

Equation 17)   park&charge_points_planned =

(desired_park&charge_points - Park&Charge_Points)*fitness_of_grid*available_resources

Section 4.1.2 described the reinforcing feedback loop "Chicken and Egg" which describes the growth (or decay) in infrastructure development: the more BEVs, the higher the expected ROI from building charging points, the more investments in charging infrastructure, the higher relative BEV performance, the higher BEV sales, and the more BEVs; but the lower the charging station density, the lower the sales, the lower the expected ROI, and the less the investments in charging infrastructure. The reinforcing loop can be of virtuous or vicious nature, depending on the initial momentum of the loop. The infrastructure sector has however one more important feedback loop which defines the growth of infrastructure: the more BEVs, the more charging points are needed, but the more charging points are built, the less are needed. The balancing behaviour is here called "Closing the Gap" and the causal loop diagram is illustrated in Figure 28. In the simple system depicted in the picture, the balancing and the reinforcing feedback loops interact to create an S-shaped growth in the number of charging points: at first, the reinforcing loop will dominate and drive growth; as the required number of

charging points will be approached, the balancing loop will slow down the building rate. In the more complex system, the non-linear effect of grid fitness, public subsidies and BEV fleet growth will cause a more complex behaviour to happen.
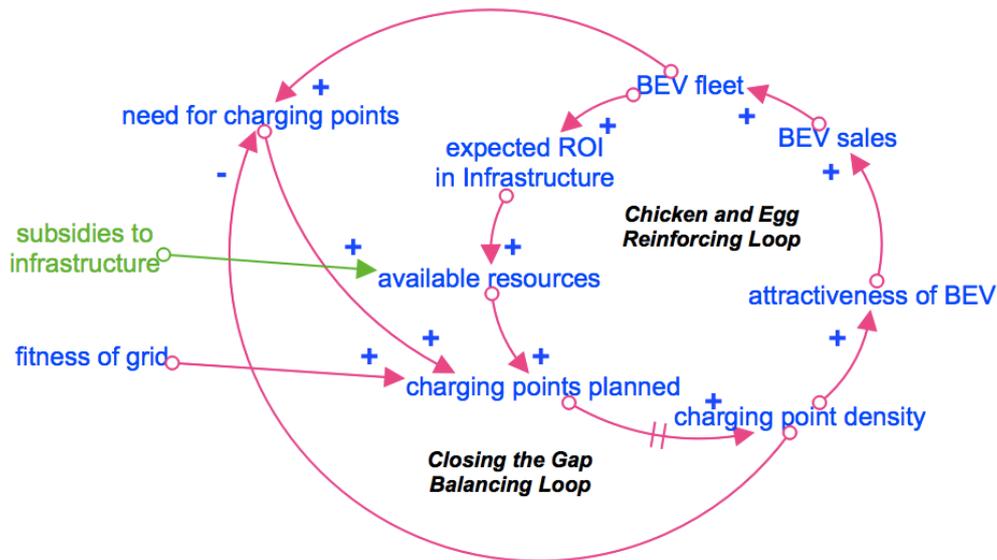
Figure 28. Causal Loop Diagram for infrastructure sector

From an aggregate perspective, it is reasonable to assume that some proportion of the total number of locations is fit for the installation of plugs, while another proportion will not. This is due to a number of factors such as the parking space availability, the population density and the grid capacity.

The starting value is of the grid fitness 50%. Over time however, the grid is strengthened, widened and renovated, so that the fitness of the grid to the installation of charging points grows over time. It is assumed that a full fitness (100% value) is reached by the end of the simulation time. The development of the fitness parameter is illustrated in Figure 29.
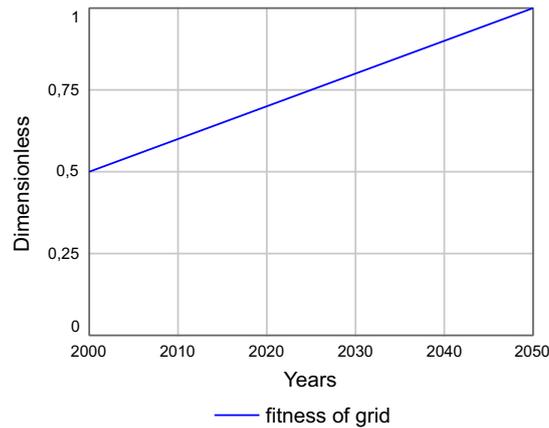
Figure 29. Graphical function for fitness of grid

In this section, the details of the infrastructure development process were outlined, showing more concretely where the delay factors in the process lie: the time to build infrastructure, the fitness of the grid, and available resources all determine the speed at which the desired charging point density can be achieved.

4.3   Complete causal loop diagram

The model structure can serve as a dynamic hypothesis describing the problematic behaviour over time. The shift in the vehicle system's drivetrain composition towards battery-electric is driven by many reinforcing and balancing feedback loops. The previous sections have separately described the main loops: the "Word of Mouth", "Chicken and Egg" and "Risk Aversion" loops, which were causally relating variables across sectors, the loops "Sales to Replacements" in vehicles and the "Closing the Gap" mechanisms in the vehicle system and in infrastructure development. It was qualitatively described how these loops act in isolation and the reinforcing and balancing forces that they can put in place. There are nevertheless external forces determining the strength and direction of the feedback loops: among these are time delays, other variables which are not part of the loops, and the effect of the interaction between multiple loops. Among the variables there are not only policy instruments, but also system characteristics such as prices, technological development rates and grid fitness. The complete causal loop diagram, including the main drivers and barriers, is illustrated in Figure 30 and will be analysed in this section. The role of policies must be considered in the perspective of the system's causal map in order to evaluate their effectiveness. This is being done here in a descriptive fashion; in the next chapter, the same analysis will be done through simulation.

A note on the illustration: even though a causal loop diagram normally only includes variable names and causal relations, this illustration includes also the stocks ICEV and BEV fleet and the connected flows. This is done to better illustrate the nature of the main problem variable, namely the growth of the BEV fleet. In addition, the sign of the causal relation is not included in the graph in order to reduce visual complexity.
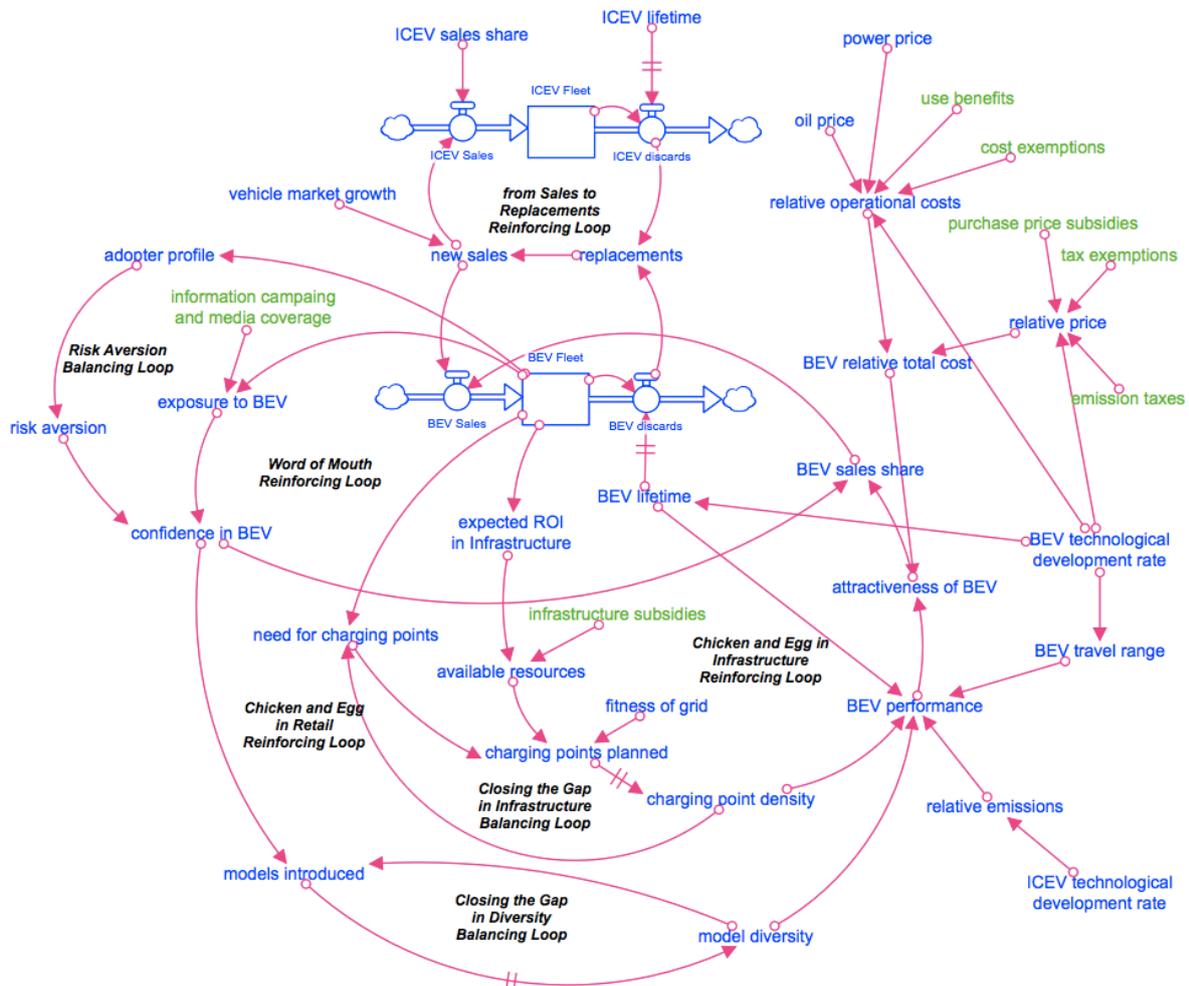
Figure 30. Complete Causal Loop Diagram

The shift from ICEV to BEV is driven in the model by the change in BEV sales share. This is determined by the BEV attractiveness, and confidence represents a possible barrier to reflect this attractiveness: if confidence is low, the attractiveness is not perceived as fast; if confidence is high, the perception is rapid.

Confidence is determined by a reinforcing and a balancing loop in interaction. The reinforcing Word of Mouth loop is influenced by the policy variable "information campaigns", which increases exposure. The exposure is otherwise directly proportional to the market share, which can be very low in the first years of diffusion; hence proactive exposure through this policy

increases the reinforcing effect of this loop. The balancing Risk Aversion loop is assumed to be solely determined by the level of market penetration; policy action cannot directly influence consumer's risk aversion. The objective attractiveness drives BEV sales share.

BEV attractiveness is defined by the combined effect of relative performance and cost. The Chicken and Egg Reinforcing loops are halted by a number of time delays and barriers, which can cause the reinforcing behaviour to be more vicious than virtuous if attractiveness does not increase by other means. In the case of charging infrastructure, the determinants for growth are: the availability of resources, the exogenously defined fitness of the grid, and the need for charging infrastructure. The availability of resources is part of the feedback loop, and is hence a dynamic barrier, dependent on the system behaviour. Governmental subsidies can increase the resource availability and remove this barrier. The fitness of the grid can determine the speed of infrastructure development by setting where the building of charging stations is feasible; it is assumed in this case to grow progressively over time as a consequence of grid expansion and reinforcement, so that the barrier is lower and lower over time. The need for charging infrastructure is defined by the Closing the Gap balancing mechanism: the nearer to the target, the lower the need to close the gap. Similar mechanisms appear in the Retail sector: diversity of BEV models is increased if confidence increases. In this case however, there are no policy instruments which can, at least in this model, increase the retail sector's BEV model diversity. The building of charging stations and the development of new BEV models are slowed down by natural delay times. The performance components diversity and charging density are driven by endogenous reinforcing mechanisms, and hence also by policy action in infrastructure subsidies and information campaigns; travel range and lifetime are instead driven by the exogenously defined development rate of BEV technology; the emission level changes over time depending on the development rate of ICEV technology, since BEVs are assumed to already set the target in emissions (at least for Norwegian and Swedish electricity production sources), while ICEV technology can achieve improvements over time.

Costs are purely exogenously driven: either by technological development rate and fuel prices, which represent forces at supranational level, or by national policy action. Most BEV policies act in fact in this sector and target both the purchase price and the operational costs.

Finally, the relative BEV lifetime can speed up or slow down the transition process: assuming constant sales share, if BEV lifetime is lower, then the BEV stock will deplete at a faster rate than the ICEV stock and lose market. In order to gain market share, the growth in sales share must be high enough to overcome the barrier of a short lifetime.

This section has outlined how BEV diffusion is driven by both pushing and pulling forces: technological development at international level pulls BEV prices down and performance up; policy action can push towards parity between the two drivetrain technologies. The extent to which policy action can be effective in this aim, how long policy action needs to be in place and other similar questions can only be answered through simulation. The next chapter will make an extensive exploration in order to more precisely understand the balances (and unbalances) between feedback loops, pulling and pushing forces in the system.

But first, the parametrization of the model to the national contexts is presented.

4.4 Parametrization to Norwegian and Swedish contexts

Starting from the common model structure described above, certain parameters and model structures have been specified to each context based on historical data and context information presented in sections 3.7 and 3.8. This has resulted in two separate models, each of which represents a nation's vehicle system.

The following table lists all the model variables that needed to be contextualized, sector by sector. Some variables have a constant numerical value; others are functions of other variables; - in most cases a function of time, but also of other variables, as in the case of emission taxes. Hence the expression used in the table "f(..)" stands for "function of …". When the national context does not include a certain variable, the sign "---" is reported. All variables in the table will be discussed in this section.

Table 6. List of contextualized variables

Variable	Norway	Sweden
Vehicle market		
INIT BEV fleet	278	0
INIT ICEV fleet	1.8 M	3.9 M
Indicated vehicle density	f(TIME) [Figure 31]	f(TIME) [Figure 31]
Consumer choice		
Media coverage effort	f(TIME) [Figure 32]	f(TIME) [Figure 32]
Cost module		
Base price BEV	f(TIME) [Figure 33]	f(TIME) [Figure 33]
Base price ICEV	300 000 Kroner	225 000 Kroner
Switch for exemption from VAT	f(TIME)	---
Switch for exemption from purchase tax	f(TIME)	---
Emission tax	f(ICEV emission level)	f(ICEV emission level)

Purchase subsidy	---	f(TIME)
Annual road tax	3000 Kroner for ICEV, f(TIME) for BEV	1500 Kroner for both ICEV and BEV
Switch for bus lane access	f(TIME)	f(TIME)
Switch for free parking	f(TIME)	---
Switch for free ferry	f(TIME)	---
Switch for free road tolling	f(TIME)	---
Switch for free charging	f(TIME)	---
Oil prices	f(TIME)	Oil prices NORWAY[13]
Power prices	f(TIME)	Power prices NORWAY*1,5[14]
Charging Infrastructure		
Number of gas stations	1580	4100
Subsidy coverage for charging infrastructure	f(TIME)	f(TIME)
INIT Park&Charge stations	INIT BEV fleet*2	INIT BEV fleet*2
INIT Fast Charging stations	0	0

The values that are assigned to the contextualized variables for the time period 2018-2050 are a first set of assumptions for a most-likely behaviour. In chapter 5.3 a range of scenarios will explore alternative assumptions on chosen variables. The model has indeed a flexible structure that allows to study the effect of alternative parameter values and policy strategies.

In the sector of the vehicle market, the variables that need to be contextualized are the initial stock values, which are based on historical data, and the indicated vehicle density. The former has been derived by comparing historical values of population size and vehicle fleet. For future values, the historical trend is used. As discussed in section 3.7 and 3.8, vehicle density is expected to grow only moderately in both countries as a consequence of low growth in GDP per capita and population growth. Sweden has had a relatively stable vehicle density over the observed period. Norway has had a more significant growth, starting in 2000 below Swedish values, and surpassing from 2012. This growth has slowed down since 2014. It is thus assumed that both contexts will have a moderate increase in vehicle density converging towards 0.5 vehicles per person by 2050. The trend of the indicated vehicle densities over time is illustrated in Figure 31. These assumptions will be kept constant for all scenarios in the present study.

[13] Oil prices are assumed to be the same in Norway and Sweden even though they are not in reality, because of the high volatility in the currency exchange.
[14] Power prices are on average 50% higher in Sweden than in Norway due to higher taxes and production costs in the case of nuclear and biofuels.
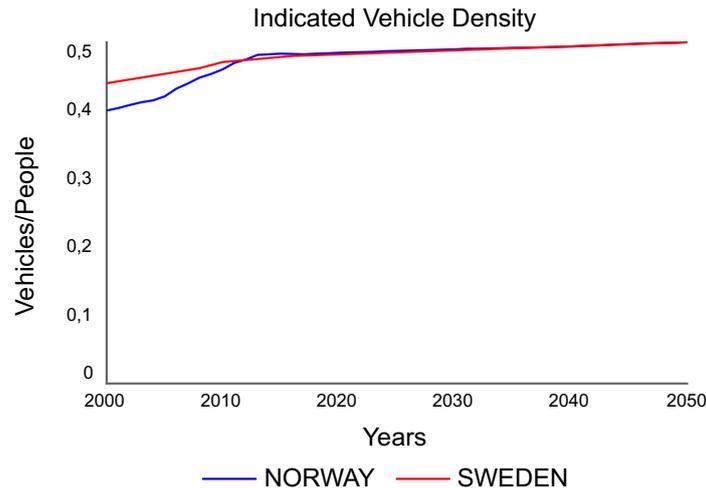
Figure 31. Indicated vehicle density for Norway and Sweden compared

Among the drivers of consumer choice, only the marketing effort is contextualized for each model. As discussed in the theoretical chapter, Norway started its EV campaign quite early, with the first tax exemption policies in 1990. Sweden, on the other hand, embarked its journey towards a greener vehicle fleet by initially giving subsidies and benefits to biofuel-driven vehicles; only from 2008 EVs were included in the environmental policy, and nowadays the attention seems to be shifting from biofuels to EVs. Hence, in the model we assume that the media coverage on BEVs in Sweden is a shifted parallel of the Norwegian behaviour, as represented in Figure 32. The variable is defined on the interval [0, 1] but the precise value is only indicative since it is subjectively defined; the comparison between contexts is nevertheless the main factor of interest. As media attention is normally periodical, we can expect the effort to reach a maximum, and then decay: if the product has taken over the market, its novelty will have faded away, and there will be less interest in talking about it; if the product disappears from the market, media will not consider it as a topic any more (Sterman 2000, p. 339) In the case of BEVs, it is assumed that these for an unforeseeable time will have a market share, and hence media coverage will never decay to zero, but in the long run converge to a minimum. These assumptions will be kept constant for all scenarios.
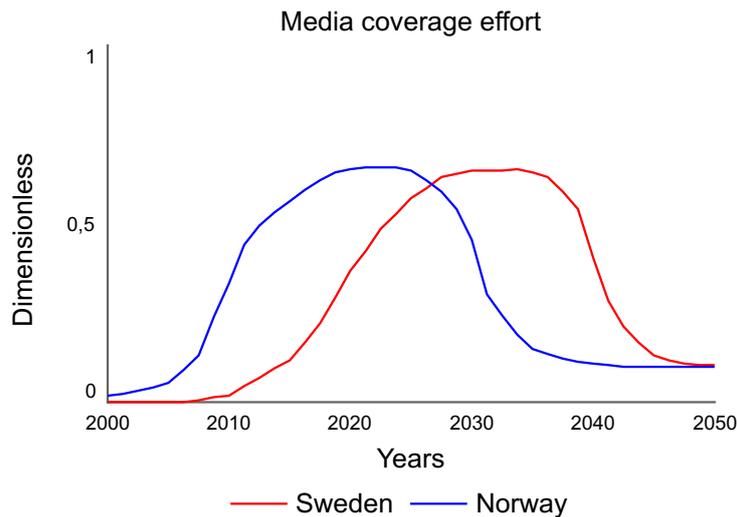
Figure 32. Graphical functions for Media coverage effort for Norway and Sweden

The majority of contextualized variables are located in the Costs module, as can be seen from Table 6. The start (or base-) price[15] of both ICEV and BEV is different because of the different levels of taxation in Norway and Sweden. Norway has among the highest taxation levels on vehicles in Europe, so that the price of a vehicle in Norway is on average 25% higher than the price in Sweden. The price of the ICEV is taken as a reference and it is assumed to be normalized to present values, and is therefore constant over time. The price of the BEV is assumed to fall over time as a consequence of favorable feedbacks of market of scale, technological development and returns on investments. The development over time of the respective base prices are represented in Figure 33. This price development is assumed to be constant for all scenarios in the next chapter.

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[15] The model defines a start or base price for each vehicle type considering the base price and purchase taxes. Emission taxes are excluded. This definition is functional to implement the exemption from taxes: a percentage of the start price is detracted.
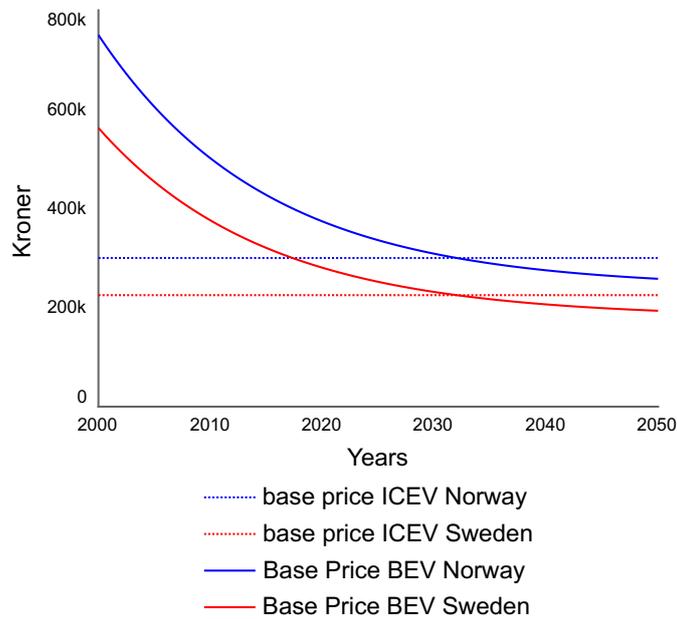
Figure 33. Base price for ICEV and BEV, contextualized

The switch variables indicate whether a policy is in place[16]. The definition of the switch variables, of the value of subsidies and tax exemptions for the time period 2000-2017 is based on the discussion in chapters 3.7 and 3.8 and is illustrated in Figure 34 and Figure 35 for Norway and Sweden respectively (note that the vertical axis has opposite meaning in the top and bottom figure: in the top figure, policies are active when the switch value is 0; in the bottom figure, policies are active when the switch is equal to 1). The policies described in the top figure cover different aspects of operational costs such as recharging costs and access to bus lane; in the bottom figure, are policies targeting BEV price and subsidy policy for construction of charging stations (this is included in this discussion for comparative purposes even if it is not part of the Costs module).

In the Norwegian case, the main instrument introduced to reduce the price differential is tax exemptions, of which the value added tax and the purchase tax represent the most significant reductions. The BEV has received support over time through an increasing number of instruments, and today the policy strategy is "all-inclusive": policies are directed to purchase price, charging infrastructure development and use costs and benefits.

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[16] The switches for price take the value 1 when they are in place and 0 when they are not. The switches for operational costs are defined in the opposite way: 1 when those costs need to be paid, and 0 when those cost are removed. This different definition is due to the way the functions are defined in the model.
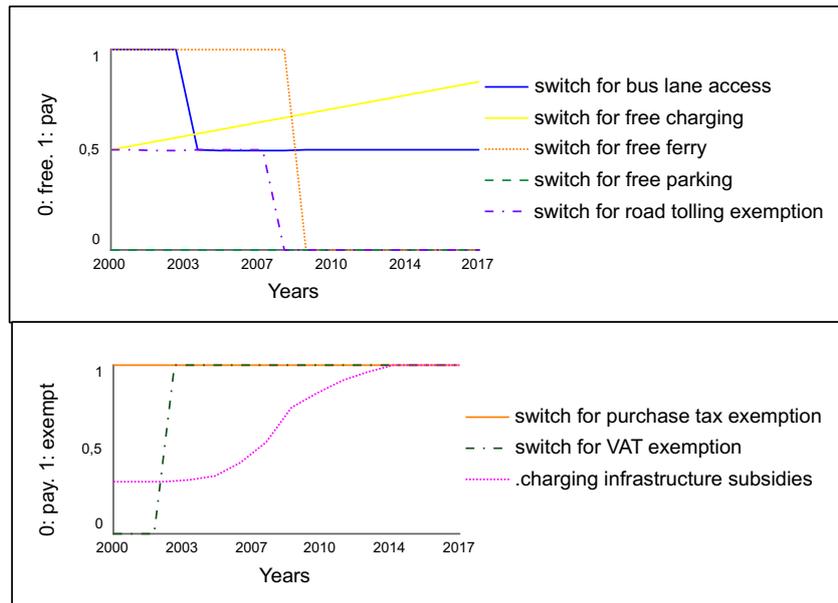
Figure 34. BEV policy instruments in Norway 2000-2017

In the Swedish case, the price differential between BEV and ICEV is reduced by purchase subsidies, which were first introduced in 2007 and then increased in value from 2012. When compared to the Norwegian context, BEV policies in Sweden were introduced later and at a slower rate. Bus lane access and free parking have been slowly introduced over a range of municipalities starting from 2007, but not at national level. Purchase subsidies were introduced in 2007 and increased from 2012. Charging infrastructure subsidies have slowly been introduced through the action of Vinnova. BEVs are exempt from road tolls for only the first five years of ownership. Free charging and free ferry access are not included in the Swedish policy package. Sweden has, however, a policy strategy directed to all "*miljobilar*", as discussed in section 3.8; hence, also vehicles from the ICEV class fulfilling specific environmental conditions receive certain tax reductions and use benefits. Since it is chosen in the model to keep ICEV costs constant references, this fact is reflected in the degree to which BEVs benefit of policies: as can be seen in Figure 35, policy switches do no reach the value 0, which would give a full relative benefit.
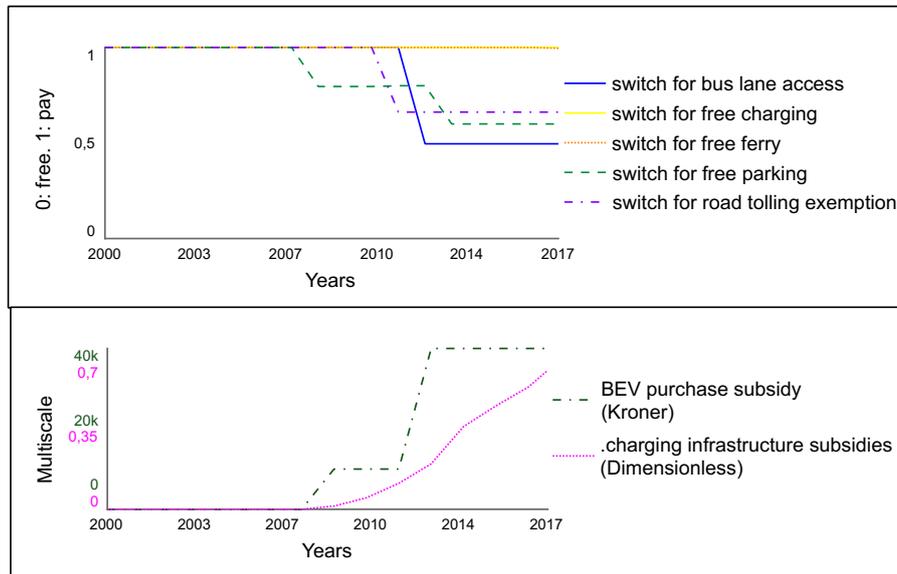
Figure 35. BEV policy instruments in Sweden 2000-2017

In order to define the policy parameter values for future time values, it is necessary to make assumptions on the policy strategies that each country will take in the next years. Since a large variety of strategies can be taken, the next chapter will consider a series of scenarios and study the different outcomes (sections 5.2, 5.3 and 5.3)

Oil and power prices are important variables in the model since they determine the cost of refuelling for an ICEV owner and recharging for a BEV owner. An average of gasoline and diesel price is used for ICEVs. The price of power delivered at home is used for BEVs, since this is the main source of charging for BEV drivers (see 3.6.2 on recharging density). Past oil and power price curves are based on historical data and on the forecasts made in the ETO model for the European region. Because of the high volatility in the currency exchange, equal oil prices are assumed for Sweden and Norway, even though they are not in reality. The price of power delivered to the households in Sweden is on average 50% higher than that in Norway. Oil prices are a highly uncertain and volatile variable, so that the value of this prediction is low. In later sections (5.3) the effect of alternative pathways for the oil price curves on the BEV market will be explored. The price of power is expected to fall over time as a consequence of growing production of cheap energy from renewable sources. The price assumptions for the base model lead to the cost per kilometre illustrated in Figure 36.

NORWAY COMPARISON COST/KM

SWEDEN COMPARISON COST/KM
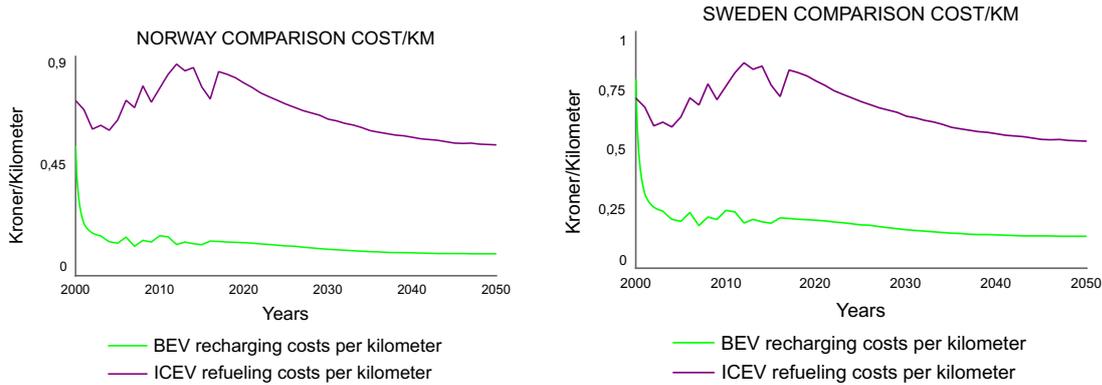
Figure 36. Cost of refueling vs recharging, for Norway (left) and Sweden (right)

In both contexts, the emission tax is a linear function of average CO2 emissions per kilometer. The functions differ however for each context:

Equation 18)   Emission tax NORWAY =

IF(Vehicle_Performance.ICEV_emission_level > 75)

THEN (1000 Vehicle_Performance.ICEV_emission_level- 76000)**
conversion_factor_gram_to_money*scaling_factor_for_emission_tax
ELSE 0

Equation 19)   Emission tax SWEDEN =

IF(Vehicle_Performance.ICEV_emission_level> 60)
THEN 540 + Vehicle_Performance.ICEV_emission_level*22*
conversion_factor_gram_to_money*scaling_factor_for_emission_tax
ELSE 0

Formulation for Norway is retrieved from The Norwegian Tax Administration's websites (Norwegian Tax Administration, 2017); the formulation for Sweden is retrieved instead from the European Automobile Manufacturers' Association websites (European Automobile Manufacturers Association, 2017). In both cases, rounded values are used.

The formulations retrieved are valid for the current year. However, the price of the emission tax varies over time, and is expected to grow in the future, as an adaptive method to falling emissions. Hence, a scaling parameter is multiplied with the emission tax to define a more correct net taxation cost.

In both countries, the marginal increase in price of the ICEV due to emission taxes is not significant, while somewhat higher in Norway (see Figure 37 showing the simulation in the period of the base ICEV price in the period 2000-2017).
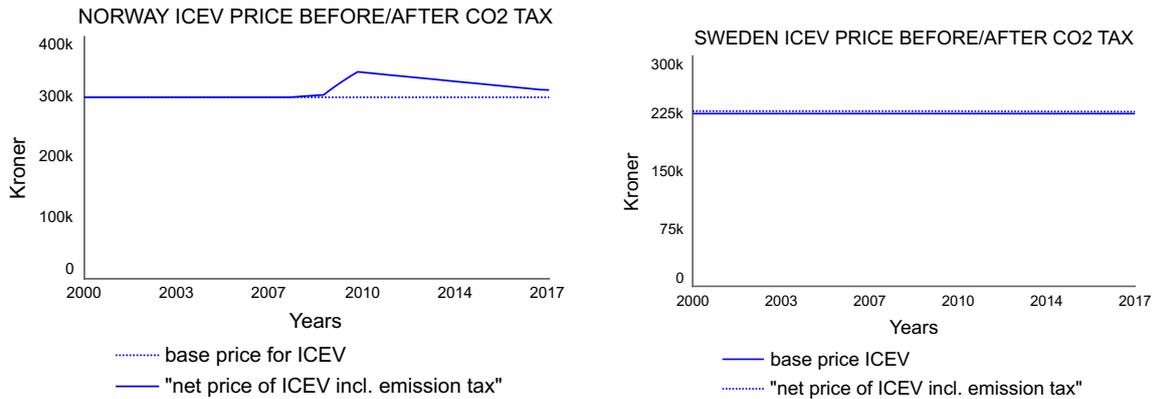
Figure 37. ICEV price comparison before and after CO2 tax for Norway (left) and Sweden (right)

On the other hand, policies directed to the purchase price of the BEV seem to create a considerable effect. Sweden has in place since 2007 purchase premiums of 40 000 kroner to BEVs; Norway has a considerable tax exemption. The net effect of these price reductions is illustrated in Figure 38 over the time span 2000-2017. In Sweden, a reduction of 40 000 kroner from base price is achieved, while in Norway it can be up to 37,5%.
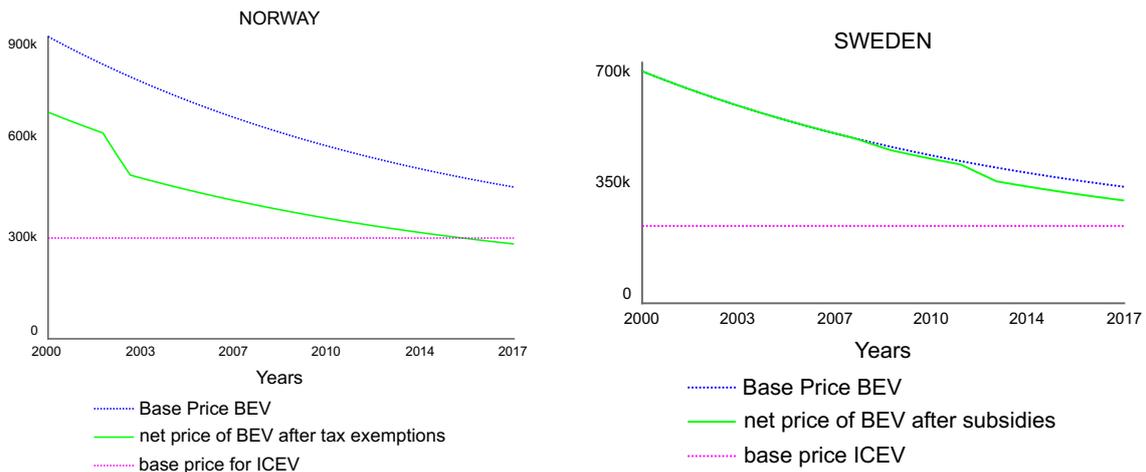
Figure 38. Gross and net BEV price for Norway (left) and Sweden (right)

The last parameters contextualized are in the charging infrastructure sector. These are the number of existing gas stations and the subsidy coverage for the construction of charging stations. For simplicity, the number of gas stations is assumed to be constant in the model, as in reality the change has only been marginal in the period 2000-2016; the most recent value retrieved is used. The subsidy coverage was represented in Figure 34 and Figure 35. This is a parameter defined over the range [0, 1] to indicate percentage. The values are qualitatively

estimated, so the preciseness of the parameter is halted by the lack of available information. As in the case of media coverage, the value of this parameter is mainly comparative across contexts. Norway initiated full support of infrastructure development from the beginning of the period and at increasing percentages, first of all through the establishment of the agency Enova. In Sweden, such a system does not exist to present, but can be expected to be developed, as a part of the declared intent to develop the BEV system. Different scenarios will be developed in the next section to explore different strategies with relation to support to charging infrastructure.

5 Model simulation results

The objectives of the research are the following, as stated in section 1.3 and by the research questions in section 1.5:

- Identify the driving differentials between the Norwegian and Swedish context
- Evaluate the policy effectiveness of each country's BEV strategy in terms of BEV sales
- Estimate the timing of cost parity and performance parity in each of the two countries considered, including and excluding policies

A system dynamics model has been built to help find these answers. In the previous chapter, the model's structure and underlying assumptions have been presented for the Norwegian and Swedish contexts. The present chapter discusses the results of the study from exploration with simulation. First, a comparison of the simulation results with historical data will be presented. Then the model results for the time period $2017 - 2050$ will be outlined for a Base case scenario. A series of alternative scenarios have been developed in which different system conditions and policy strategies are explored; this has helped to evaluate the effectiveness of the existing policies and assess what policy strategies are required to achieve the stated goals. The chapter concludes with a discussion on the national targets for BEV diffusion, compared to simulated behaviour.

5.1 Comparison with historical data

First, a comparison of the main model variables with historical data will be presented. More than a validation process, this is a way to check that the model simulates the real behaviour with a satisfactory degree. Due to the high number of "soft" variables, a full accuracy cannot be expected. As discussed in section 2.1.3, the value of the model is one of exploration and understanding, not of "point prediction" (Forrester, 1961, s. 123).

Contemporarily, the comparison can be used as a behaviour-reproduction test, following the guide-lines by Forrester and Senge (Forrester & Senge, 1979). Both the values and the curve shape will be evaluated. It will be evaluated whether the simulation model is able to reproduce

historical behaviour adequately. Many other model validation procedures have been performed however: these are documented in the discussion chapter 6.3 and in the appendix (chapter B). The variables represented are: the total national fleet, the BEV fleet, the total vehicle sales and the BEV sales. The time frame is 2000 – 2016. The historical data are illustrated with black solid lines, while the model simulation is illustrated in red dashed line.

5.1.1 Comparison in the Norwegian context

The model simulation of the growth of the BEV fleet in Norway resembles quite well the historical development for BEV stock and sales (Figure 39). The simulated sales flow (bottom left corner) anticipates the historical behaviour by some margin, but seems to slow down and meet again the historical trend by 2016; while, in 2011, 1 400 BEVs were sold, the model overestimates to 6 800. The simulation curve does not reflect as strongly the s-shape. The stock (upper left corner of Figure 39) reflect the sales accumulation, even though the values are slightly higher for most simulation times.

Considering the total fleet, the discrepancy is not large either. Considering the stock (upper right corner), the simulation underestimates the actual size by some thousand vehicles throughout the simulation time. On the other hand, start time and end time correspond quite well. As for the flow, the model does not reflect the large drop in sales of around 40 000 cars in 2009. This is possibly due to the fact that macro-economic factors, that can have a strong impact on the consumers' confidence, are not included in this model.

The error in the simulation of the total fleet size is probably related to the model's definition of market growth. Market growth is directly related to discard rate and to an exogenously defined indicated vehicle density. The vehicle density is a function of GDP per capita. However, in reality there are many other factors that come into play in defining whether an individual will choose to buy a vehicle or not. These factors are not included in the model; GDP per capita is the only proxy.

The comparison also supports in evaluating whether the "model recreates the symptoms of difficulty that motivated the construction of the model", hence symptom-generation (Forrester & Senge, 1979). The model reflects indeed the exponential growth in the BEV fleet starting approximately in year 2008. Increased attractiveness of the BEV, together with increased confidence (Figure 40), are the basis for this behaviour.
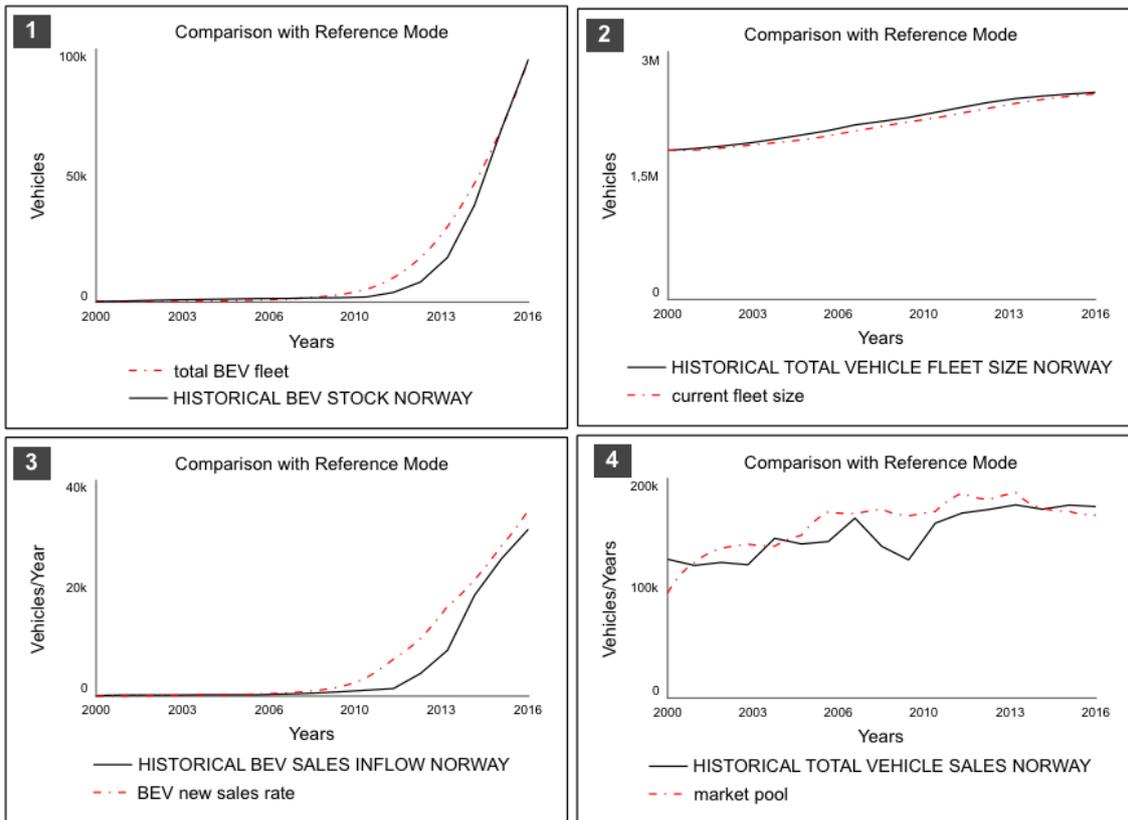
Figure 39. Comparison of simulation with reference mode for Norway. 1: BEV fleet. 2: Total fleet. 3: BEV sales. 4: total sales
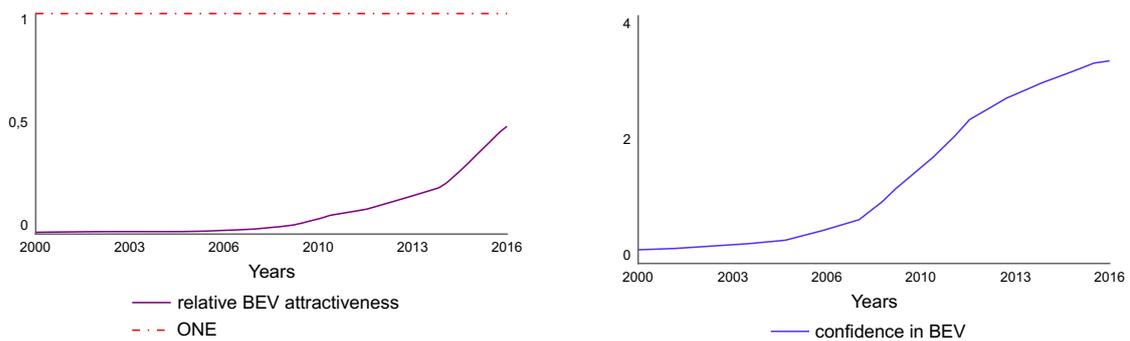
Figure 40. Drivers of BEV growth in Norway in the period 2000-2016: attractiveness (left) and confidence (right)

5.1.2 Comparison in the Swedish context

Historical values and simulation of the Swedish vehicle system also show a good fit, as can be seen in Figure 41. The model overestimates slightly BEV sales and stock in the first part of the historical period, while it underestimates these slightly from 2015. In addition, the model does not reflect the oscillating nature of sales, which is in line with what discussed above; the average values show, however, a strong resemblance with the trend. As for the total fleet, the model

instead shows on average an underestimation of the stock and overestimation of the flow. The reason for this apparent inconsistency is in line with what has been discussed above: the lack of data on discards and its simple model formulation. As the model of Norway, the model of Sweden does not replicate the drop in sales following the 2008 financial crisis.

Also in this case, the comparison between model simulation and historical behaviour supports in the validation of symptom-generation: the model replicates, however with a little anticipation, the exponential growth in BEV sales starting 2012. This is the year when the *supermiljobilspremium* of 40 thousand Kroner was introduced, hence increasing BEV attractiveness, and therefore sales share. The overall gain in attractiveness is however relatively smaller than in the Norwegian case, as can be seen in Figure 42. Confidence is also growing slowly, as a consequence of gain in market share and first phase of media coverage.
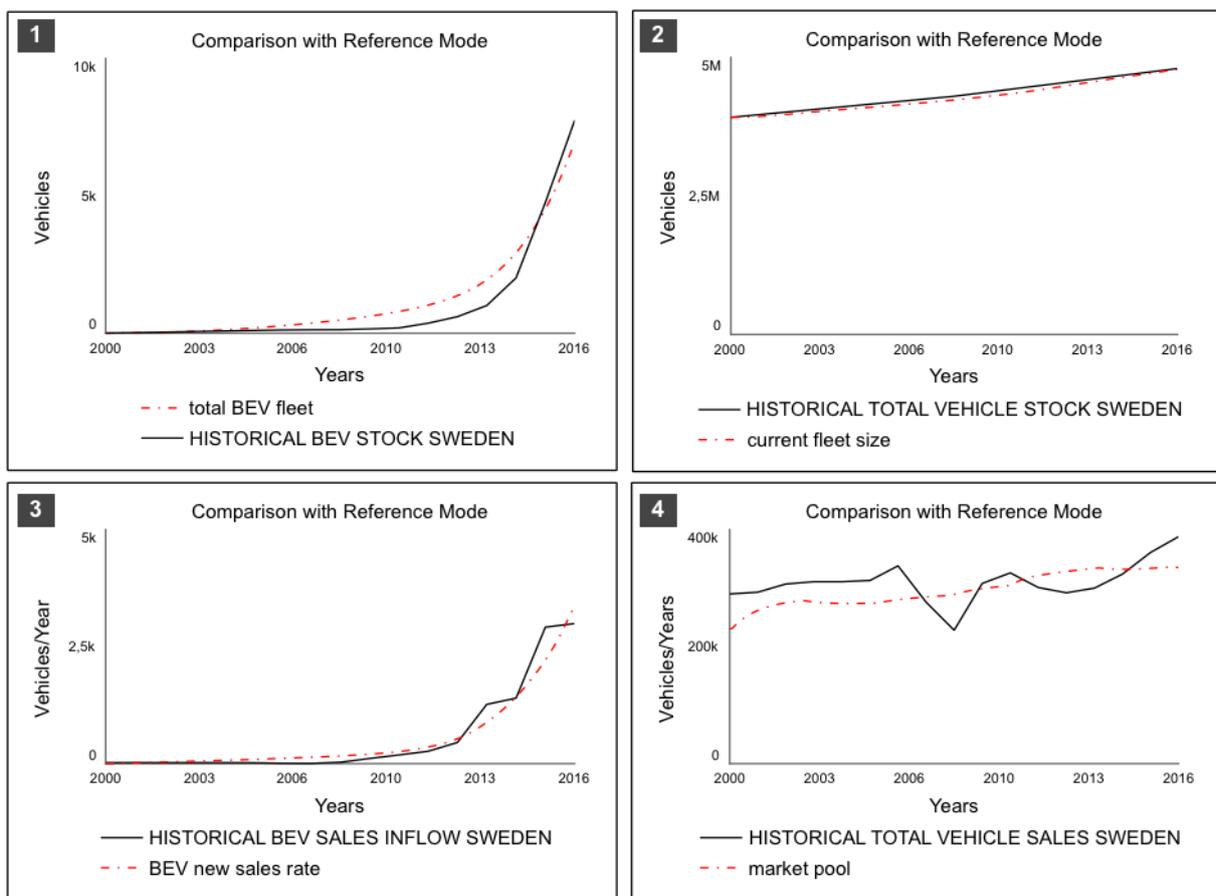
Figure 41. Comparison of simulation with reference mode for Sweden. 1: BEV fleet. 2: Total fleet. 3: BEV sales. 4: total sales
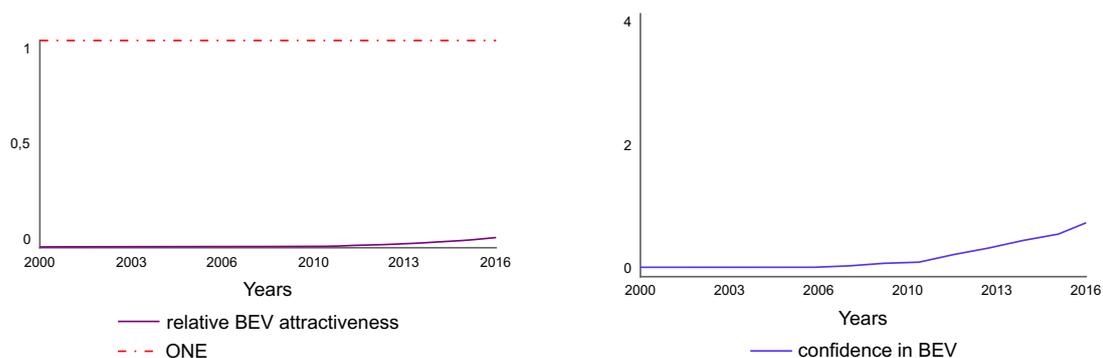
Figure 42. Drivers of BEV growth in Sweden in the period 2000-2016: relative attractiveness (left) and confidence (right)

In both contexts, **the simulation of the system dynamics model is able to show the slow but steady gain in market share that has been observed**. BEV diffusion is not immediate but progressive; contemporarily, **the momentum that is built in this growth creates not a linear but an exponential behaviour**. The factors underlying the reinforcing cycles have been mapped, and their simulated behaviour is consistent with reality. We conclude that the model simulates reality with a satisfactory level of precision, given the stated assumptions.

5.1.3 Altering history

What if no policies had been implemented in Norway or Sweden? Would the same diffusion rate of the BEV have been observed? In other words, what was the effectiveness of the implemented policies until 2016? In this section, we explore this question through the simulation of the model. Figure 43 and Figure 44 show the simulations for this hypothetical setting. All policy parameters have been set to zero. The difference is significant, and especially in the Norwegian context: BEV Sales do not surpass 600 vehicles a year, and the total BEV fleet results in 2016 in 2 600 vehicles, less than 3% of what actually happened. In the Swedish context, where historically the fleet reached 7 800 vehicles in 2016, the simulation shows only 2 300 vehicles. The difference between the Norwegian and Swedish context derives probably from the difference in power prices and from the different initial value in the BEV fleet in year 2000 (0 in Sweden, 278 in Norway). Note that the scales in the graphs for the Norwegian and Swedish contexts are not the same, and hence the comparison can be misleading.

This simulation supports the hypothesis that policy action made a considerable impact in both contexts, but in particular in Norway, were policy action was introduced earlier and more comprehensively across stages of BEV ownership.
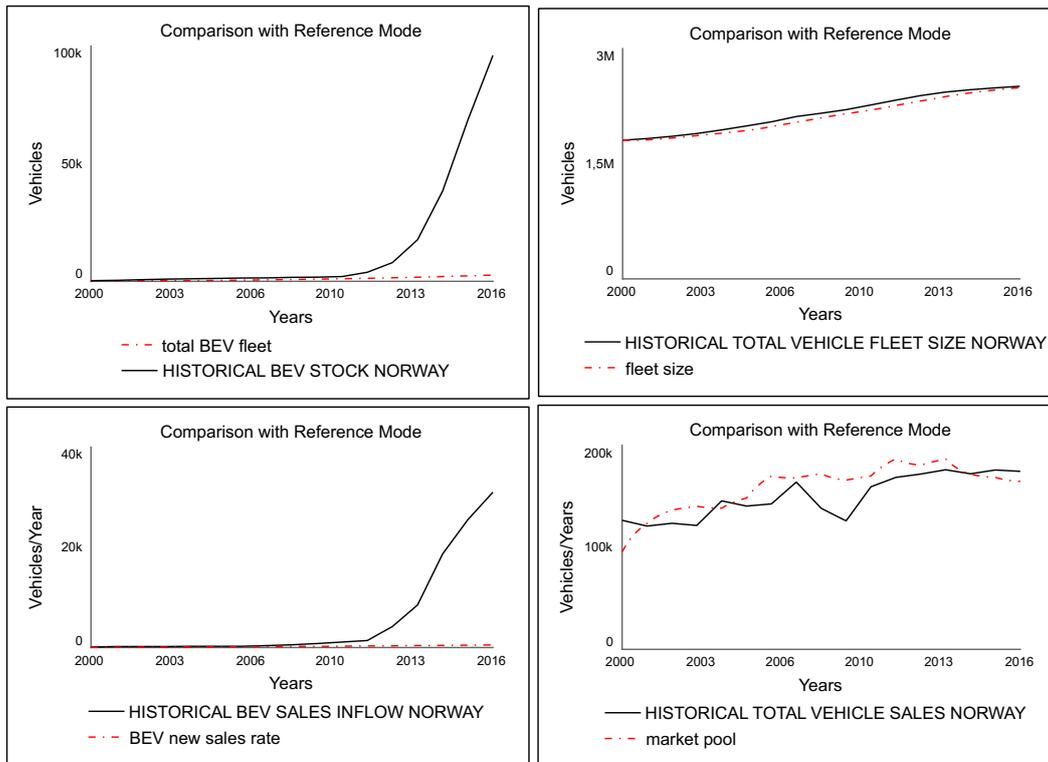
Figure 43. Norway 2000-2016 if no policies had been implemented
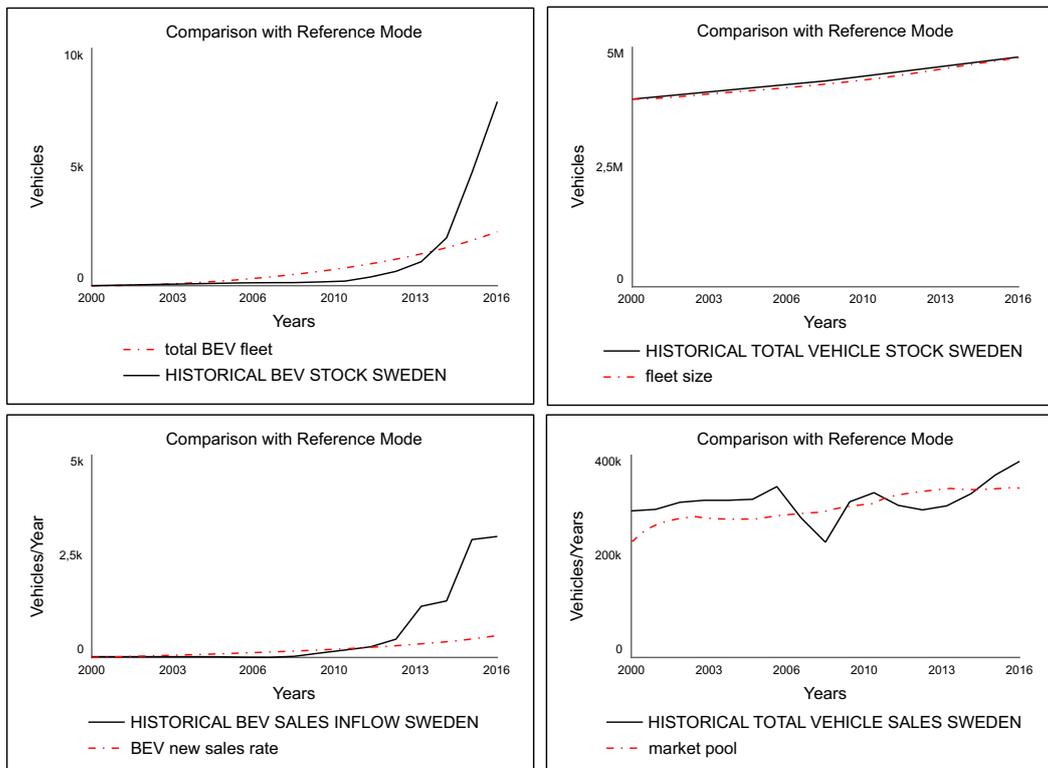
Figure 44. Sweden 2000-2016 if no policies had been implemented

Next, the model will be used to explore the behaviour of the system after year 2017.

5.2 Base case scenario towards 2050

The objective with this research is to better understand what the different policy strategies in Norway and Sweden have meant and what they will mean for the future BEV market share. In the next sections, this topic will be explored. An exploratory approach fits well to the purpose: a series of scenarios for the BEV fleet will be presented based on the exploration of the assumptions made in in chapter 4 and on different policy strategies. The diffusion of the BEV is indeed driven or curbed by both policies and characteristics of the vehicle system, such as relative costs, performance and consumer behaviour. First, a Base case scenario will be discussed, keeping system conditions constant at the assumed values in chapter 4; in the following section, different policy strategies will be explored; finally, alternative assumptions on the system conditions will be tested.

The Base case scenario is designed to reflect the current policy strategies planned, assuming no major regulatory change will come in place. Reasonable assumptions needed to be made in the cases that the policy timeline was not specified. The Base case scenario will be presented first for Norway and subsequently for Sweden.

5.2.1 Base case in Norway

The Norwegian government has expressed its intention to achieve the target of creating a low-emission society by 2050. The transportation sector is recognized as one of the most relevant sources of emissions, and specific targets are set: by 2025, all new sales of vehicle emissions of personal and light freight vehicles are expected to become zero-emission vehicles. In the National Transport plan 2018-2029 (Norwegian Department of Transportation, 2017), the political strategy of the Norwegian government to achieve the stated goals is outlined: electric vehicles are considered the driving force of the transition, support will be given to develop the required infrastructure, incentives will be given to speed up technological development, and it will be made sure that it is more convenient to choose zero-emission at purchase price. Exemption from VAT and purchase tax will be kept until 2020; from 2018, municipalities will determine whether local policies such as free parking, free road tolls and bus lane access will be granted; in either case, the road tolls will not be higher than 50% of the price for ICEVs. Biofuels are not considered a zero-emission fuel and are therefore not included in the policy strategy for light vehicles; they are instead considered as a suitable climate-neutral fuel for heavy vehicles. Hence, ICEVs with a low carbon footprint are not expected to receive benefits and tax exemptions.

In the SD model, these political strategies have been implemented accordingly. Free charging and free parking are assumed to be removed progressively by 2025, while access to bus lanes and free access to ferries is assumed to be removed at once. Travel tolls are expected to be reduced to 50%. Subsidies to charging infrastructure are assumed to be reduced progressively by 2025. The policy switches take the values shown in Figure 45.
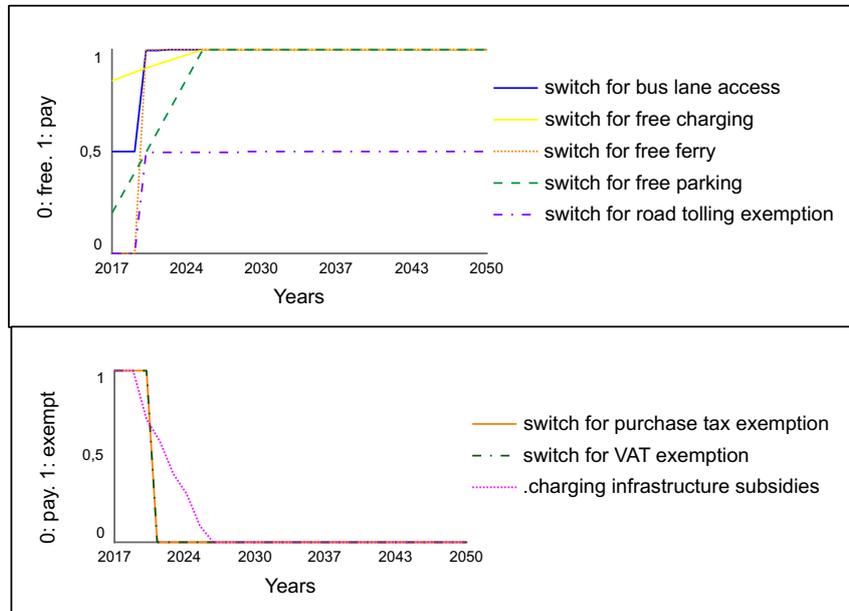
Figure 45. BEV policies in Norway for the period 2017-2050 under Base case

The central variable of interest is the size of the BEV fleet compared to the ICEV. This is depicted in Figure 46 left: while the BEV market share shows a continuous growth, the ICEV fleet seems to stagnate starting from 2016, and thereby decay from 2020. **The BEV sales share reaches 50% in the year 2032 and converges towards 68% by the end of the simulation time**, converging towards the indicated sales share (Figure 46 right) [17]. The main factors driving BEV sales share are depicted in Figure 47: relative costs, relative performance and confidence in the BEV. Considering the total cost of ownership, **cost parity is reached in 2017**; due to the gradual removal of subsidies and benefits however, the relative total cost of the BEV is again higher than the ICEV in the years 2020-2027; after 2027, the market forces have brought the BEV price at a competitive level with the ICEV, without the need for governmental supports. **As of performance, parity with the ICEV is only reached in 2030**. Confidence in the BEV grows strongly in the first decades of simulation and remains thereby high, even after

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[17] The value 1 is included in the plots in order to show the maximum value for sales share as an expression of percentage.

information campaigns and media coverage decrease (by the assumptions depicted in Figure 32).

When comparing with the stated goal of 100% zero-emission new sales in 2025, the simulation does not show the desired behaviour: in 2025, the sales share is still below 50%, due to the temporary increase in relative BEV costs and the slow gain in relative performance. **Only from 2025**, as the simulation shows, **market dynamics driving cost and performance allow the BEV to be significantly competitive against the ICEV without the need of policies.**

Figure 46. Diffusion of the BEV (left) and sales share (right) in Norway under Base case
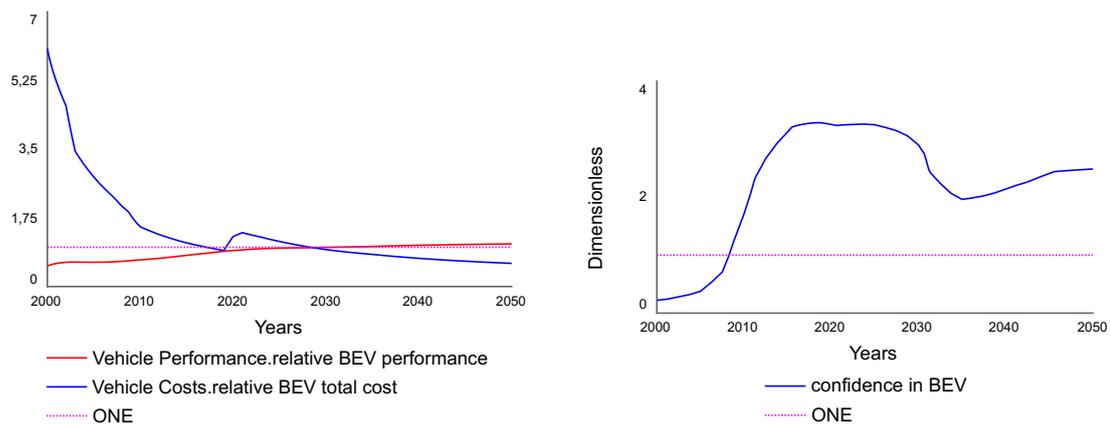
Figure 47. Relative cost and performance (left) and confidence (right) in Norway[18]

5.2.2 Base case in Sweden

In section 3.8 the main Swedish policies directed to light vehicle transportation were outlined: Sweden follows a technologically neutral strategy which considers a class of low emission

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[18] The value 1 is included in the plot in order to show the threshold from a negative effect (below 1) to a positive effect (above one).

vehicles (*miljobilar*) including both electric vehicles, hybrids, biofuels, and fuel-efficient diesel and petrol cars. Being part of the European Union, Sweden follows EU directives, regulations and targets. This approach is in line with the European strategy: the EU sees electric vehicles as one of more alternative fuels in the strategy for sustainable mobility. Compressed natural gas, liquefied natural gas and hydrogen are also considered important.

The Swedish government has set the target of reducing transport emissions by 70% by 2030, compared to 2010 levels. The EU has a strong focus on creating the necessary conditions for these AFVs to be able to travel, and points on development of infrastructure as the main strategy. Year 2020 has been given as a target for member states to develop the required charging infrastructure for alternative fuels. In the case of electric vehicles, one charging point every 10 EVs is expected as the satisfactory amount. As discussed in section 3.8, Sweden has to present a very low density of charging points, and major investments are required. The 2013 infrastructure plans for the period 2014-2025 include charging infrastructure (Swedish Government, 2013), but the development has been slow.

The Swedish Energy minister outlined the future strategy for private vehicles in May 2017, (Lovin & Andersson, 2017): biofuels will be exempt from taxes from 2018; the bonus-malus-system will be reinforced, subsidy to *miljobilar* of 10 000 kroner will be kept until 2020; investments in infrastructure will be increased until European goals are met; the exemption from road tolls will be removed from 2018. The strategy is translated in the model in these terms: the switch for road toll exemption is turned to 1 starting 2018; the purchase subsidy is turned to 10 000 kroner until 2020; infrastructure investments are assumed to increase up to 2025. The model does not include biofuel tax exemption because the start price of the biofuel is in fact higher than that of gasoline and diesel, and the tax exemption is in place to create greater competitiveness for biofuels; from an aggregate perspective however, this does not change considerably the average price of ICEV fuel, which is an umbrella term. For the policies on which no explicit intention has been found, moderate assumptions have been made. The policy switches take the values shown in Figure 48.
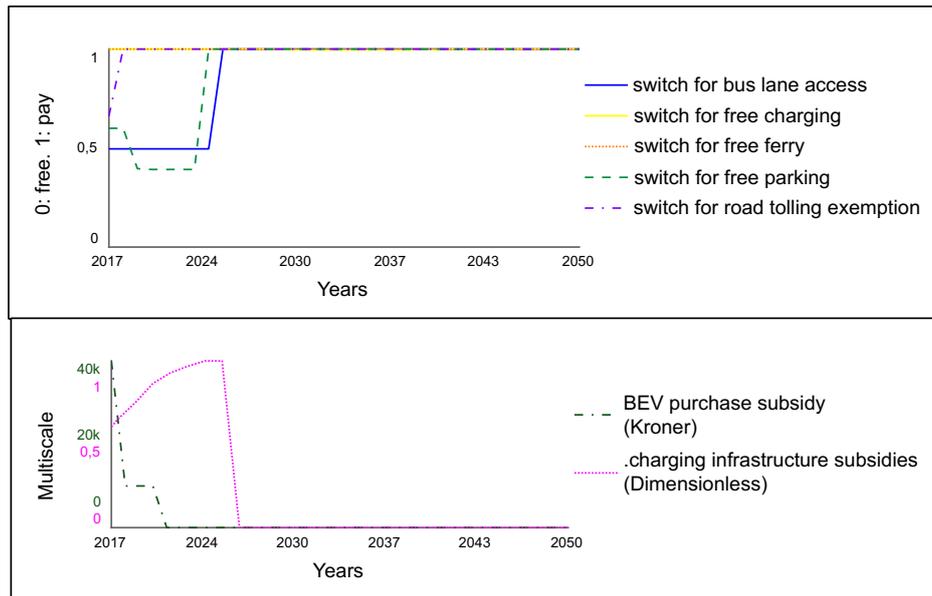
Figure 48. BEV policies in Sweden for the period 2017-2050 under Base case

The model of the Swedish system results in a slightly poorer and slower diffusion of BEVs, but nevertheless **the sales share of BEVs converges in the long run to 55%**(Figure 49), similarly to the Norwegian setting. Since subsidies in infrastructure development are concentrated in the years 2018-2025, the charging density does not grow significantly, and performance remains low over the whole simulation time; **performance parity is not reached**. **Cost parity is reached in 2030** as a consequence of market dynamics and less to subsidies (Figure 50 left). Confidence in the BEV increases significantly in the second half of the simulation time as a result of growing marketing efforts and sales share (Figure 50 right). By 2050, the market share is still dominated by ICEVs, but the ICEV fleet is decreasing over time and the BEV market share continues growing. 50% BEV sales share is reached in year 2037.
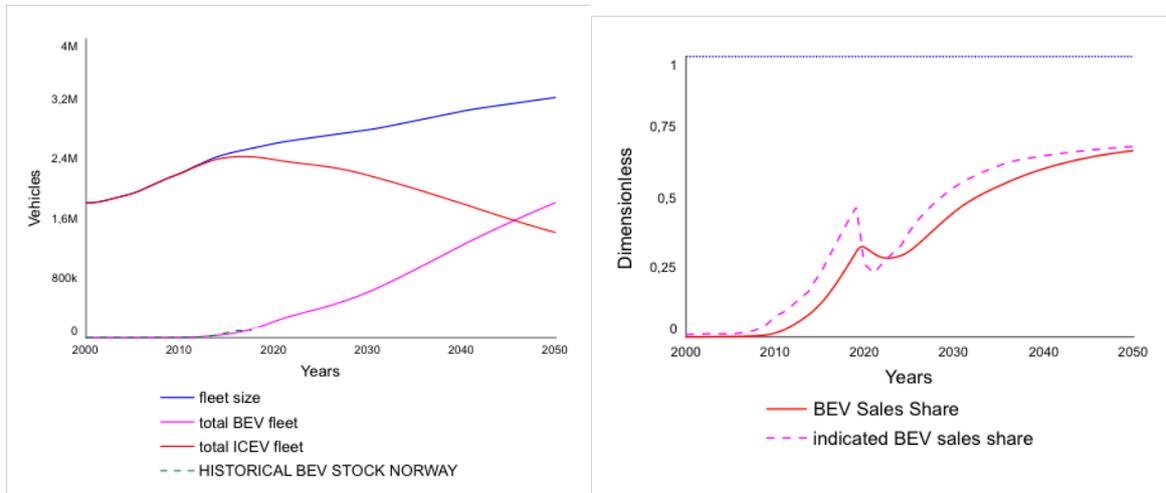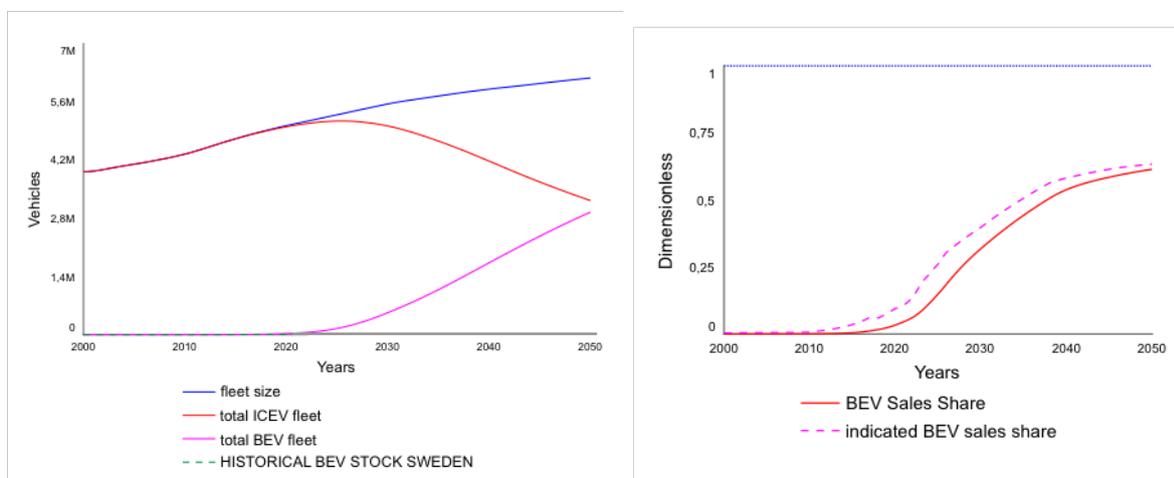

Figure 49. Diffusion of the BEV(left) and BEV sales share (right) in Sweden under Base case.
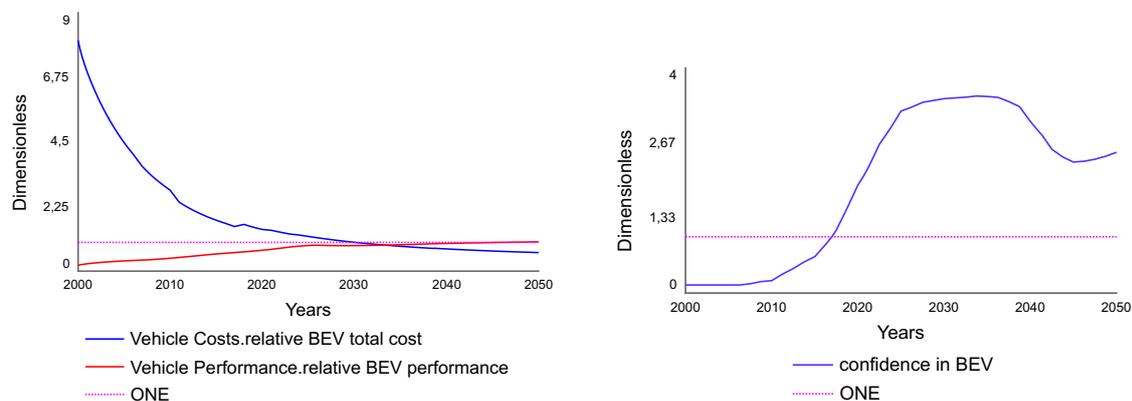
Figure 50. Relative cost and performance (left) and confidence in the BEV (right) in Sweden.

5.3 Policy Analysis

Section 5.2 described the base scenario with business-as-usual policies, considering the most recent declared political strategies by each government. As discussed in section 3.2, BEV policies typically aim to induce early adoption of BEVs through reducing costs or improving performance of the "eco-innovation" (Brown, 2001), and thus allowing the eco-innovation to start a self-sustained growth; however, policies represent additional costs for the government, and hence they normally stay in place for a short period. The timing of removal can depend on the observed market behaviour, on a country's financial situation or on other factors. Hence the stated intentions may not be followed as planned. In addition, the simulations in the previous section suggest that the desired goals will not be reached with the present strategies. What policies are therefore necessary to achieve these targets, is another question that this research tries to answer. A series of policy scenarios will be described in this section.

The policy analysis does not include the policy Information campaign because of the high sensitivity of short term sales share to this variable (see chapter B 6): it was preferred to keep this variable constant in order to derive a more robust, less sensitive, comparative analysis.

As for the system conditions, the set of most-likely values described in section 4.4. from the Base scenario will be used. One context at a time will be analysed, and a discussion on the scenario outcomes will follow. The plots start at year 2017.

5.3.1 Policy analysis for Norway

In Norway, most policies have been introduced in the first decade of the period considered (see Figure 34). In the Base case scenario, all policies are removed between 2019 and 2025, according to the intended policies stated by the Norwegian Government. It is however

interesting to test different timings for the removal of BEV policies and what effect that might have on BEV adoption. In addition, the effect of the Swedish BEV strategy in the Norwegian context is tested. In this section, the following policy analyses will therefore be explored:

a) *what if current BEV policies are kept until 2030*

b) *what if only purchase policies are removed tomorrow, the rest is kept until 2030*

c) *what if only use benefits are removed tomorrow, the rest is kept until 2030*

d) *what if only infrastructure subsidies are removed tomorrow, the rest is kept until 2030*

e) *what if the Swedish policy strategy (Base case) is imitated from 2018*

Table 7 schematizes the policy analyses that are performed.

Table 7. Description of policy analyses in the Norwegian context

Scenario	Policy variable		
	Purchase policies	**Use benefits**	**Infrastructure subsidies**
Base case	Tax exemption until 2020	100% benefits until 2025, apart from road tolling at 50%	Until 2025
a)	Tax exemption until 2030	Until 2030	Until 2030
b)	Tax exemption until 2018	Until 2030	Until 2030
c)	Tax exemption until 2030	Until 2017	Until 2030
d)	Tax exemption until 2030	Until 2030	Until 2017
e)	40 000 Kroner subsidy until 2020	Until 2018 apart from bus lane and parking at 50% until 2025	Until 2025

Figure 51 and Figure 52 illustrate a comparison of key variables under the different policy strategies, including the Base case scenario: in the first figure, the development of relative cost (left) and performance (right); in the second, the BEV sales share (left) and market share (right). The strategies where purchase policies are kept until 2030 (a, c, d) seem to bring a considerable impact on sales share through the low relative BEV cost. This translates in higher market shares compared to Base case. In the case that use policies are removed, the BEV does not lose much market share; in the case that infrastructure subsidies are removed however, the effect is a bit more negative, since relative performance is much lower. The scenario in which only purchase subsidies are removed (b) results in similar trends as the Base case in the long run. Adopting the Swedish strategy would result in a strong loss of sales share in the short run, similarly to strategy b, and lower BEV penetration values in the long term as well. Relative costs are highest

among all scenarios, and relative performance is similar to Base case (this due to the high initial values in charging station density in Norway from 2017).

Hence, keeping purchase subsidies in place until 2030 can contribute considerably to the relative attractiveness of the BEV in Norway, while infrastructure and cost subsidies seem to have a smaller role in determining attractiveness. Infrastructure has already reached in 2017 satisfactory density for most consumers; costs are relatively low, compared to price.
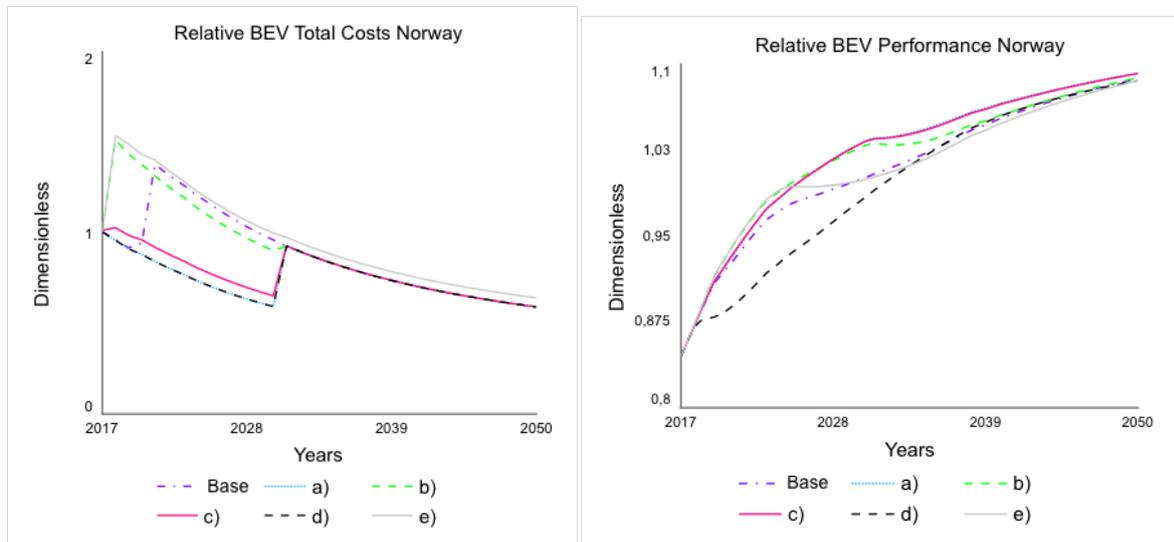
Figure 51. Future development of relative BEV costs (left) and performance (right) in Norway under 6 policy scenarios[19].

One last element can be noticed: the sales share is very reactive to changes in policies, or in other words, policies seem to have an immediate effect on consumer choices. **Short term BEV sales can be boosted or halted significantly by different policy strategies. In the long term however, the BEV sales share converges to equal levels, driven by market mechanisms.**

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[19] Observe: the vertical scale for relative performance starts from 0.8 and not from zero.
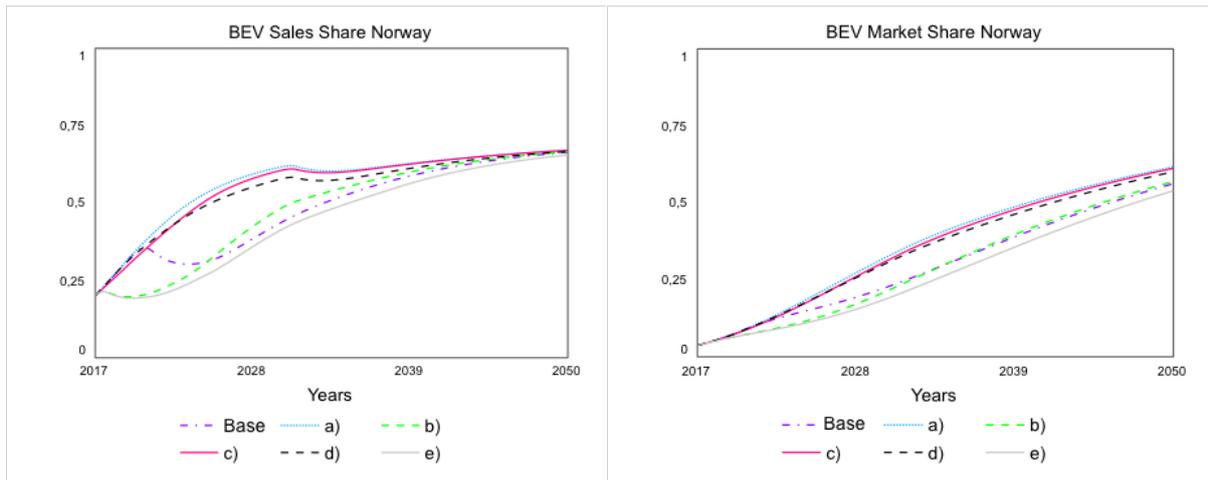
Figure 52. Future development of BEV sales share (left) and market share (right) in Norway under 6 policy scenarios

5.3.2 Policy analysis for Sweden

While, in the Norwegian context, BEV policies have been in place for more than a decade, in Sweden the introduction of policies directed to BEVs is very recent, and a full policy package has not been implemented yet at a full national scale. The targets for electrification are however high towards 2050 (Swedish Government, 2013), and removing policies already in the years 2019-2025 could be premature, as shown in the Base case scenario. This scenario also does not include free charging or free ferries as a strategy. Hence, it is of interest in this policy analysis to consider both times of removal of the existing policies, possible introduction of new policies, and increase in existing policies.

The following scenarios will therefore be explored:

a) *what if an integral policy (including benefits and cost reductions in all components of BEV use: charging, parking, ferry, road tolls, bus lane access) is introduced and is kept until 2030*

b) *what if purchase subsidies are removed tomorrow, the rest is kept until 2030*

c) *what if use benefits are removed tomorrow, the rest is kept until 2030*

d) *what if infrastructure subsidies are removed tomorrow, the rest is kept until 2030*

e) *what if the Norwegian policy strategy (Base case) is imitated from 2018*

The key characteristics of the policy strategies are summarized in Table 8. Policies b), c) and d) are defined equally as the Norwegian case in order to compare the effect of the same policy strategies starting 2018, but with different history until 2017. This is done in the next section.

Table 8. Description of policy analyses in the Swedish context

Scenario	Policy variables		
	Purchase policies	**Use benefits**	**Infrastructure subsidies**
Base case	10 000 Kroner subsidy until 2020	Until 2018 apart from bus lane and parking at 50% until 2025	Until 2025
a)	Tax exemption until 2030	Until 2030	Until 2030
b)	Tax exemption until 2018	Until 2030	Until 2030
c)	Tax exemption until 2030	Until 2017	Until 2030
d)	Tax exemption until 2030	Until 2030	Until 2017
e)	Tax exemption until 2020	100% benefits until 2025, apart from road tolling at 50%	Until 2025

Figure 53 and Figure 54 illustrate, as in the previous section for Norway, the development over time of the key variables of interest impacted by different policy strategies. Introducing an integral policy until 2030 (strategy a) has a strong effect both on relative BEV cost and performance. The sales share is increased by 20% in 2030, and the market share at the end of the simulation time is 9% higher. Following the Norwegian strategy (e), which is also integral and includes tax exemption instead of purchase subsidies, brings added attractiveness and higher sales shares compared to the Base case scenario. Removing cost benefits (c) does not seem to bring considerable difference. When infrastructure subsidies are removed (d), the attractiveness of the BEV seems to be however weakened considerably: BEV performance is lower than ICEV performance at all simulation times, and the sales share grows slowly, reaching 50% only by year 2050.

The Swedish BEV system seems therefore to be very sensitive to infrastructure subsidies, and less so to reductions in BEV costs and price.

The simulation result provides some additional insights. Firstly, Swedish BEV sales are less reactive to policy changes in the short term, but more so in the next decade. This can be explained by the low initial share: no matter the strategy, **the growth in BEV sales has not yet reached the momentum that has put other system reinforcing loops into action**, as the Word of Mouth and Infrastructure/Retail Chicken and Egg loops. Hence reaction is slow, and proportional to policy action. Secondly, **different policy strategies result in different levels of sales share in the long term**, while in Norway the sales share in 2050 is the same for all policy strategies. This can be explained by the low level of relative performance at year 2017: due mainly to low charging station density, BEV relative performance is low. In addition, the

market's confidence in the BEV is still low, so that investments in infrastructure are not large. If subsidies to charging infrastructure are removed, the charging infrastructure does not develop at a fast rate. The drivers of growth lie in the cost dynamics and in the exogenously defined performance attributes; endogenous performance attributes as charging station density and BEV offer diversity remain low, and slow down growth. Therefore, long term sales share is lower if subsidies to infrastructure are removed.
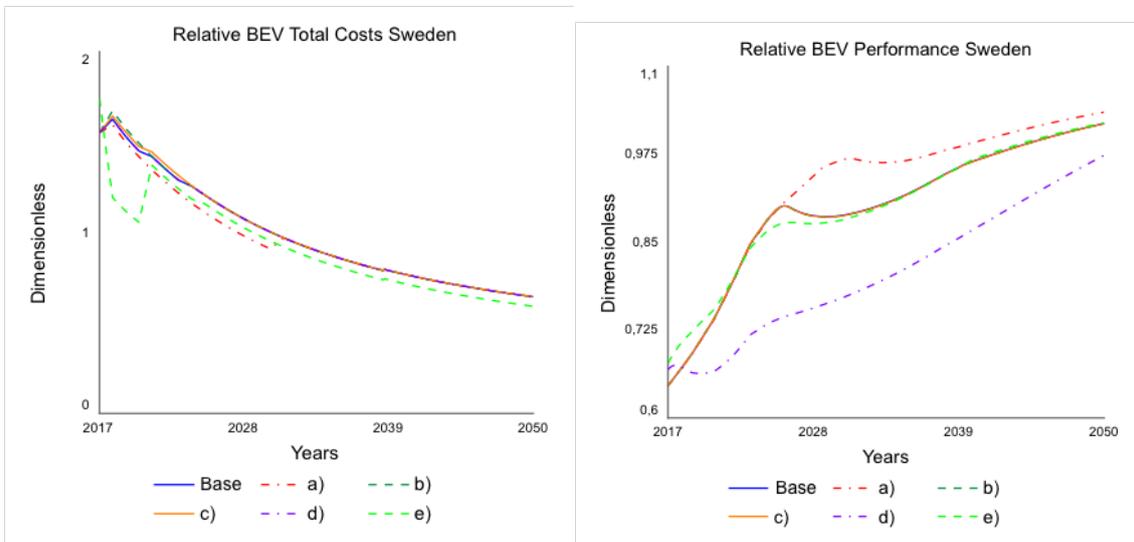
Figure 53. Future development of relative BEV costs (left) and performance (right) in Sweden under 6 policy scenarios.[20]
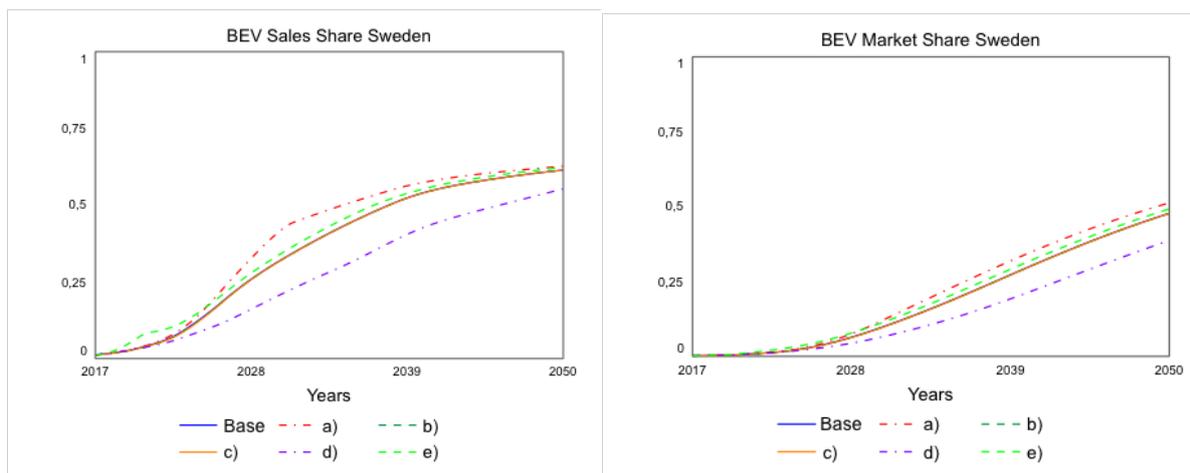
Figure 54. Future development of BEV sales share (left) and market share (right) in Sweden under 6 policy scenarios

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[20] Observe: the vertical scale for relative performance starts from 0.6.

5.3.3 Comparison of policy strategies across contexts

Finally, the effect of similar policies in different contexts will be studied. As mentioned in the previous section, policy strategies b), c) and d) are defined to be equal in Norway and Sweden. Strategy e) was defined as imitating the other country's strategy: Norway adopting the Swedish policy strategy, and Swedish adopting the Norwegian. Strategy a) instead was context-specific, and does not suit for comparison across contexts. The following table summarizes the key differentials observed from the simulations run in the previous two sections.

Table 9. Comparison between Norway and Sweden on equal policy strategies

Scenario	Context	
	Norway	**Sweden**
b)	Cost parity reached in 2028, 10 years later than base case. Loss in market share in the short term, similarly to base case but 5 years in advance. Long term sales share equal to other scenarios. Market share in 2050 at 55%.	Trend equal to base scenario and strategy c). Cost parity reached in 2030. Sales share is low in the short term and equal to all other scenarios in the long term. Market share in 2050 at 46%.
c)	Cost parity from 2017, only slightly weakened compared to strategy a). Sales share is relatively high. Second highest market share at 60% in 2050, after a).	Equal effects to strategy b) and base case in all parameters.
d)	Cost parity from 2017 and lowest across scenarios, equally to strategy a). Lowest relative performance across all scenarios. Sales and market share are not strongly impacted given initial value of relative performance near to 1: market share at 58% in 2050.	Relatively worst scenario: relative performance is lower than 1 across the simulation time, sales share is lower and market share 15% lower than results from other strategies by 2050, being nevertheless at 38%.
e)	Relatively worst scenario: relative costs are highest and relative performance loses momentum from 2025. Loss in sales share in the first years of simulation after 2017, but equal sales share to other policy strategies in the long run. Market share is lowest across simulation time, reaching 50% in 2050.	Highest cost competitiveness. Relatively higher performance competitiveness in the short term but less so from 2025, which is when Norwegian infrastructure subsidies are stopped. Sales share and market share achieve second highest values (68% and 48% respectively).

The reason why similar policy strategies differ between the two contexts has already been mentioned in the discussion above, and will be briefly summarized here. **The different BEV sales rates from year 2017 derive primarily from the initial values at year 2017**. Norway, through early aggressive policy action, has anticipated cost and performance parity by a decade compared to what would happen in a policy-free environment; this way it has managed to put in action reinforcing mechanisms at society and industry level (the Word of Mouth and Chicken

and Egg reinforcing loops), and has thus created robust conditions for sustained growth. Sweden, by introducing BEV policies later on and in a less aggressive manner, has still not reached cost and performance parity, and confidence is still low among consumers; the reinforcing mechanisms come into action later, driven by system conditions rather than policy action.

5.4 Alternative scenarios towards 2050

The previous section described the development of the Norwegian and Swedish fleet under different policy strategies. The characterization of the surrounding system was based on the assumptions outlined in chapter 4.4. The assumptions were defined as most-likely, but in the long timeframe up to 2050, most parameters are indeed highly uncertain and can show large changes. In this section, new assumptions on the system conditions will be made in order to use the model as an experimentation tool. A series of scenarios will be developed based on these assumptions. These assumptions will be made in parallel for Norway and Sweden, so that a comparison based on equal criteria is possible. The scenarios are nevertheless defined starting from year 2018, so that history will have a weight in the future behaviour- under equal future system conditions, it will be possible to see where the difference between the two contexts lies.

The axes on which the scenarios are developed are two: the level of BEV policy effort, ranging from no effort to full support, and the system conditions: whether they are favourable or not to BEVs. Low policy effort implies that, from 2018, all policies directed to BEVs are removed; high policy effort is expressed in all BEV policies being active in the period 2018-2035. Favourable system conditions for the BEV are high oil prices, low power prices, a high rate of BEV technological development and high consumer sensitivity to change in relative cost and performance. The developed scenarios are four, and are placed at the four corners of the scenario map in Figure 55. The scenarios are characterized by a similar approach to that taken by Pasaoglu et al. (2015), but in a different context. They are chosen because of three reasons: the proximity with an already existing approach, their simplicity, and the fact that they include most variables of interest. The scenario *ICEV Persistence* includes no policy support to BEVs and unfavourable system conditions. The scenario *Market Pull*, instead, has favourable system conditions while low policy support. In *Policy Push*, the support is high, while the system conditions are not favourable. In *BEV Transition*, both policies and system conditions are

favourable to BEVs. The Base scenario simulated in section 5.2 is also illustrated for comparative purposes and reflects moderate values on both axes.
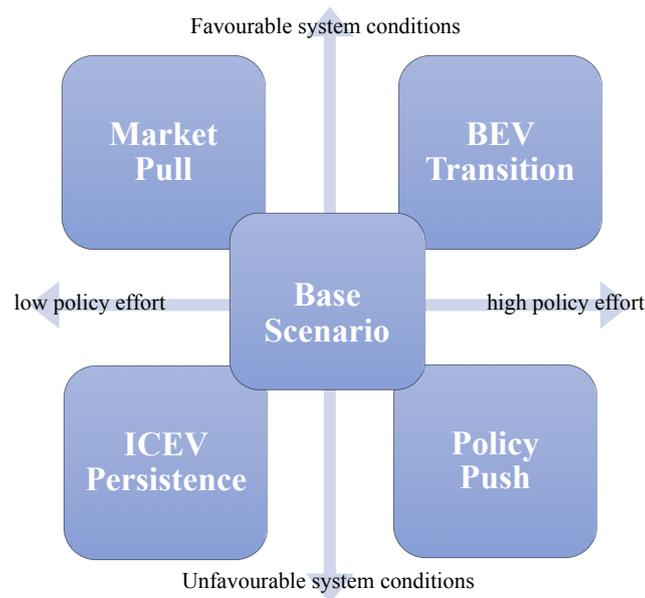
Figure 55. Scenario map

More specifically, the following model elements are used to describe different future scenarios:

-   *Policies directed to BEVs*

All the policies included in the model are considered in the scenarios, apart from information campaign- as in the policy analysis: infrastructure subsidies, policies directed to purchase price, to costs of use and use benefits. Two opposite scenarios will be experimented: on one side, all BEV policies are removed starting in 2018; on the other, all policies are implemented fully and are kept until 2035.

-   *Oil and power prices*

The base scenario uses the assumptions from the ETO model (DNV GL, 2017). Alternative trends could however happen, and two extreme scenarios applied are represented in Figure 56. Note that the figure represents Norwegian power prices, and that the model assumed that Swedish prices are proportional to Norwegian with a factor 1.5.
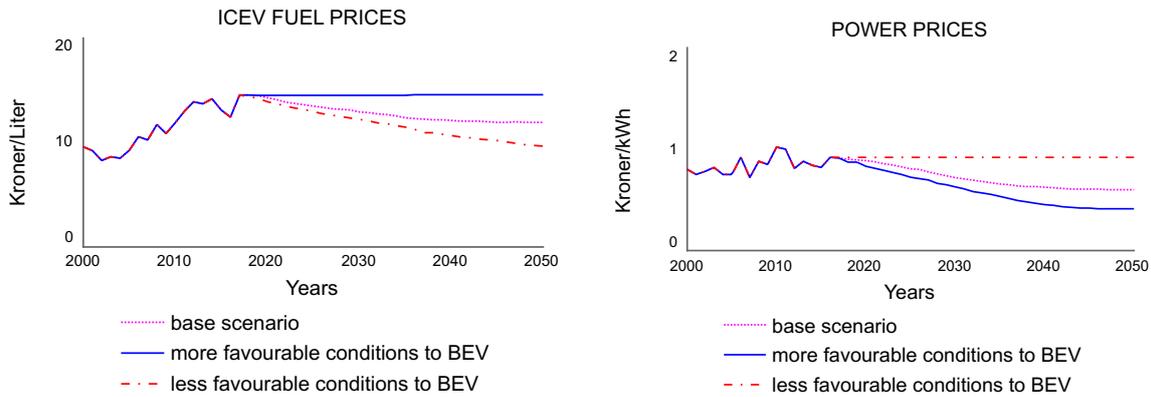
Figure 56. Scenarios for ICEV fuel (left) and power (right) prices

- *Effect of relative cost and performance on BEV attractiveness*

In section 4.2.2, Figure 10 represented the graphical function illustrating the effect of the relative cost and of the relative performance on the consumer's attractiveness for the BEV. While Prospect Theory was applied to define the shape and the asymmetric nature of the curve, the extreme values were subjectively defined. In this section, alternative extreme values will be explored. The attractiveness of the BEV could be indeed more or less strongly impacted by marginal changes in relative cost and performance. Differences of this kind derive from different consumer behaviour, which are indeed difficult to predict. Different shapes on the effect function and different extreme values will lead to different indicated sales share ranges, and hence different market shares in the long run. In Figure 57, two alternative effect functions in addition to the base function are illustrated: option 2 has for all relative values a weaker positive effect than the base; option 3, on the opposite, has stronger effect for all relative values than the base. The indifference point (1, 1) is kept for all curves.
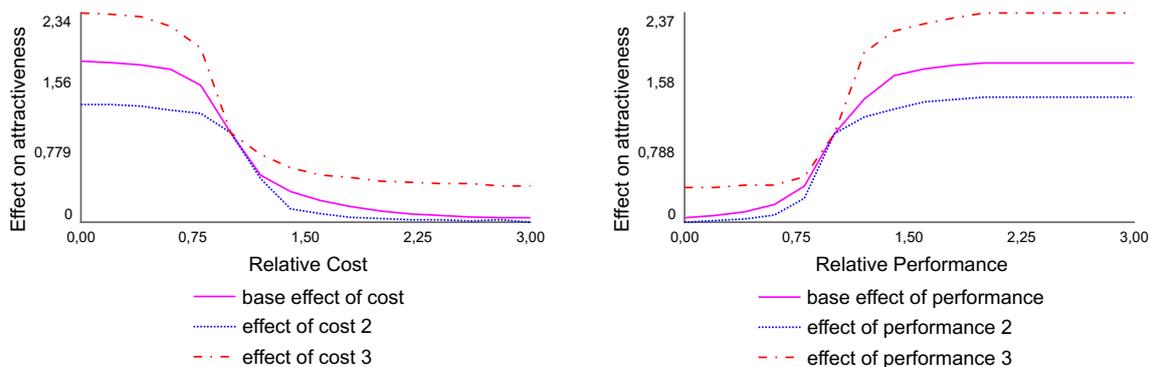
Figure 57. Scenarios on effect of relative cost(left) and performance (right)

- *BEV performance development*

The parameter rate of BEV performance development reflects the rate at which different attributes of BEV performance improve over time. The parameter influences three important characteristics of the BEV: the travel range, the recharging time and the battery capacity. The value 0.1 (in units 1/Year) is assumed in the base scenario, since it replicates historical data to a satisfactory degree. In the scenarios, the value has been changed to 0.05 and 0.15 for unfavourable and favourable BEV conditions respectively, starting from year 2018: if the rate of technological development is low, the BEV will use more time to catch up with the competition.

- *BEV price reduction time*

The price of the BEV is related to the price of the battery, and hence the price is very dependent on the rate of research and development around the battery technology. In the model, a delay time for price reduction is applied to simulate the BEV price. A favourable scenario for the BEV would be that this time is reduced; in an unfavourable scenario, the opposite.

Table 109 provides a summary of the characteristics of each scenario.

Table 10. Description of alternative scenarios

		System variables				
		BEV policies	**Oil and power prices** (Figure 56**)**	**Effect functions** (**Figure 57)**	**BEV rate of performance development (1/Year)**	**BEV price reduction time (Years)**
Scenarios	**Base case**	Context-dependent	ETO model	Moderate effect (purple line)	0.1	10
	Market Pull	All removed from 2018	High oil prices, low power prices	Effect 3	0.15	5
	ICEV Persistence	All removed from 2018	Low oil prices, high power prices	Effect 2	0.05	15
	Policy Push	All removed from 2035	Low oil prices, high power prices	Effect 2	0.05	15
	BEV Transition	All removed from 2035	High oil prices, low power prices	Effect 3	0.15	5

In the next sections, the simulation outcomes of each scenario will be presented for six chosen variables: relative BEV costs performance, BEV Sales and Market Share, average and total fleet emissions.

5.4.1 Relative cost and performance

Figure 58 illustrates the five scenarios for Norwegian and Swedish relative BEV costs. The combined effect of policies and system conditions can be seen: **while the overall trend is a decrease in relative costs (and hence a gain in BEV attractiveness compared to the ICEV), the speed at which cost parity is reached is different for each scenario and each context**. In Norway, past policies have brought cost parity in 2017, given the model definition; in Sweden, this is reached in 2030 under Base case, while in 2017 the BEV is still more than 50% more costly than the ICEV. The scenarios in which BEV policies are removed (ICEV Persistence and Market Pull) show however an initial radical increase in relative costs compared to the Base case scenario; the difference is more prominent in Norway than in Sweden, since the existing policies represent a significant contribution to cost reduction. In the long run however, both scenarios show a relative cost lower than 1, which is slightly higher in the unfavourable system situation (ICEV Persistence) compared to the case in which conditions are favourable (Market Pull). In the case of active policies (Policy Push and BEV Transition), the cost of BEV remains lower than that of the ICEV for all future years, and the lower the better system conditions there are (BEV Transition). A small shock in the relative cost is seen in year 2035, when policies are assumed to be removed. In reality, this process may be done in a progressive way, so that no shocks are caused. In Sweden, cost parity can be reached already in 2022 if favourable system conditions and an aggressive, integral policy strategy is implemented from 2018. Under unfavourable conditions (Policy Push), cost parity will still be reached in 2024. Under favourable conditions and no policy action, cost parity will be reached in 2028.
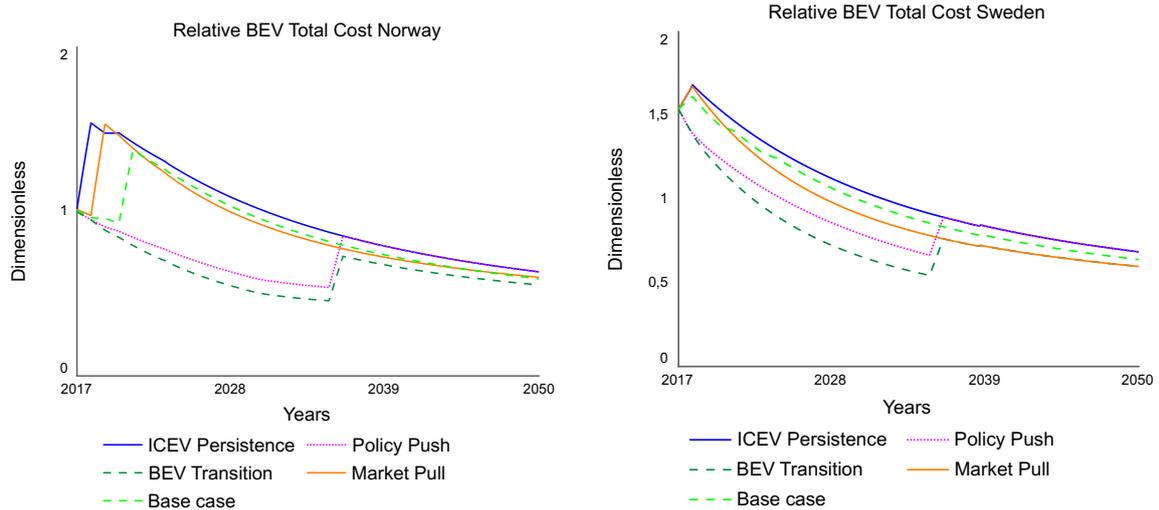
Figure 58. Scenarios for the future development of relative BEV costs in Norway (left) and Sweden (right)

Figure 59 illustrates the relative BEV performance under the five scenarios. **In all scenarios, BEV relative performance increases over time as an effect of technological development rate**. In Norway, the initial value at year 2017 is higher than in Sweden thanks to early incentives in charging infrastructure. **The future behaviour seems however to be highly dependent on the past and future policy strategies, more than the system conditions**. Indeed, the cases where the development rate is slower than Base case (ICEV Persistence and Policy Push), have radically different long-term behaviours. This seems to be valid for both contexts. In ICEV Persistence, the value is lower than 1 for most of the simulation time, and hence the BEV is not competitive in performance; in Policy Push, performance parity is reached in 2027 for Norway, and 2034 for Sweden. Also in the case that the technological development is high, but there is no policy directed to the building of charging infrastructure (Market Pull), the relative performance is lower than Base case. This however differs considerably between contexts, because while in Norway a satisfactory charging density has already been reached, and little more policy effort is needed, in Sweden the development of charging infrastructure is dependent on an initial subsidy programme from the government. Apart from ICEV Persistence however, all scenarios reach a situation where the BEV is superior in performance to the ICEV in the long run: this is thanks to the natural process of technological development.
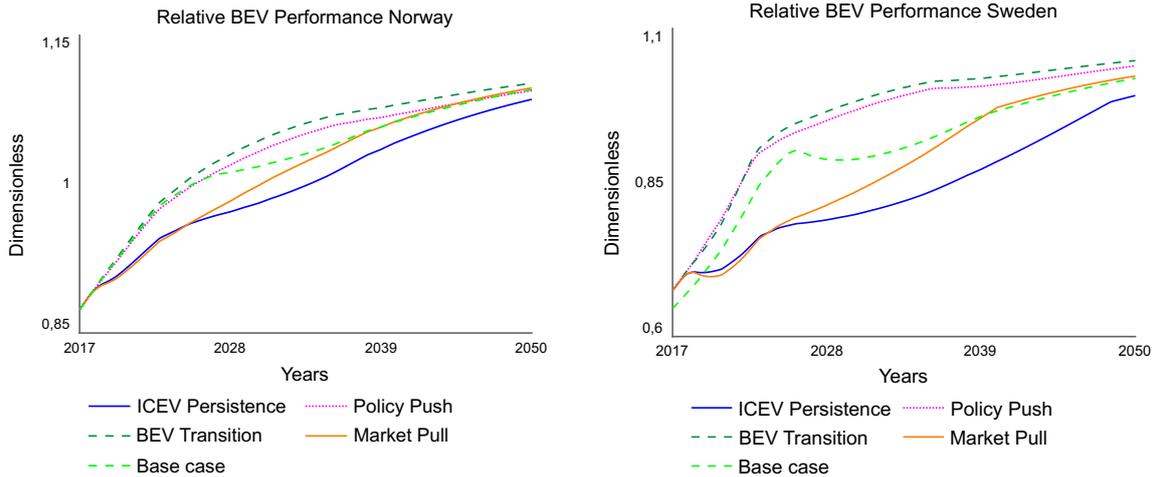
Figure 59. Scenarios for the future development of relative BEV performance in Norway (left) and Sweden (right)[21]

5.4.2   BEV sales share and market share

Different levels of relative costs and performance lead to different values for sales share[22]. Figure 60 illustrates the BEV sales share for the five scenarios, comparing Sweden and Norway. The sales share is driven by low costs and high performance, a combination which can be found in the BEV Transition scenario only. Other scenarios offer a trade-off between the two; ICEV Persistence is the only scenario in which neither costs nor performance of the BEV reach competitive values.

In the base scenario, the sales share converges in the long run to approximately 67% in Norway and 62% in Sweden. Convergence is more rapid in Norway: 50% sales share is reached in 2032 in Norway, while in 2037 in Sweden. In the case of active BEV policies and favourable system conditions (BEV Transition), the sales share can reach over 70%. In very unfavourable conditions (ICEV Persistence), the sales share stagnates at 37%.

Without favourable conditions but with an active policy strategy (Policy Push), the growth in sales share is fast after a poor initial value, and a stable equilibrium is reached early and at a lower level compared to average system assumptions (Base case). With favourable conditions and no BEV policies (Market Pull), the sales shares reached are higher. While in Norway BEVs have conquered large shares of sales already by 2016 and the market development seems in its

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[21] Observe: different scales on the y-axis

[22] In the model the relative BEV attractiveness determines the indicated BEV sales share, which defines the actual sales share after being compared with the time to perceive the change in attractiveness (see section 4.2.2). The behaviour of the confidence parameter will not be discussed in this scenario presentation.

mature phase, in Sweden the real growth phase starts after 2017: in all Swedish scenarios, we observe an exponential growth in the next 10 years - at different rates depending on the assumptions; in Norway instead, the growth is more moderate and it shows an initial stagnation in the cases that policy support is removed. An important difference is however manifest: while in Norway, both ICEV Persistence and Policy Push converge to the same sales share, in Sweden the ICEV Persistence scenario achieves only a 60% of the share achieved under Policy Push: hence**, in Norway, even with strong policy efforts, if the system conditions are not favourable, the long-term sales share will be the same; in Sweden instead, policy action can make a considerable difference in the sales share of 2050**.

It therefore seems that there are **three important factors behind sales share: the policy effort, the system conditions and the initial value**. It seems that policies have a strong impact in the short term, but that the system conditions determine the long-term distribution in sales. For all scenarios, Norway reaches higher sales shares than Sweden, indicating that the initial value is determinant for success. The BEV seems not to disappear even in adverse conditions, thanks to the natural rate of technological development driving both gain in performance and fall in costs.
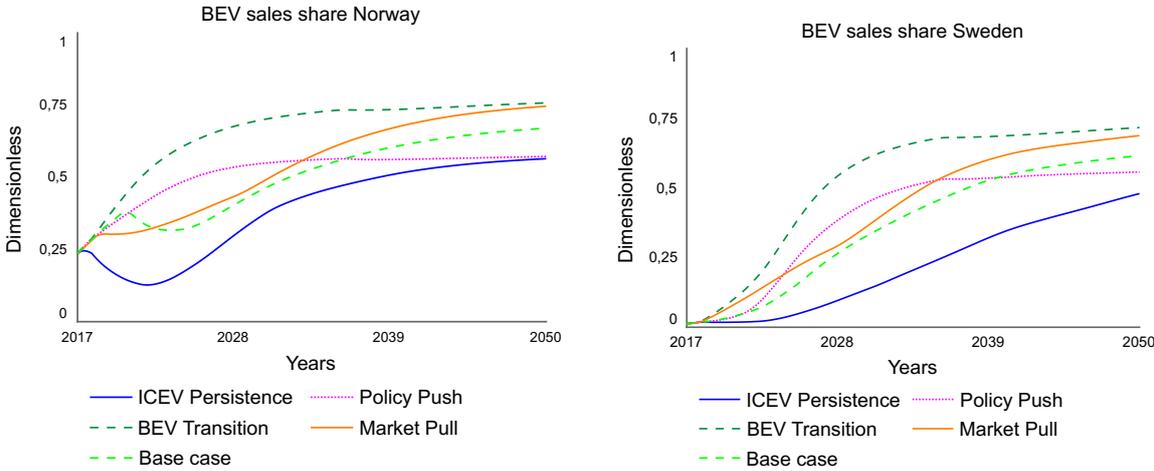
Figure 60. Scenarios for development of BEV sales share in Norway (left) and Sweden (right)

The sales share translates after accumulation into the market share, seen in Figure 61. While it is intuitive that scenarios with active BEV policies result in higher BEV market shares in the long run, the simulation shows that **Base case, Policy Push and Market Pull result in very similar market share trends**. Hence whether a strong policy effort, very favourable conditions or a moderate value of both is in place, the market share in the long run achieves approximately 50% in 2050 for all three contexts.
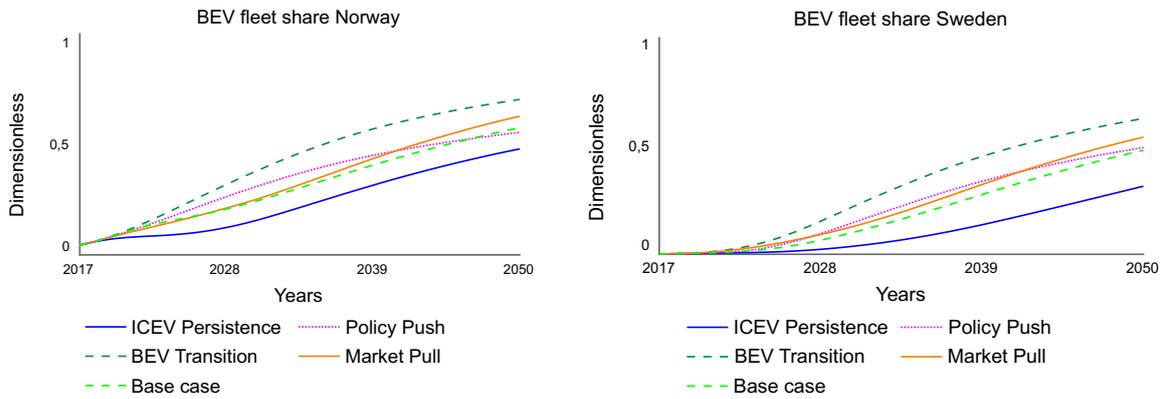
Figure 61. Scenarios for development of BEV market share in Norway (left) and Sweden (right)

5.4.3 Fleet emissions

The market share of BEVs relative to ICEVs translates in specific levels of emissions from the vehicle fleet. In Figure 62 and Figure 63 the total and the average fleet emissions are simulated for each scenario. As can be expected, the higher the BEV market share, the lower the average and cumulative emissions. The average emissions are proportional to the total emissions, scaled by the total number of vehicles. In both countries, total and average emissions decrease over time despite the growth in the size of the fleet, driven by higher shares of hybrids and low emitting ICEs and by increasing shares of BEVs.

Cumulative emissions are directly related to the size of the fleet and to the average vehicle emissions and they are calculated in the model starting from year 2000. Cumulative emissions are higher in Sweden compared to Norway because of the larger fleet and also because of the relatively higher average emission level. On average, emissions are slightly higher in Sweden than in Norway due to the lower share of BEVs.
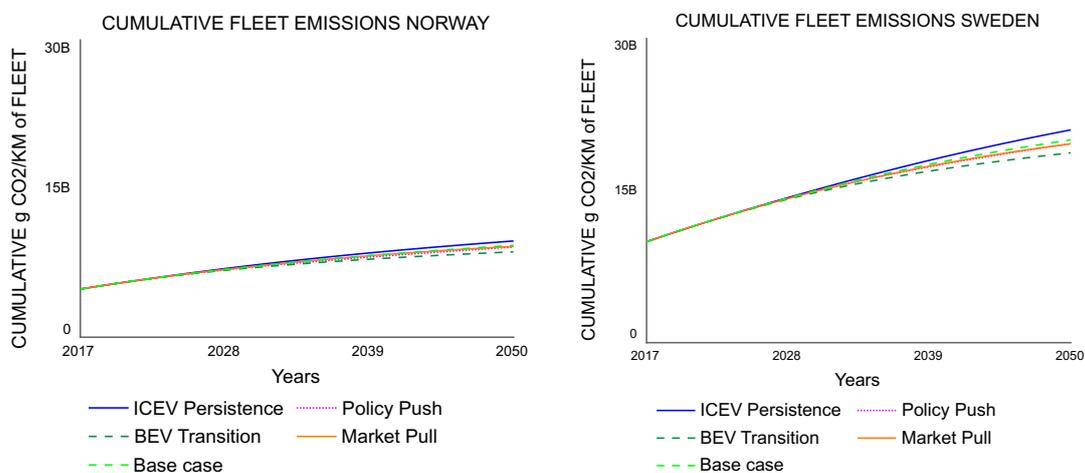
Figure 62. Scenarios for development of total fleet emissions in Norway (left) and Sweden (right)

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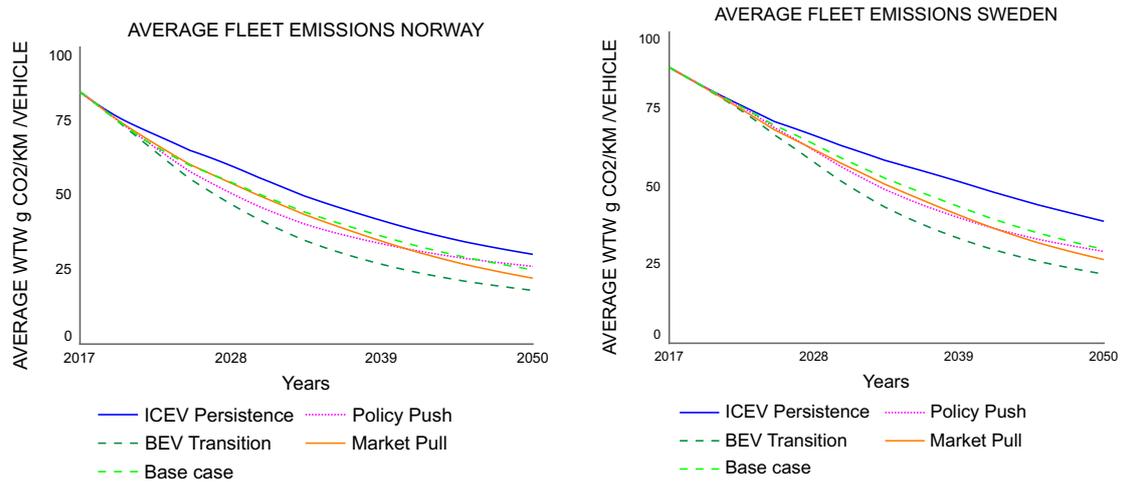
Figure 63. Scenarios for the development of average fleet in Norway (left) and Sweden (right)

Section 5.4 described a set of scenarios for policy strategies and system conditions which can be described as quite extreme and perhaps lacking some realism. Nevertheless, this exploration brought value to the investigation by considering a range of different conditions in a long-term scenario, which entails a high uncertainty. In the last section of this chapter, the simulation results are discussed in relation to the national targets for the vehicle fleet of the future.

5.5 Comparison with national targets

The previous sections explored the effect of different policy strategies and system conditions on the diffusion of the BEV in Norway and Sweden compared. It could be seen that different strategies can lead to very different outcomes in the short run and in the long run. These strategies must be considered in relation to the stated targets.

The Norwegian government has set the target of **100% BEV sales share by 2025, and a 100% BEV market share by 2040** (Norwegian Department of Transportation, 2017). Zero-emission vehicles are defined in Norway as full-electric vehicles and hydrogen-fuel vehicles; hybrids and biofuels are defined as low-emission and are hence not included in the definition (Norwegian Department of Transportation, 2017). Assuming that hydrogen-driven vehicles will not cover a large market share before 2050 in Europe (as derived in the study by Pasaoglu et al. (2015)), the simulations run in the previous sections do not reach the desired targets for any of the defined scenarios. Even with highly favourable system conditions and a high sales share in 2017 (20%), the model does not allow an increase of 80% within 8 years in any of the explored scenarios. **Under the BEV Transition scenario, the market share reached in 2050**

is only 75%, but the BEV sales share is no higher than 75% throughout the simulation, for any of the simulations. The sales share seems to converge to 75% and hence, by integration, no more than an 85% market share can be achieved. Hence a 100% market share cannot be reached. The reason why the desired targets seem not to be reached in the simulation model has to do with the way the sales share is defined[23], which is considered realistic and reasonable based on the discussion in chapter 4.2.2.

In the Norwegian case, the use of stronger regulatory instruments may be necessary to achieve the stated targets. As a simple exploration exercise, two more scenarios are compared to the Base Case: a BuyBack policy and a ban policy. The model structure representing the two policies is very rudimental, as this is not the focus of the thesis; it is however explored to gain an idea of what effect these policies would have on BEV diffusion. The model structure is illustrated in the Appendix (A 3).

One of the barriers of transition to BEV is the long lifetime of vehicles: ICEVs can run on the streets 17 years on average. Hence, it takes time for the whole vehicle fleet to transit from one vehicle type to another (see sensitivity analysis on lifetime in chapter B 6). In the time span 2017-2050, the average driver will make 2 vehicle purchases, or in other words, two times the choice between an ICEV and a BEV. The first policy therefore introduces a BuyBack program from 2018 under which 150 000 ICEVs are discarded each year, in addition to the ones at the end of their lifetime. The average lifetime of an ICEV becomes therefore shorter than BEV lifetime in the long term. This policy is intended to speed up the transition process by enabling earlier replacements, and surpassing the delay barrier of a long vehicle lifetime.

The second policy represents a stricter and simple model assumption: ICEV attractiveness is halved by the hypothetical introduction of bans for ICEVs in specific times and places, for example in city centres, or in rush hours. In Figure 64, the effect of these policies on BEV sales share and market share are shown. It can be seen that an aggressive BuyBack policy creates the conditions for a 100% market share in 2050, while the Ban increases sales share to desired levels in a few years, but not equally so for the market share.

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[23] This is determined by BEV attractiveness, which is in turn defined by relative cost and performance and by the relation between these relative values and the perceived attractiveness (the function "effect or relative cost/performance on attractiveness). In section 5.4, an alternative scenario where this effect is higher than the Base case was explored (in both Market Pull and BEV Transition); but as noted above, the sales share does not surpass 75%. This also has to do with the values achieved in relative performance and costs. Relative performance as defined in the present model does not achieve values above 1.2; this is considered realistic based on the model's definition of performance: a weighted average of charging station density, lifetime, emission level, travel range and diversity.

These scenarios are very simplified in nature compared to the ones performed in the previous sections. The objective was to give two hypotheses on the necessary conditions for reaching the targets set. It seems that stronger policies, or lower targets, are needed in the Norwegian BEV system.
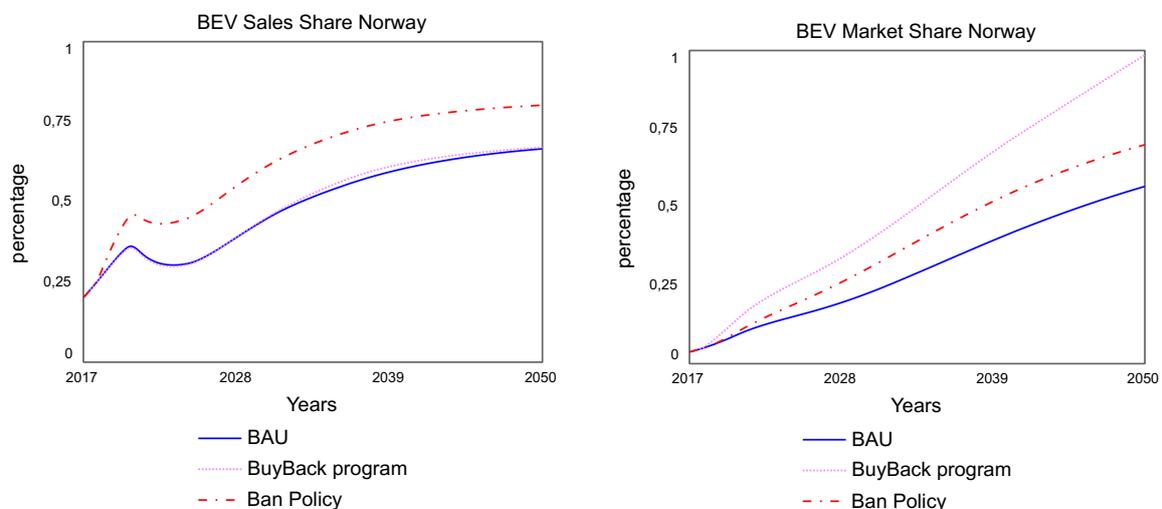
Figure 64. BuyBack policy and Ban policy in Norway

In Sweden, the transportation sector should achieve fossil fuel independence by 2030 (Trafikanalys 2016), considering both biofuels and electric vehicles as part of the strategy. The targeted **market shares for the BEV are 20% in 2030, 40% in 2040 and 60% in 2050** (Swedish Government, 2013**).** Under Base case, the market share reached in 2050 is below 50%. Under the 6 different policy scenarios run in section 5.3, no strategy would allow to achieve the targets; under the alternative scenarios, the setting with both strong policy effort and favourable conditions (**BEV Transition) allows to achieve the stated goal**. However, most strategies achieve values on average 20% away from the target, which can be still considered satisfactory.

The definition of the equations in the model (in specific the variables effect of relative performance/cost on attractiveness and indicated sales share) limits in fact the possibility to achieve a 100% sales share for the BEV. This is discussed in more depth in the Appendix, where sensitivity tests are run (Appendix part B). Nevertheless, the model structure aims to represent in an integral way the drivers and barriers of diffusion. Among these are considerable delay factors, which shall not be underestimated.

6 Discussion

This chapter gives a discussion of the model simulation results in light of the project's declared objectives. Answers to the research questions are sought and the dynamic hypotheses are discussed. A detailed comparison of the Norwegian and Swedish BEV systems is presented. The chapter closes with a discussion on the validity of the model, limitations of the study and possible topics for future research.

6.1 Causal analysis

In the chapter describing the model (chapter 4), the drivers and barriers to BEV diffusion were identified from a descriptive perspective through a causal loop diagram. The system is complex, including multiple, interacting feedback loops with different delay times. The model simulation supports in the understanding of the effective driving forces and barriers to BEV diffusion in such a complex system through a fully quantified approach. In particular, the effect of different policy variables on the dynamics of each context has been studied. What have Norwegian and Swedish policies meant until now and what will they mean in the future? In chapter 4.3 the pushing effect of policies was discussed, and chapter 5 showed the effectiveness of policies in relation to the stated targets. The pulling force of system conditions was also explored in chapter 5.4. Here we summarize the most important conclusions regarding the causal dynamics of the system considered.

Transition inertia

The system changes with a considerable inertia, caused by factors across all system sectors. These include the rate of development of vehicle technology and infrastructure, the time to build confidence among consumers and investors, the process of aligning system components, and the rate of replacement of old vehicles (driven by vehicle lifetime). The simulations have shown that the desired targets are not met by 2050. Even though strong policy action is implemented, the change in attractiveness of the BEV, whether it is from cost or performance, is marginal. The system conditions determine the overall speed of change. The reinforcing mechanisms involving consumers and investors come into play only after a considerable share

of the market has been taken by the BEV. Alignment between system components is necessary for growth, as in the case of infrastructure: not only resources, but also need for infrastructure and fitness of the grid must be in place. This is also the case for vehicle attractiveness and consumers' awareness: if the second is not present, the sales share will not converge towards the indicated sales share. Hence the transition process is slow. The vehicle lifetime has a considerable impact on the rate of transition, as shown in the Appendix (B 2). A BuyBack program can speed up the rate at which vehicles are replaced, and thus BEV diffusion. The topic has however not been explored in this thesis to a sufficient extent, and barriers to implementation as drivers' low adhesion or financial aspects should be considered.

Inevitable change

The simulation shows that system conditions drive BEV adoption in the long run. Over time, technological improvements and fall in costs and price make the BEV more and more attractive; in 10-15 years, the BEV will have a competitive advantage in the majority of aspects. This will happen with or without policies, as can be seen in the simulations. Sales in the short term may be halted by lack of policy support, but for all scenarios, growth is a constant.

The shape of the growth curve is an interesting factor: on one side, there are multiple reinforcing feedbacks that should drive the BEV fleet to grow exponentially; on the other side, there are balancing loops and system delays that weaken this growth, and eventually lead the growth to converge to steady-state. All simulations show a growth of the BEV fleet that resembles an S-shape, but with many different growth coefficients. In all cases, a first phase of exponential growth can be seen, driven by reinforcing mechanisms. In the long term, balancing processes come into play: the growth slows down, and in most cases, converges to a constant level (when convergent behaviour is not seen, it means that this will happen after 2050). The steady state is defined by the relative cost and performance.

Policy leverages

The comparison of the historical BEV diffusion with what would have happened if no policies had been in place (chapter 5.1.3), shows clearly how important policies have been in driving BEV adoption. This is especially the case in Norway, where policy action has been overarching and aggressive. Policy action is able to anticipate the time that cost and performance parity is reached; it creates momentum for the key reinforcing mechanisms in infrastructure, retail and consumer confidence. The simulations also showed how Sweden is lagging behind by 10 years compared to Norway since it has yet not invested in infrastructure development.

Policy action also compensates for unfavourable system conditions, as shown in the comparison of the scenarios Market Pull and Policy Push. However, in the Swedish case, if policies are not directed to development of infrastructure, the Chicken & Egg reinforcing loop will not take off at a sufficient speed. Subsidies to infrastructure development are needed in Sweden because otherwise investor confidence is too low. Policy action that is correctly directed can boost reinforcing mechanisms in the system that lead to exponential growth.

6.2 Dynamic hypotheses and research questions

The series of simulations presented in the previous chapter supports the validation of the dynamic hypotheses stated in section 3.9 and to answering the research questions. This section describes this process. The hypotheses will be denoted with the letter "H", while the research questions with the letters "RQ".

Dynamic hypotheses

H1: Through the continued use of current BEV policies, the Norwegian BEV fleet will reach 1.5 million units in 2030 (Norwegian Ministry of Watercourses and Energy/ NVE, 2016)

Figure 65 illustrates the growth of the BEV fleet under the explored policy analyses and alternative scenarios. Two lines illustrate the intersection between Year 2030 on the x-axis and the value 1.5 million vehicles on the y-axis. The level predicted by NVE in 2016 does not correspond to the policy scenario a) described in chapter 5.3.1 (which assumes a continued implementation of current policies up to 2030). It does not correspond either to any of the other scenarios or policy analyses performed.
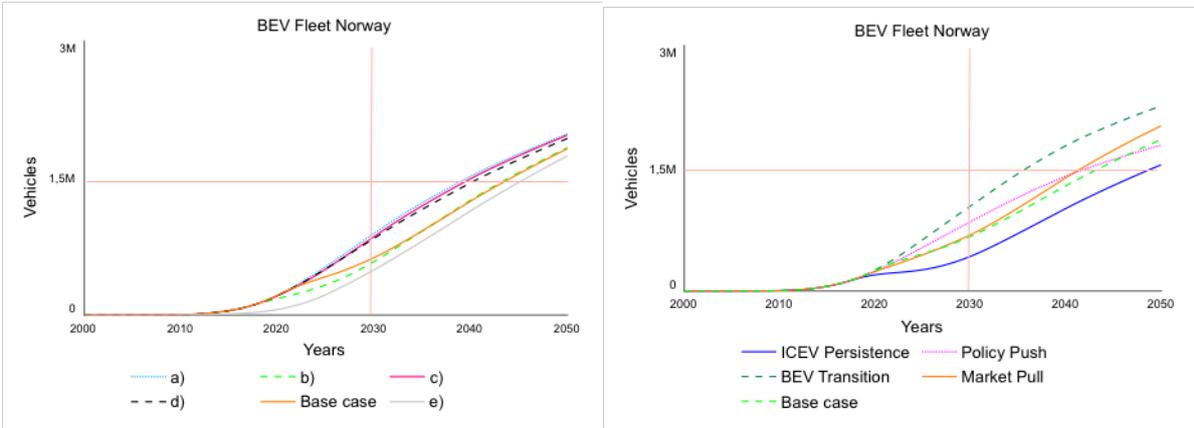
Figure 65. Comparison of simulations with H1

- *H2: The Swedish BEV fleet will also reach 1.5 million units by 2030*

Figure 66 illustrates the same analysis as above, but for the Swedish context. The simulations don't meet the hypothesis. Scenarios with a strong policy effort, and favourable system conditions (policy analyses a), e) and scenario BEV Transition), reach 1.5 BEVs a few years after 2030; but none of them before or in 2030. The total vehicle fleet is larger in Sweden than in Norway, so that it the same fleet size does not reflect the same fleet share.
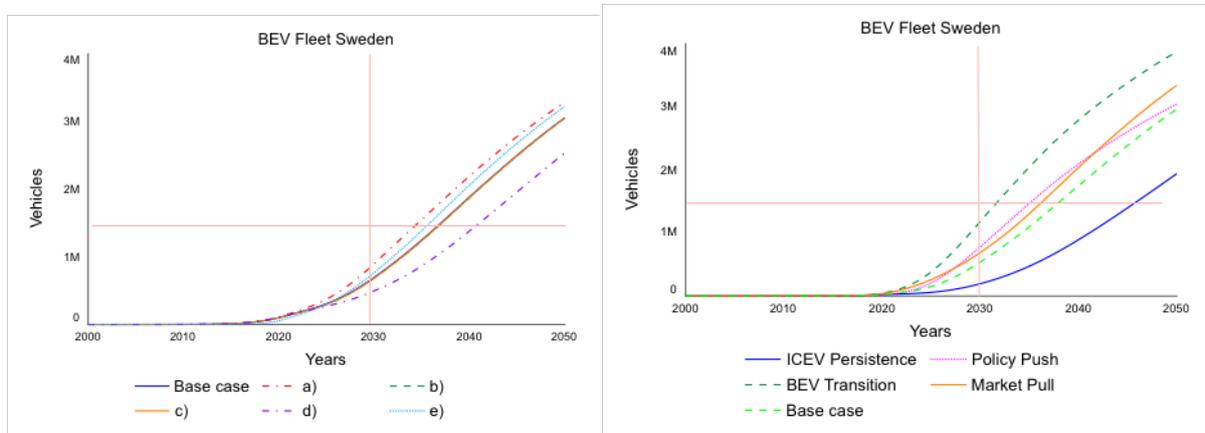
Figure 66. Comparison of simulations with H2

- *H3: If current BEV incentives are reduced in Norway by 2020, the BEV system will not be able to maintain a self-sustaining growth* (Figenbaum, et al., 2015)

All the simulations show that, even though all BEV policies are reduced starting year 2018, the BEV fleet will continue growing. Short-term sales will be impacted, but there are other mechanisms driving the growth in BEV attractiveness: the fall in price and costs, the improvement in performance, and the growing consumer and investor confidence. Hence the hypothesis by Figenbaum et al. is refuted: the Norwegian BEV fleet is, under the study's assumptions, able to maintain a self-sustaining growth.

- *H4: If current BEV incentives are reduced in Sweden by 2025, the BEV system will not be able to maintain a self-sustaining growth*

The same results as for H3 are obtained for the Swedish context.

- Hypotheses 5 to 7: *The main driver of difference in BEV adoption between the Norwegian and Swedish system is:*
  - *H5: the BEV policy strategy* (Figenbaum, Assum, & Kolbenstvedt, 2015)

The simulations show that the policy strategy chosen has a considerable impact on BEV adoption. If Norway and Sweden had not implemented any policy (as explored in section 5.1.3), the results would have been very different. The impact is however much stronger in Norway due to a broader and stronger policy action. The policy analysis also included an experiment

where one country adopted the policy strategy of the other country (analysis e)). This analysis shows that if Norway adopts the Swedish strategy, BEV adoption is lower than with all other strategies (see Figure 52); if Sweden adopts the Norwegian strategy, BEV adoption is higher than with all other strategies (Figure 54). Hence the BEV policy strategy seems to be a main driver of the difference between adoption rates in the two contexts.

- *H6: Geographic and demographic characteristics of each country*

The developed SD model considers some geographic and demographic aspects: the total population size, fitness of grid and the number of gas stations. The vehicle fleet size is proportional to the population size, and is therefore larger in Sweden than in Norway. The fitness of the grid is assumed to be equal for the two countries. The number of gas stations is higher in Sweden than in Norway due to more roads. This determines the goal for the number of on-road charging stations, and hence more charging stations will be required in Sweden, compared to Norway. Further geographical information could have been implemented through the integration of spatial modelling, but was not done here.

The simulations show that the transition to BEVs is slower in Sweden compared to Norway. Figure 67 shows however that this is not due to geographical and demographical differences: in the Norwegian model, population size and number of gas stations has been set equal to Swedish levels, and the model has been run. The BEV sales share is minimally impacted. Hence H6 is refuted.
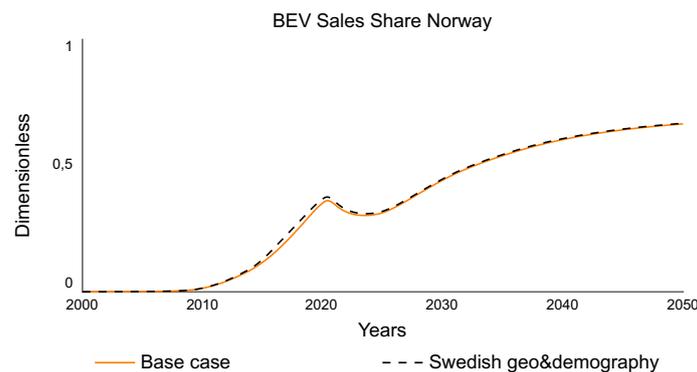
Figure 67. Simulation testing H6

- *H7: "it's just a matter of time": Norway started earlier with policy action*

The simulations have shown that, since BEV policies were introduced later in Sweden, the BEV diffusion is lagging behind. On average, there is a 10-year difference between the Norwegian and the Swedish curve (see Figure 68). This difference is however smaller after 2025, as policy action is reduced in both countries and market dynamics lead BEV attractiveness in cost and performance. The key role of early, strong policies for Norwegian BEV adoption has already

been discussed above, and supports the hypothesis. However, it is not only a matter of timing, but also of strength of the policy action. Applying the Swedish strategy to the Norwegian system would not have given the same adoption rates (Figure 52). Hence the hypothesis is only partially supported.
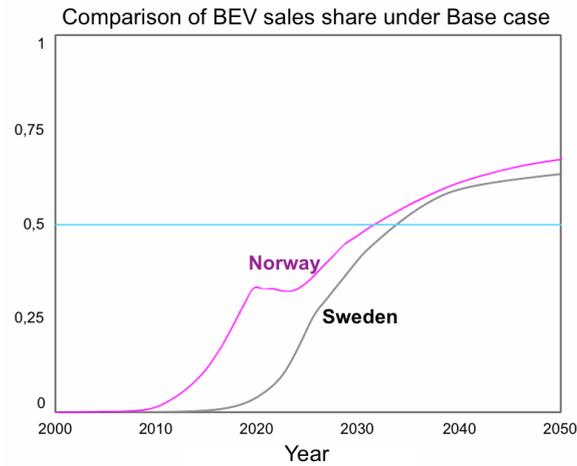
Figure 68. Comparison of BEV sales share

- *H8: Cost parity between ICEV and BEV will be reached in 2030 (BNEF 2017)*

Considering the total cost of ownership as defined in the present study (see chapter 4.2.3), the time at which cost parity is reached will depend on the policy strategy. In Norway, strong policy action has driven the BEV cost to equal ICEV cost already in 2017; in Sweden, this will only happen in 2030. If policies are not considered, cost parity will be reached around year 2032 in both contexts. However, it must be noted that the main focus of this study is not an economical representation of BEV competitiveness, but rather to offer a systemic analysis. Hence, the preciseness of these estimates is reduced by necessary simplifications and aggregations. The position taken by BNEF in 2017 seems anyhow to fit with the estimates of this study, excluding policy intervention.

Research Questions

- Central Research Question: *What are the country-specific drivers of BEV diffusion?*

The study has shown that system conditions and policy action both have had, and will have, a strong impact on BEV diffusion in both countries. The differentials in system conditions (population size, density of gas stations) do not seem to drive the difference between the two contexts. It is instead the policy strategy which determines this difference.

- *RQ1: What factors define BEV attractiveness for potential buyers?*

The literature review has included among others customer surveys and behavioural economic theory to best understand what factors define BEV attractiveness. Vehicle total cost, including purchase price and operational costs, and five main performance attributes have been identified.

Consumer awareness has also been included as an important factor in the consumer's preference. The model presentation described how these factors where quantitatively calibrated to define attractiveness.

- *RQ2: How do purchase policies influence the cost attractiveness of BEVs?*

Surveys described in the literature review reveal that drivers are most concerned with purchase price than with the total cost of ownership. Hence, purchase subsidies can have a significant influence on BEV attractiveness. The degree of influence depends on how much the price is reduced from the base price, and how much the net price still differs from the price of an ICEV. In Norway, purchase policies have a key role in the adoption since they reduce BEV price by up to 50%. In Sweden, in contrast, BEV price is reduced by a few percentages (see Figure 38). Hence BEV cost attractiveness is higher in Norway than in Sweden, until purchase policies are in place.

- *RQ3: Based on the experiences from 2000 to 2017, what was the effectiveness of BEV policies in Norway as compared to Sweden?*

Chapter 5.1.3 answers to this question: if no policies had been implemented, the adoption of BEVs would have been much lower, in particular in Norway.

- *RQ4: What policies are determinant for a sustained BEV adoption?*

In the discussion of hypotheses 3 and 4, it was already defended how BEV adoption will continue growing, no matter the future policy strategies and system conditions. Hence there are not specific policies today which are determinant for a sustained BEV adoption. Something can be said, however, about what policies will boost BEV sales in the near future: this depends on the context. In both Norway and Sweden, there is the need for large purchase subsidies that eliminate the difference in price between ICEVs and BEVs. These policies should be in place until cost parity is achieved, which is otherwise not expected to be reached before 2030. The simulations show that, if purchase policies are removed before 2030, sales stagnate or fall in the next few years; the growth however continues later on, driven by system conditions. In Sweden, BEV attractiveness is also highly dependent on BEV charging infrastructure development.

- *RQ5: When will performance parity be reached in Norway, and when in Sweden?*

Under base case conditions, performance parity is reached in 2030 in Norway, and after 2050 in Sweden.

- *RQ6: When will cost parity be reached in Norway, and when in Sweden?*

Under base case conditions, cost parity is reached in 2017 in Norway, and in 2030 in Sweden.

6.3   Validity

The validity of the model has been evaluated on the basis of a series of tests on both model structure, behaviour, and relation between structure and behaviour. In this section, the most relevant results from a more extensive validation process documented in the Appendix (section B) will be presented.

The model has dimensional consistency and is robust to extreme conditions (B 1 and B 2). The boundary is considered adequate in function of the stated objectives (B 3). The structure of the model and parameter values are considered adequate (B 4) and reflect most proximately the knowledge on the system presented in chapter 3. Alternative model structures for indicated sales share bring a different interpretation of the dynamics of the system than the one advocated in this study. The model replicates historical behaviour to a satisfactory degree (B 5 and 5.1). The sensitivity analysis conducted in section B 6 for four model parameters shows that there exist some variables to which the model is sensitive, undermining the robustness of the model. It is sensitive to the two graphical functions Information campaign and the effect of relative BEV cost and performance on BEV attractiveness. Based on the chosen definitions of these variables, BEV sales share can therefore vary greatly. The graphical function information campaign influences the speed at which the indicated sales share is met; the effect function influences directly the indicated sales share. This is indeed a weakness of the model, caused by the lack of empirical data to better quantify the graphical functions. Because of this, the policy information campaign has not been included in the policy analysis and scenario exploration conducted in chapters 5.3 and 5.4. Future improvements of the model should include a deeper research on these variables, so that the values are based on more robust empirical information. Nevertheless, the objective of the thesis has been to develop a comparison between the Norwegian and Swedish contexts. Therefore, as long as the same graphical functions are applied to both contexts, the comparative value shall not be lost. Additionally, the model is not designed as a predictive tool, and hence the simulations into the future shall not be considered as predictions, but as explorations into the causal relations of the system.

The model takes a conservative position by assuming that consumer choice is driven in the first place by the relative cost and performance; word-of-mouth effects speed up the change in preferences, but not the preference itself. This decision avoids that the reinforcing word-of-mouth effect influences consumer choice in the long run. The model has finally been developed

to have dimensional consistency and robustness to extreme conditions, hence counter-intuitive behaviour is not expected to be observed from the simulations.

The validation process has supported the demonstration that the model operates in a consistent manner with its built and purpose, even though limitations apply. The defined structure is valid for experimentation and analysis of causal relations.

6.4 Limitations

The results presented in chapter 5.1 and the discussion on validation indicate that the current model structure is able to reproduce certain behavioural patterns in a realistic way and that the model is robust to most validation tests. However, there are many opportunities for improvement of the model. A model is, by definition, a simplification of reality and cannot be fully accurate. Simplifications and aggregations are necessary due to the modelling method, the model boundary defined, and the limited time and data availability. In particular, the sensitivity of the model to the two graphical functions Information campaign and the effect of relative BEV cost and performance on BEV attractiveness is a limitation that should be addressed in future work. The following section will list topics of the thesis with limitations.

Choice of model structure

Alternative model structures could have been developed, based on different interpretations of reality: each model is a way of "reading" reality. The model takes a conservative position by assuming that consumer choice is driven in the first place by the relative cost and performance; word-of-mouth effects speed up the change in preferences, but do not change the preference itself. This decision avoids that the reinforcing word-of-mouth effect influences consumer choice in the long run (see Appendix B 4). This however excludes the possibility that the model shows a complete conversion of the fleet to battery technology. This decision is supported by the idea that the BEV can coexist with other vehicle technologies, as long as the required infrastructure is in place for each.

Vehicle specification

Fridstrøm et al. have developed a stock-flow model of the Norwegian vehicle fleet specifying 22 vehicle segments and 31 age classes (Fridstrøm, Østli, & Johansen, 2016). The present model only specifies 2 segments and 2 age classes. The umbrella term ICEV has been used in this study for all vehicle types using fully or partially the mechanism of internal combustion as powertrain. This choice limits the study by not modeling the competitive dynamics between different types of ICEVs. In particular, the model does not represent the phenomenon of

knowledge spill-over to other vehicle platforms (Struben & Sterman, 2006). This may be an important factor reducing the competitiveness of the BEV.

First- and second-hand vehicle markets are not distinguished, and hence it is not possible to consider early vehicle discards. Import and export of vehicles are not considered, and some sources mention vehicle trade as a barrier to BEV diffusion in Sweden (Nykvist & Nilsson, 2015).

Charging infrastructure

There are many kinds of charging points, and two classes have been artificially defined in the present study (on-road charging stations and park&charge points). This artificial definition may reduce realism and possibility to validate the simulation with real data.

Spatial dimension

The model does not include a spatial differentiation. The diffusion of a technological innovation is a contextual phenomenon that is dependent on characteristics of the environment: population density, air quality (hence urgency of a "green" transition), fitness of power grid to installation of charging networks, driver behaviour and more. Each of these factors influences the probability of success of BEV diffusion, and each varies across the national landscape (Struben & Sterman, 2006). The role of geographic premises is inherent in incentives (Bjerkan, Nørbech, & Nordtømme, 2016) and hence the penetration of BEVs should be locally managed. The success of a BEV diffusion is dependent on the penetration in all environments. Indeed, Figenbaum and Kolbenstvedt (2016) have mapped the geographical distribution of BEV owners over Norway, and we can observe a large variety from one region to the other. The highest penetration is, as can be expected, around the urban areas. While the declared objective by the government is to reach a transformation of the whole vehicle fleet, certain geographic market segments may represent important bottlenecks to the transition.

Endogenous policies

Policies are defined exogenously in the model; in reality however, policies are adaptive to the system conditions, and hence should be endogenously defined. This brings a double limitation to the model: on one hand, the introduction and removal of policies is not organically reactive to the system conditions but pre-determined by the parameter definition; on the other hand; there is not space for new policies arising in future years.

Contextualized model structure

The models for Norway and Sweden have a very similar model structure and hence the same causal structure. The contextualization has been based on the knowledge gained from the

literature review performed. This similarity could however be a limiting factor in the comparison, and the research could benefit from a deeper analysis of the structural differences.

Deep uncertainties

No deep uncertainties are explored. Hence possible modal shifts such as the transition to automated vehicles or stronger regulations on vehicle emissions is not considered as a possible option: the present travelling patterns are assumed to remain in place for the next few decades.

6.5   Suggestions for further research

The present study presents intrinsic limitations. Addressing these limitations can bring higher precision to the research and broader understanding on the topic. This project can be considered as a platform for further development, with many opportunities for improvement. Among the limitations mentioned above, the following are considered of particular importance for future research. In addition, some possible pathways of further development are described.

Further work should, in general, aim at developing an endogenous representation of more factors. An endogenous representation of policies directed to vehicles should be implemented, which also takes into consideration regulations towards ICEVs in greater detail. Supra-national regulations should also be included. The competition between alternative internal combustion technologies should be modelled endogenously.

Two opposing pathways have been envisioned, each with valuable benefits. The models for Norway and Sweden could benefit from a deeper structural contextualization of each context. This would bring further knowledge on the causal dynamics governing each context and making each context different from others. At the same time, it would be useful to develop a general model structure that can be parametrized to any context, national or other. This could for example be done through an interface. An interface can transform the system dynamics model into a boundary object (Star & Griesemer, 1989) for discussion with stakeholders, decision makers and other scientists.

The simulation results bring to the conclusion that ICEVs and BEVs will coexist in the future. Sterman (2000, ss. 349-406) describes instead a competitive setting where the "winner-takes-it-all": a first competitive advantage drives powerful reinforcing mechanisms that increase the gap in relative attractiveness and in relative access to complementary resources, such as infrastructure and fuel/power. This setting is not considered fit for the present problem, and this position has been defended in the previous chapters and guided the modelling. What has not

been explored however, is the effect of radically new business models in the vehicle and infrastructure market. These could bring an additional competitive advantage to the BEV, and a loss in value to the ICEV. Future research should develop a deeper comparison between these two modelling paradigms on competition.

Finally, the limitations of this study flag one challenge that system dynamicists often face: the parametrization of soft variables. Future research should deepen into a robust development of the confidence parameter and of graphical effect functions, based, for example, on the techniques described by Sterman (2000, ss. 597-629) and Luna-Reyes & Andersen (2003).

7 Conclusion

Electrification in the transportation sector is seen as a key step towards a low carbon future. This study has been performed under request of the company DNV GL as part of a larger research on the transition in the energy sector. The client was interested in a detailed analysis of the possible future developments of the BEV market. The special cases of Norway and Sweden have been chosen to perform a comparative study on two countries similar in many traits, but where different BEV policy strategies have been implemented- and very different BEV penetration rates have been achieved to date.

The main research question asked to detect the drivers and barriers to BEV diffusion for each of the contexts considered. In this intention, the study has brought together knowledge from many disciplines. The BEV is part of a greater "ecosystem", where vehicle costs, vehicle technology, consumer preferences, driver behaviour, infrastructure related to transportation, macro-economic theory and policy making all play a role. The problem involves many actors with own decision rules and whose interests and times of action are often not aligned.

The system dynamics method has been chosen because of its fitness to represent problems in interdisciplinary contexts and to allow simulation of the system behaviour over time. A simulation model has been developed and used for analysing the problem. The effectiveness of different policy strategies has been tested in both contexts, comparing with historical behaviour. The analysis also explored the impact of other conditions of the system on BEV diffusion, such as oil prices and rate of technological development. Five scenarios have been developed based on different combinations of policy strategies and system conditions.

Although the model has limitations, it serves as a dynamic hypothesis to describe the system's structure and behaviour over time. The simulations of the Norwegian and Swedish models have brought to a number of conclusions: Firstly, delays and barriers are underestimated. Policy action is not immediately answered with a growth in BEV fleet share, but the growth is progressive. Time factors such as the vehicle lifetime, the development time of infrastructure, and the time consumers need for gaining confidence with the BEV slow down what could be expected as an exponential growth. Comparing Norway and Sweden, one can see that multiple

factors need to be in place contemporarily to allow a strong growth in BEV sales: not only the BEV must be competitive in both price, costs and five performance attributes, but costumer confidence needs also to be high. The alignment of these requirements to adoption is one of the main challenges for BEV diffusion.

The inertia of the transition can only marginally be overcome. Policy action can anticipate by many years the cost and performance parity of the BEV and the ICEV and thereby gives strong momentum to the growth. In the long term however, it is the system conditions that drive BEV attractiveness; policy action can only be expected to be in place for the first years of market penetration. For both countries, the targets set by each government are not met under any of the policy scenarios.

Secondly, the market share of the BEV will grow over time under all scenarios: system conditions in the long run are favourable to the BEV. The diffusion of the BEV is also driven by strong reinforcing mechanisms involving consumers, infrastructure operators and the vehicle fleet. These mechanisms are starting to run, and policy action only drives the initial speed. The transition seems therefore "unstoppable".

The model simulation has also brought understanding on the differences and similarities between the Norwegian and Swedish vehicle system. The diffusion of BEVs will benefit from different policy strategies for each context because of the policy effort that has already been implemented. In Norway, the purchase tax is still very relevant for the next years, while infrastructure subsidies are key in Sweden. Norwegian drivers show a higher confidence in the BEV and hence they are reactive to changes in BEV attractiveness; in Sweden, even if strong policy action is put in place, this will be reflected in adoption numbers only some years from now. Sweden's technologically neutral policy strategy has not given the BEV the competitive advantage that it has in Norway, where policy efforts have been concentrated on the BEV only. On the other hand, the two countries show a similar long-term behaviour: the growth in the BEV fleet is steady, but not exponential. Also, the BEV is expected not to push the ICEV out of the market by 2050 in any of the two contexts. Instead, BEV penetration rates will converge towards 2/3 share, irrespective of policies pursued. This steady state is driven by the relative costs and performance, which also converge to steady state in the long run.

The study concludes that a future of coexistence between the ICEV and the BEV technologies is probable. What has not been explored, is the effect of radically new business models in the

vehicle and infrastructure market. These could bring an additional competitive advantage to the BEV, and a loss in value to the ICEV.

Conceptually, a key question remains as to whether a future with a steady state with significant fraction of ICEVs can coexist with a dominant BEV fleet. This question, together with the limitations of the study in terms of sensitivity to soft variables, represent important implications for the system dynamics community and future research.

The study has aimed at creating value for both policy-makers, scientists, and all other readers with a curiosity for BEV diffusion and technological transitions in general. Through the presentation of the model, policy-makers are guided to identify the leverages of change in the vehicle system. Scientists in the field of transitions can gain a more systemic understanding on the topic. Readers can understand the value of applying the system dynamics method to a complex topic such as the BEV.

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Appendix

The Appendix of this thesis is composed of a series of sections aiming at providing an integral presentation of the model, complementary to what has already been presented in the thesis' main text. The first section is dedicated to model documentation, including equations, parameter values and specification of units (section A). The second section presents the complete procedure of model validation (B). Finally, a short discussion on how green the BEV actually is, is presented (C).

Due to the high repetitiveness between the models for the Norwegian and Swedish context, it has been chosen to provide the model documentation and to run the model validation for one of the two versions only, in this case the Norwegian model.

A. Model documentation

The model documentation includes three sections. The first provides a complete list of the model variables, their value or equation, and the unit. The second provides a table reporting the values of four main variables: fuel prices, power prices, historical and forecasted population sizes for Norway and Sweden. The last section illustrates the model structure for the extreme policies explored in chapter 5.5.

A 1. List of variables

Variable name	Equation / Value	Units
MAIN MODULE		
average charging station density	(density of fast charging stations+density of park&charge points)/2	Dimensionless
BEV adopter profile	GRAPH(BEV total market share)	Dimensionless
BEV Sales Share(t)	BEV Sales Share(t - dt) + (change in BEV sales share) * dt	Dimensionless

INIT BEV Sales Share
  INFLOWS:
    change in BEV sales share
	INIT BEV market share + 0,000000001
	
	(indicated BEV sales share-BEV Sales Share)/time to perceive change in attractiveness
		
		1/Year

BEV time as mature	Vehicle Performance.BEV lifetime*2/3	Years
BEV time as young	Vehicle Performance.BEV lifetime*1/3	Years
BEV total market share	total BEV fleet/fleet size	Dimensionless
charging infrastructure subsidies	GRAPH(TIME)	Dimensionless
combined effect on CS requirements	effect of change in charging behaviour on charging station requirements*effect of travel range on charging station requirements	Dimensionless
confidence in BEV	effect of exposure to BEV on confidence*effect of risk aversion on confidence	Dimensionless
conversion factor 2	1	1/Year
conversion factor cars to plugs	2	charging points/Vehicles
conversion factor stations to points	3	charging points/stations
density of fast charging stations	"Fast On-road Charging Stations"/desired fast charging stations	Dimensionless
density of park&charge points	Park&Charge Points/desired park&charge points	Dimensionless
desired fast charging stations	reference number of gas stations NORWAY*effect of change in charging behaviour on charging station requirements*effect of travel range on charging station requirements	stations
desired park&charge points	total BEV fleet*conversion factor cars to plugs+1	charging points
effect of change in charging behaviour on charging station requirements	GRAPH(TIME)	Dimensionless

Variable name	Equation / Value	Units
effect of exposure to BEV on confidence	GRAPH(total exposure to BEV)	Dimensionless
effect of performance on attractiveness	GRAPH(Vehicle Performance.relative BEV performance)	Dimensionless
effect of relative cost on attractiveness	GRAPH(Vehicle Costs.relative BEV total cost)	Dimensionless
effect of risk aversion on confidence	GRAPH(BEV adopter profile)	Dimensionless
effect of travel range on charging station requirements	(1/Vehicle Performance.effect of relative range capacity on BEV performance)^sensitivity of vehicle performance to CS requirements	Dimensionless
expected replacements	ICEV discards+BEV discards	Vehicles/Years
fast CS planned per year	IF(Fast On-road Charging Stations < desired fast charging stations) THEN (desired fast charging stations/years set to achieve infrastructure goal)*fitness of grid*available resources ELSE 0	stations/Years
Fast On-road Charging Stations(t)	Fast On-road Charging Stations(t - dt) + (fast CS building rate) * dt	stations
INIT "Fast On-road Charging Stations"	0	
INFLOWS:		
fast CS building rate	fast CS planned per year	stations/Years
fitness of grid	GRAPH(TIME)	Dimensionless
fleet size	total ICEV fleet+total BEV fleet	Vehicles
gap current to indicated fleet size	indicated fleet size - fleet size	Vehicles
HISTORICAL BEV SALES INFLOW NORWAY	GRAPH(TIME)	Vehicles/Year
HISTORICAL BEV SALES SHARE NORWAY	GRAPH(TIME)	Dimensionless
HISTORICAL BEV STOCK NORWAY	GRAPH(TIME)	Vehicles
HISTORICAL NUMBER OF PUBLICLY ACCESSIBLE CHARGING POINTS NORWAY	GRAPH(TIME)	stations
HISTORICAL POPULATION NORWAY	GRAPH(TIME)	People

Variable name	Equation / Value	Units
HISTORICAL TOTAL VEHICLE FLEET SIZE NORWAY	GRAPH(TIME)	Vehicles
HISTORICAL TOTAL VEHICLE SALES NORWAY	GRAPH(TIME)	Vehicles/Years
historical vehicle density	HISTORICAL TOTAL VEHICLE FLEET SIZE NORWAY/HISTORICAL POPULATION NORWAY	Vehicles/People
ICEV FUEL PRICES	GRAPH(TIME)	Kroner/Liter
ICEV lifetime	17	Years
ICEV sales growth rate	(ICEV new sales rate-last year ICEV sales)/last year ICEV sales	Dimensionless
ICEV sales share	1-BEV Sales Share	Dimensionless
ICEV time as mature	ICEV lifetime*2/3	Years
ICEV time as young	ICEV lifetime*1/3	Years
indicated BEV sales share	relative BEV attractiveness/(relative BEV attractiveness+reference ICEV attractiveness)	Dimensionless
indicated fleet size	"TOTAL POPULATION, HISTORICAL AND FORECASTS NORWAY"*indicated vehicle density NO	Vehicles
indicated vehicle density NO	GRAPH(TIME)	Vehicles/People
information campaign	GRAPH(TIME)	Dimensionless
INIT BEV fleet	INIT(HISTORICAL BEV STOCK NORWAY)	Vehicles
INIT BEV market share	INIT(total BEV fleet)/(INIT(total BEV fleet)+INIT(total ICEV fleet))	Dimensionless
INIT ICEV fleet	INIT(HISTORICAL TOTAL VEHICLE FLEET SIZE NORWAY)	Vehicles
INIT ICEV market share	INIT(total ICEV fleet)/(INIT(total BEV fleet)+INIT(total ICEV fleet))	Dimensionless
INIT proportion of Young to Mature BEVs	1/2	Dimensionless
INIT proportion of Young to Mature ICEVs	1/3	Dimensionless
last year ICEV sales	DELAY(ICEV new sales rate; 1)	Vehicles/Years
market pool	expected replacements + gap current to indicated fleet size*conversion factor 2	Vehicles/Years
Mature BEV fleet(t)	Mature BEV fleet(t - dt) + (BEV aging rate - BEV discards) * dt	
INIT Mature BEV fleet	INIT BEV fleet*(1-INIT proportion of Young to Mature BEVs)	Vehicles
INFLOWS:		
BEV aging rate	Young BEV Fleet/BEV time as young	Vehicles/Year
OUTFLOWS:		
BEV discards	Mature BEV fleet/BEV time as mature	Vehicles/Year

Variable name	Equation / Value	Units
Mature ICEV fleet(t)	Mature ICEV fleet(t - dt) + (ICEV aging rate - ICEV discards) * dt	
INIT Mature ICEV fleet	INIT ICEV fleet*(1-INIT proportion of Young to Mature ICEVs)	Vehicles
INFLOWS:		
ICEV aging rate	Young ICEV Fleet/ICEV time as young	Vehicles/Years
OUTFLOWS:		
ICEV discards	Mature ICEV fleet/ICEV time as mature	Vehicles/Years
NATIONAL VEHICLE MARKET GROWTH, HISTORICAL AND FORECASTS NORWAY	64700	Vehicles/Year
ONE	1	Dimensionless
Park&Charge Points(t)	Park&Charge Points(t - dt) + (building rate of park&charge points) * dt	
INIT Park&Charge Points	INIT BEV fleet*conversion factor cars to plugs	charging points
INFLOWS:		
building rate of park&charge points	park&charge points planned/time to build park&charge point	charging points/Years
park&charge points planned	(desired park&charge points-Park&Charge Points)*fitness of grid*available resources	charging points
POWER PRICES	GRAPH(TIME)	Kroner/kWh
private investment coverage	BEV total market share	Dimensionless
public park&charge points	Park&Charge Points/2	charging points
reference ICEV attractiveness	1	Dimensionless
reference number of gas stations NORWAY	1580	stations
reference time to perceive	10	Years
relative BEV attractiveness	effect of relative cost on attractiveness*effect of performance on attractiveness	Dimensionless
sensitivity of vehicle performance to CS requirements	0,5	Dimensionless
time to build park&charge point	2	Years
time to perceive change in attractiveness	reference time to perceive/confidence in BEV	Years
total BEV fleet	Young BEV Fleet+Mature BEV fleet	Vehicles
total exposure to BEV	BEV total market share+information campaign	Dimensionless
total ICEV fleet	Mature ICEV fleet+Young ICEV Fleet	Vehicles

Variable name	Equation / Value	Units
TOTAL POPULATION, HISTORICAL AND FORECASTS NORWAY	GRAPH(TIME)	People
total publicly accessible charging points	public park&charge points + "Fast On-road Charging Stations"*conversion factor stations to points	charging points
years set to achieve infrastructure goal	7	Years
Young BEV Fleet(t)	Young BEV Fleet(t - dt) + (BEV new sales rate - BEV aging rate) * dt	
INIT Young BEV Fleet	INIT BEV fleet*INIT proportion of Young to Mature BEVs	Vehicles
INFLOWS:		
BEV new sales rate	market pool*BEV Sales Share	Vehicles/Year
OUTFLOWS:		
BEV aging rate	Young BEV Fleet/BEV time as young	Vehicles/Year
Young ICEV Fleet(t)	Young ICEV Fleet(t - dt) + (ICEV new sales rate - ICEV aging rate) * dt	
INIT Young ICEV Fleet	INIT ICEV fleet*INIT proportion of Young to Mature ICEVs	Vehicles
INFLOWS:		
ICEV new sales rate	market pool*ICEV sales share	Vehicles/Years
OUTFLOWS:		
ICEV aging rate	Young ICEV Fleet/ICEV time as young	Vehicles/Years

VEHICLE COSTS

Variable name	Equation / Value	Units
"net price of ICEV incl. emission tax"	base price for ICEV+emission tax NORWAY	Kroner
annual cost of congestion	500	Kroner/Year
annual cost of ferry	1000	Kroner/year
annual driving range	12500	Kilometers/Year
annual ICEV refueling costs	liters consumed per year*.ICEV FUEL PRICES	Kroner/Year
annual operational costs for BEV	BEV cost of recharging + BEV cost of ferry + BEV cost of road tolling + BEV cost of parking + BEV Cost of Travel Time + BEV circulation tax	Kroner/Year
annual operational costs for ICEV	ICEV cost of refueling+ ICEV cost of ferry+ ICEV cost of parking+ ICEV cost of road tolling + ICEV Cost of Travel Time + ICEV circulation tax	Kroner/Year
annual parking expenses	4000	Kroner/year
annual road tolling expenses	10000	Kroner/year
average kWh consumed per year	BEV energy efficiency*annual driving range	kWh/year

Variable name	Equation / Value	Units
Base Price BEV(t) INIT Base Price BEV OUTFLOWS: price reduction	Base Price BEV(t - dt) + (- price reduction) * dt base price for ICEV*3 (Base Price BEV-0,8*base price for ICEV)/BEV price reduction time	Kroner Kroner/Year
base price for ICEV	300000	Kroner
BEV circulation tax	GRAPH(TIME)	Kroner/Year
BEV cost of congestion	annual cost of congestion*switch for bus lane access	Kroner/Year
BEV cost of ferry	annual cost of ferry*switch for free ferry	Kroner/Year
BEV cost of parking	annual parking expenses*switch for free parking	Kroner/Year
BEV cost of recharging	reference costs of recharging*0,75 + 0,25*reference costs of recharging*switch for free charging	Kroner/Year
BEV cost of road tolling	annual road tolling expenses*switch for road tolling exemption	Kroner/Year
BEV Cost of Travel Time	Cost of recharging time + BEV cost of congestion	Kroner/Year
BEV energy efficiency	Vehicle Performance.Battery Capacity/Vehicle Performance.BEV travel range	kWh/Kilometer
BEV operational costs before policies	annual road tolling expenses+ annual parking expenses+ annual cost of ferry+ annual cost of congestion+ reference costs of recharging+ BEV circulation tax+ Cost of recharging time	Kroner/Year
BEV price reduction time	15	Years
BEV recharging costs per kilometer	reference costs of recharging/annual driving range	Kroner/Kilometer
BEV relative fueling time	Vehicle Performance.BEV recharging time - reference ICEV refueling time	Minutes
conversion factor gram to money	1	Kroner/(g CO_2/ Kilometer/ Vehicles)
cost of minute lost recharging	0,2	Kroner/minute
Cost of recharging time	cost of minute lost recharging*BEV relative fueling time*required rechargings per year	Kroner/Year
emission tax NORWAY	IF(Vehicle Performance.ICEV emission level > 75) THEN (1000*Vehicle Performance.ICEV emission level - 76000)*conversion factor gram to money*scaling factor for emission tax ELSE 0	Kroner
Exemption from purchase tax	0,25*switch for purchase tax exemption	Dimensionless
Exemption from VAT	0,125*switch for VAT exemption	Dimensionless
ICEV circulation tax	3000	Kroner/Year
ICEV cost of ferry	annual cost of ferry	Kroner/Year
ICEV cost of parking	annual parking expenses	Kroner/Year
ICEV cost of refueling	annual ICEV refueling costs	Kroner/Year
ICEV cost of road tolling	annual road tolling expenses	Kroner/Year

Variable name	Equation / Value	Units
ICEV Cost of Travel Time	annual cost of congestion	Kroner/Year
ICEV refueling costs per kilometer	ICEV cost of refueling/annual driving range	Kroner/Kilometer
liters consumed per year	Vehicle Performance.ICEV fuel efficiency*annual driving range	Liters/year
net price of BEV after tax exemptions	Base Price BEV - total tax exemptions	Kroner
net price of BEV including devaluation	net price of BEV after tax exemptions/Vehicle Performance.BEV lifetime	Kroner/Year
net price of ICEV including devaluation	net price of ICEV incl. emission tax/ICEV lifetime	Kroner/Year
ONE	1	Dimensionless
reference costs of recharging	average kWh consumed per year*POWER PRICES	Kroner/Year
reference ICEV refueling time	5	Minutes
relative BEV annual operational costs	annual operational costs for BEV/annual operational costs for ICEV	Dimensionless
relative BEV purchase price	net price of BEV including devaluation/net price of ICEV including devaluation	Dimensionless
relative BEV total cost	relative BEV purchase price*weight on price relative to costs+ (1-weight on price relative to costs)*relative BEV annual operational costs	Dimensionless
required rechargings per year	annual driving range/Vehicle Performance.BEV travel range	1/Year
scaling factor for emission tax	GRAPH(TIME)	Dimensionless
switch for bus lane access	GRAPH(TIME)	Dimensionless
switch for free charging	GRAPH(TIME)	Dimensionless
switch for free ferry	GRAPH(TIME)	Dimensionless
switch for free parking	GRAPH(TIME)	Dimensionless
switch for purchase tax exemption	GRAPH(TIME)	Dimensionless
switch for road tolling exemption	GRAPH(TIME)	Dimensionless
switch for VAT exemption	GRAPH(TIME)	Dimensionless
total tax exemptions	Base Price BEV*Exemption from VAT + Base Price BEV*Exemption from purchase tax	Kroner
weight on price relative to costs	3/4	Dimensionless

Variable name	Equation / Value	Units
VEHICLE PERFORMANCE		
Battery Capacity(t)	Battery Capacity(t - dt) + (change in battery	
INIT Battery	20	kWh
INFLOWS:		
change in battery capacity	(estimated max battery capacity - Battery Capacity)*BEV technological development rate	kWh/year
BEV emission level	2	g CO2/Kilometer/
BEV lifetime(t)	BEV lifetime(t - dt) + (change in BEV lifetime) * dt	
INIT BEV lifetime	5	Years
INFLOWS:		
change in BEV lifetime	IF(gap in lifetime > 0) THEN 2/5 ELSE 0	Dimensionless
BEV Offer	BEV Offer Diversity(t - dt) + (change in BEV	
INIT BEV Offer	1	Models
INFLOWS:		
change in BEV diversity	gap actual and max diversity*rate of product development in automotive industry	Models/Years
BEV recharging time(t)	BEV recharging time(t - dt) + (- change in BEV recharging time) * dt	
INIT BEV recharging time	300	Minutes
OUTFLOWS:		
change in BEV recharging time	(BEV recharging time-min recharging time)*BEV technological development rate	Minutes/Years
BEV technological development rate	0,1	1/Year
BEV travel range(t)	BEV travel range(t - dt) + (change in BEV travel	
INIT BEV travel	30	Kilometers
INFLOWS:		
change in BEV travel range	gap actual and max travel range*BEV technological development rate	Kilometers/Years
Cumulative fleet emissions(t)	Cumulative fleet emissions(t - dt) + (rate of emissions) * dt	
INIT Cumulative fleet emissions	0	g CO2/Kilometer
INFLOWS:		
rate of emissions	total fleet emissions/time factor	g CO2/Kilometer/
effect of charging availability on BEV performance	.average charging station density^sensitivity parameter to difference between platforms[CS density] + 0,1	Dimensionless
effect of relative emission level on BEV performance	relative emission level^(-sensitivity parameter to difference between platforms[emissions])	Dimensionless

Variable name	Equation / Value	Units
effect of relative lifetime on BEV performance	relative lifetime^sensitivity parameter to difference between platforms[lifetime]	Dimensionless
effect of relative range capacity on BEV performance	relative travel range^sensitivity parameter to difference between platforms[travel range]	Dimensionless
estimated max battery capacity	120	kWh
fleet average emissions	total fleet emissions/.fleet size	g CO2/(Vehicles*
gap actual and max diversity	reference offer diversity-BEV Offer Diversity	Models
gap actual and max travel range	reference travel range - BEV travel range	Kilometers
gap in lifetime	max lifetime - BEV lifetime	Years
"gCO2/liter ICEV fuel"	GRAPH(TIME)	g CO2/Liter/ Vehicles
ICEV emission level	ICEV fuel efficiency*"gCO2/liter ICEV fuel"	g CO2/Kilometer/
ICEV emission level HISTORICAL	GRAPH(TIME)	g CO2/km
ICEV fuel efficiency	GRAPH(TIME)	Liters/Kilometer
likelihood of meeting desired diversity	GRAPH(BEV Offer Diversity^sensitivity parameter to difference between platforms[diversity])	Dimensionless
max lifetime	ICEV lifetime*1,5	Years
min recharging time	6	Minutes
ONE	1	Dimensionless
product diversity HISTORICAL	GRAPH(TIME)	Vehicle models
rate of product development in automotive industry	.confidence in BEV/time factor in offer	Dimensionless/ Years
reference offer diversity	100	Models

Variable name	Equation / Value	Units
relative emission level	BEV emission level/ICEV emission level	Dimensionless
relative lifetime	BEV lifetime/.ICEV lifetime	Dimensionless
relative travel range	BEV travel range/reference travel range	Dimensionless
sensitivity parameter to difference between platforms[travel range]	1/2	Dimensionless
sensitivity parameter to difference between platforms[lifetime]	1/2	Dimensionless
sensitivity parameter to difference between platforms[CS density]	1/2	Dimensionless
sensitivity parameter to difference between platforms[emissions]	1/20	Dimensionless
sensitivity parameter to difference between platforms[diversity]	1	Dimensionless
time factor	1	Years
time factor in offer	50	Years
total fleet emissions	.total ICEV fleet*ICEV emission level +.total BEV fleet*BEV emission level	g CO2/Kilometer
weight vector for performance attributes[travel range]	0,3	Dimensionless
weight vector for performance attributes[lifetime]	0,15	Dimensionless
weight vector for performance attributes[CS density]	0,4	Dimensionless
weight vector for performance attributes[emissions]	0,05	Dimensionless
weight vector for performance attributes[diversity]	0,1	Dimensionless

A 2. Value tables

Year	Price of Fuel Kroner/Liter	Price of Power Kroner/kWh	Total Population Norway	Total Population Sweden
2000	9,595	0,8	4491000	8900000
2001	9,23	0,75		
2002	8,29	0,781		
2003	8,645	0,819		
2004	8,505	0,75		
2005	9,26	0,75		
2006	10,565	0,92		
2007	10,255	0,72		
2008	11,73	0,88		
2009	10,87	0,85		
2010	11,905	1,02	4889000	9400000
2011	13,01	1		
2012	13,915	0,81		
2013	13,72	0,88		
2014	14,2	0,84		
2015	13,12	0,82		
2016	12,45	0,919		
2017	14,56	0,912		
2018	14,56	0,9		
2019	14,5	0,894		
2020	14,31	0,887	5435400	10400000
2021	14,13	0,875		
2022	13,88	0,856		
2023	13,75	0,844		
2024	13,63	0,825		
2025	13,5	0,806		
2026	13,38	0,8		
2027	13,25	0,775		
2028	13,19	0,756		
2029	13,13	0,737		
2030	12,94	0,719	5800000	11300000
2031	12,88	0,706		
2032	12,75	0,694		
2033	12,69	0,681		
2034	12,56	0,669		
2035	12,38	0,656		
2036	12,31	0,65		
2037	12,25	0,637		
2038	12,19	0,631		
2039	12,19	0,631		
2040	12,13	0,625	6331400	11900000
2041	12,06	0,619		
2042	12,06	0,613		

2043	12,06	0,606		
2044	12	0,606		
2045	12	0,606		
2046	12	0,606		
2047	12	0,6		
2048	11,94	0,6		
2049	11,94	0,6		
2050	11,94	0,6	6700000	12400000

A 3.   Model structure for BuyBack policy (chapter 5.5)

The model structure is illustrated in Figure 69 below. The only modification from the original structure is that an additional flow depletes the stock of Mature ICEVs, and this flow is also added in the equation for expected replacements.
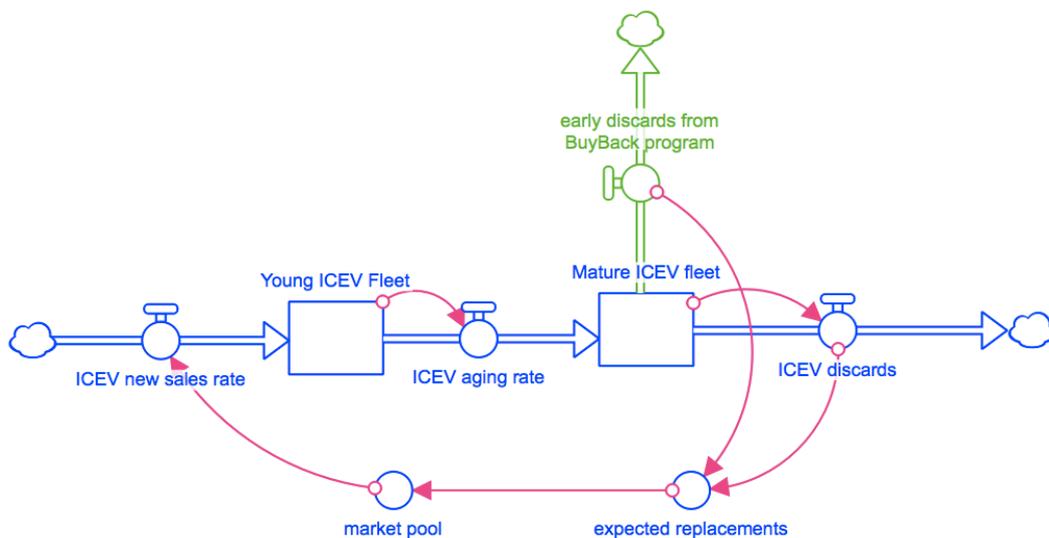
Figure 69. Simplified model structure for inclusion of BuyBack policy

B. Model validation

The tests performed to validate the model are based on the work by Forrester and Senge (Forrester & Senge, 1979) and Barlas (Barlas, 1996). They describe a variety of tests to increase confidence in system dynamics models; these include tests of model structure and model behaviour.

B 1.   Dimensional consistency

The consistency of the units in the model is an important criterion to evaluate the quality of the model structure. In the present case, both variables of tangible and non-tangible nature have been included, so that this test is even more important to assure that only "meaningful" variables have been included. This test is especially directed to rate variables. This validation process is performed first in a theoretical fashion, and then through software functionalities. All variables dimensions have been specified and consistency checked against software check function.

B 2.   Extreme conditions

"Structure in system dynamics models should permit extreme combinations of levels (state variables)" (Forrester & Senge, Tests for building confidence in system dynamics models, 1979). In the system under consideration, there are multiple variables which can be analysed in function of their extreme values, both stock, rate and independent parameters. Here the discussion and the test simulations are presented.

Test 1: Relative BEV attractiveness and indicated BEV sales share

If the relative attractiveness of the BEV does not grow, in other words costs and performance do not improve, the indicated sales rate is expected not to increase, and thus not the actual sales share either. The model seems to react as expected, as shown in the figure below.
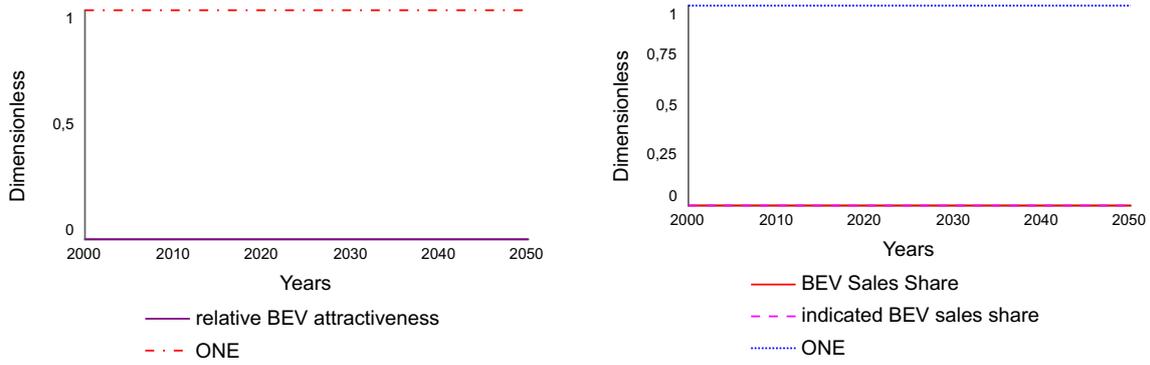
Figure 70. Extreme condition test on relative attractiveness

Test 2: Confidence and BEV sales share

If the confidence is null, the actual sales share is expected not follow the indicated sales share. The indicated sales share, on the other hand, will grow as a consequence of increasing attractiveness. If the confidence is very high, sales share shall be very near to indicated sales share. The figures below show that the model follows the expected behaviour.
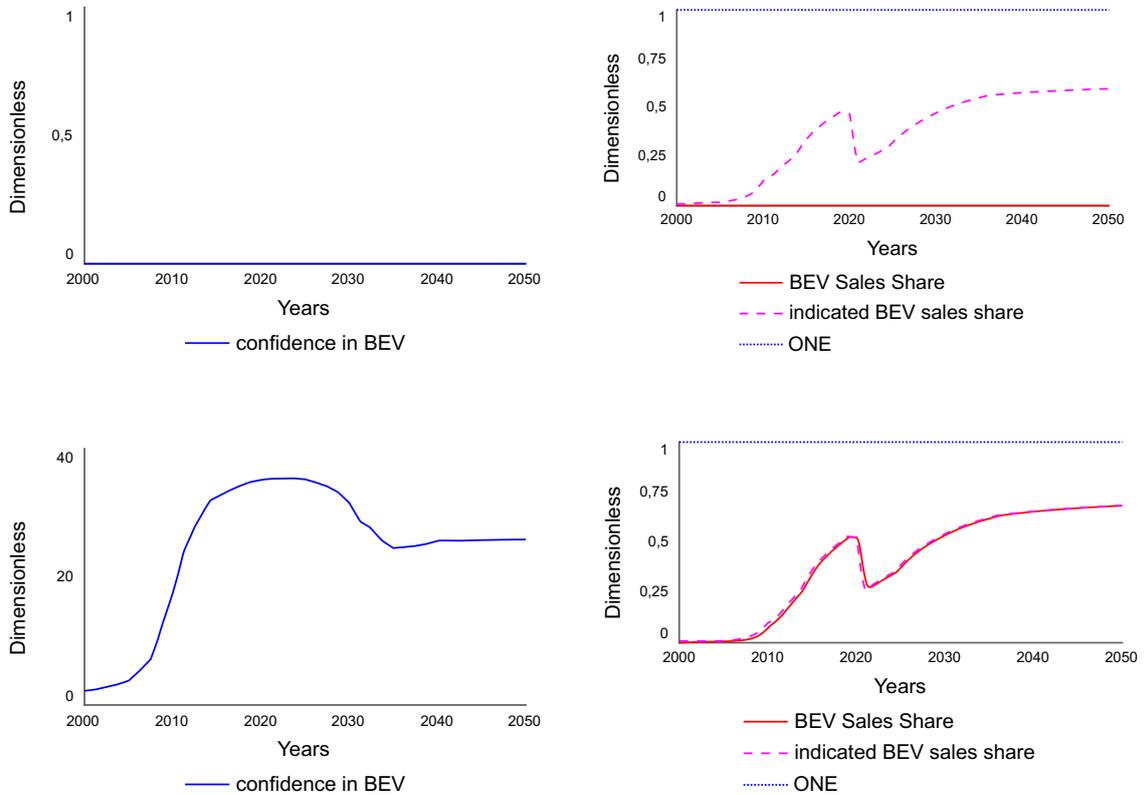

Figure 71. Extreme conditions test on confidence

Test 3: Drivers of charging infrastructure development

The development of charging infrastructure is driven by a number of factors: the need for charging stations, the fitness of the grid, and availability of resources. All of these conditions have to be in place contemporarily in order to allow construction. In this test, each will be set to zero, ceteris paribus, and the building rate of charging stations will be assessed; this is expected to remain zero. The simulation results show the expected behaviour.
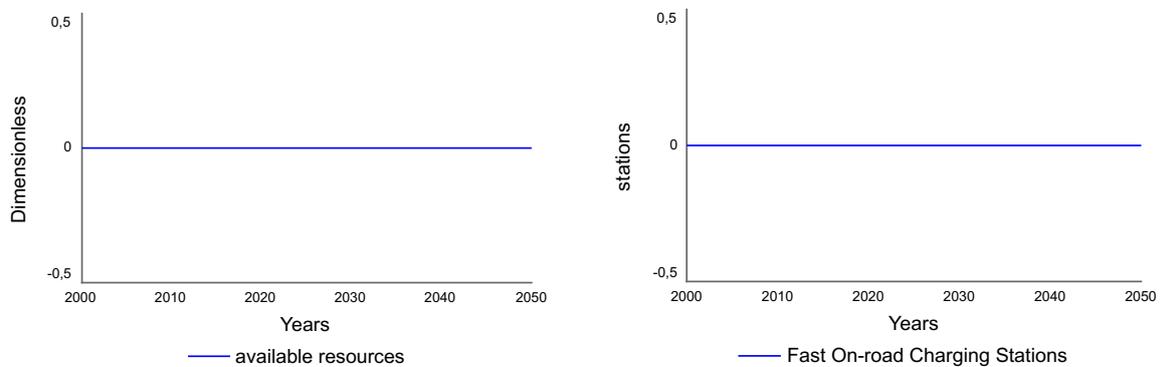
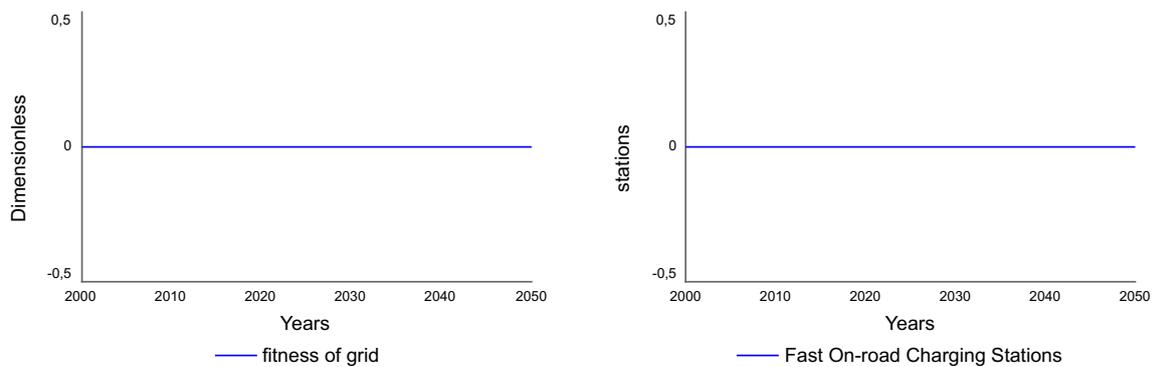*Figure 72. Extreme condition test on available resources*

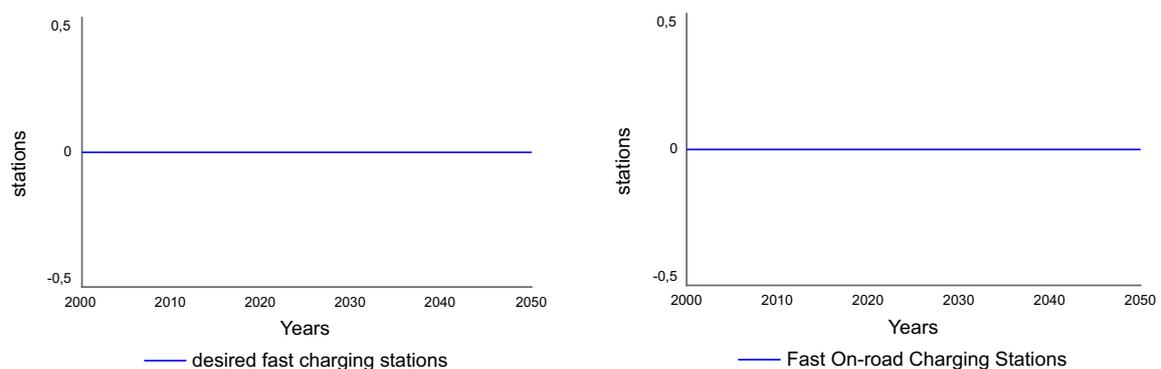*Figure 73. Extreme condition test on fitness of grid*

Figure 74. Extreme condition test on desired stations

167

Test 4: Vehicle lifetime and replacements

ICEVs and BEVs are discarded after their respective lifetimes have passed. At that point, the model simulates that discards are replaced with new vehicle purchases. The longer lifetimes, the longer it will take before a new purchase choice between ICEV and BEV is made, and hence the system will transition to a different state at a slower rate. If instead the lifetimes are shorter, the system is expected to be very reactive to changes in consumer preferences. The lifetime determines therefore the rate of change in the fleet share of ICEVs and BEVs. This extreme test will set the lifetime of BEVs and ICEVs first to 1 year and then to 30 years, and the effect of these modifications on the growth in BEV market share will be evaluated, to see if the system reacts as expected. This is shown in the figure below. The system reacts as expected.
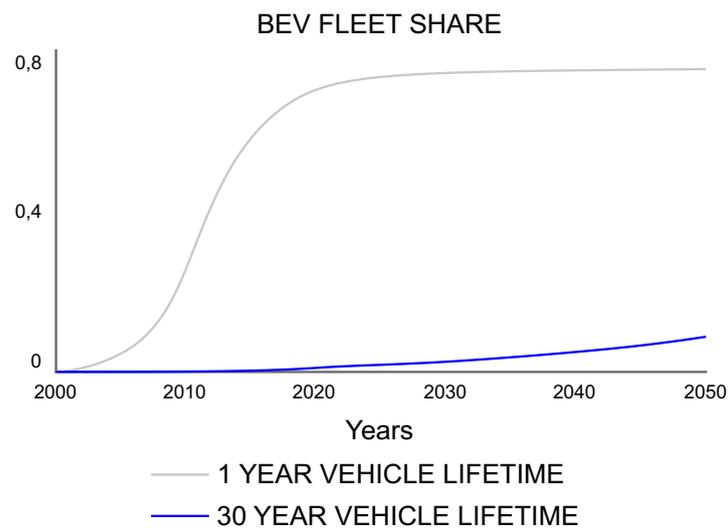

Figure 75. Extreme condition test on lifetime

Test 5: 200 years simulation time

As a last test on extreme conditions, the simulation time will be increased from 50 to 200 years. To pass the test, the model cannot show counterintuitive behaviour.

The figures below show the test simulation results for a series of key variables. Average charging station density reaches a steady state in the long run; relative costs and relative performance as well. Therefore, the sales share becomes constant over time, and so does the market share. Since the population is assumed to grow over time, the fleet also grows. With constant sales shares, the BEV fleet will continue growing, while the ICEV fleet will stop the decay behaviour observed until 2050, and grow at the same rate as the total fleet, keeping a constant fleet share.

The simulation shows that the model behaves in the expected behaviour. This brings further confidence in the model.
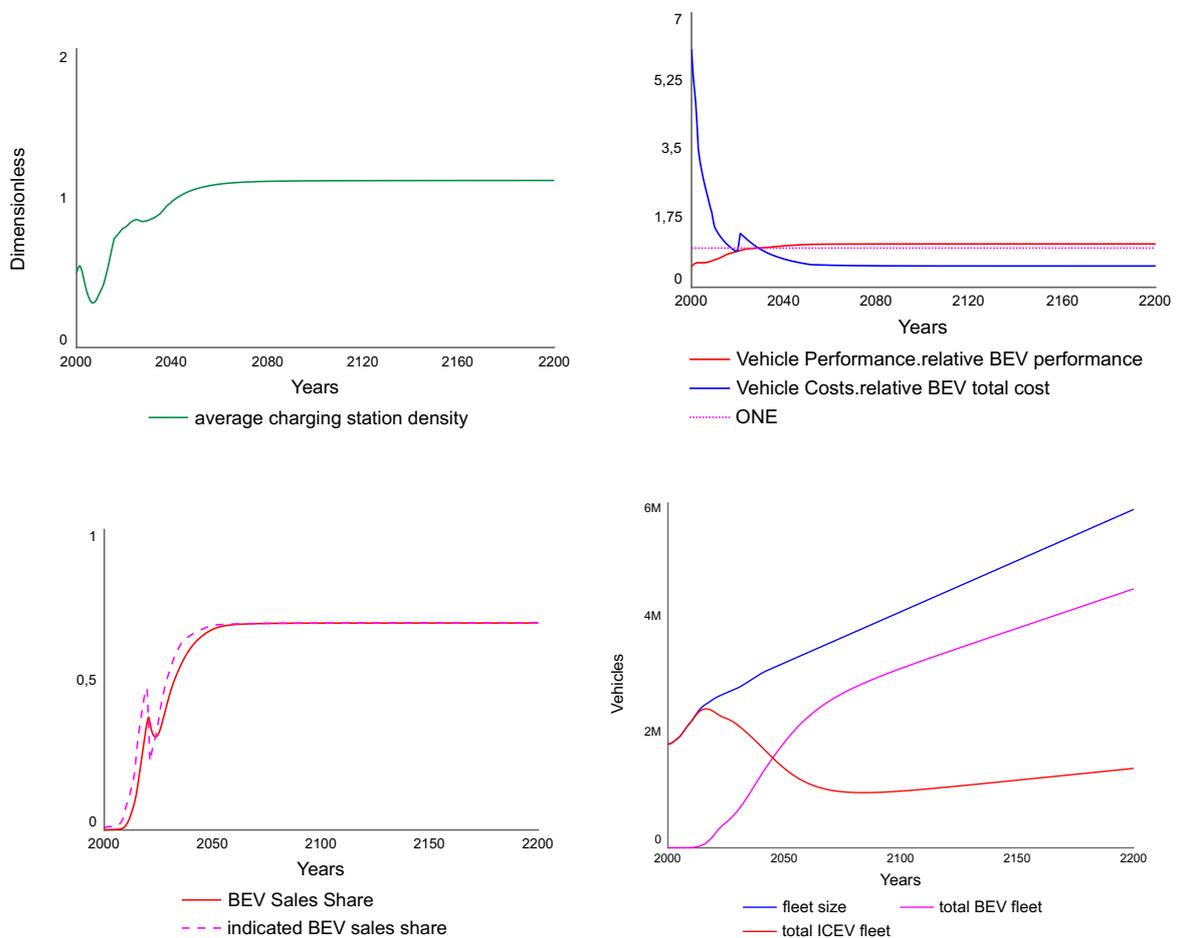

Figure 76. Extreme condition test on simulation time

B 3.   Boundary adequacy

Boundary adequacy is a test of both model structure and model behaviour. "As a test of model structure, the boundary-adequacy test involves developing a convincing hypothesis relating proposed model structure to a particular issue addressed by a model" (Forrester & Senge, 1979). This has been discussed in chapter 4.1.1, where the choice of model boundary was presented. Questions of model boundary mask a deeper question of model purpose; hence, the discussion on the limitations of the model extends on the validity of the model boundary (chapter 6.4). As a test of model behaviour, the test aims at evaluating whether the model includes the necessary structure to address the purpose; additional structure that might influence the behaviour of the model must be conceptualized; the behaviour with and without this structure must be analysed.

This procedure has been performed over the iterative process of building the model; many model versions have been built, analysed and discarded for better versions. Contemporarily, access to data has been a determinant and limiting factor in the choice between an endogenous and an exogenous parameter description.

The model presented in this text is believed to include the most adequate boundary to fit the purpose, given the available time and resources.

B 4.   Structure and parameter verification

Structure and parameter verification are interrelated, as they aim to fulfil the same objective: the model should strive to describe real decision-making processes (Forrester & Senge, 1979). "Verifying structure means comparing structure of a model directly with structure of the real system that the model represents" (Forrester & Senge, 1979). Structure and parameter verification are done in a first phase based on the model-builder's personal knowledge; in a second phase, criticism from specialists in the field should be included. In the present research, repeated confrontations with members of the ETO group (DNV GL, 2017) and with supervisors has supported in this function.

The construction of the model has followed this verification principle throughout the construction process, always trying to define variable relations and values that were most near to reality. This process has been described through chapters 3 and 4. In some cases, however, the lack of knowledge or the choice to illustrate some mechanism in a simplified way, has obliged to depict causal relations between the system variables with a nature of simplification, that can at points be interpreted as oversimplification. This has also been discussed in the chapters mentioned.

There is one specific aspect of the model structure that could have been defined differently, if a different understanding of reality had been chosen: the definition of indicated sales share. The indicated sales share is defined by relative costs and relative attractiveness. The confidence in the BEV, and hence the reinforcing mechanism Word of Mouth, does not influence the indicated sales share but only impacts the speed at which actual sales share approaches indicated sales share. The equations for relative BEV attractiveness and indicated BEV sales share are shown below, together with the structure (Figure 77).

- *relative_BEV_attractiveness = effect_of_performance_on_attractiveness* effect_of_relative_cost_on_attractiveness*

- *indicated_BEV_sales_share = relative_BEV_attractiveness /
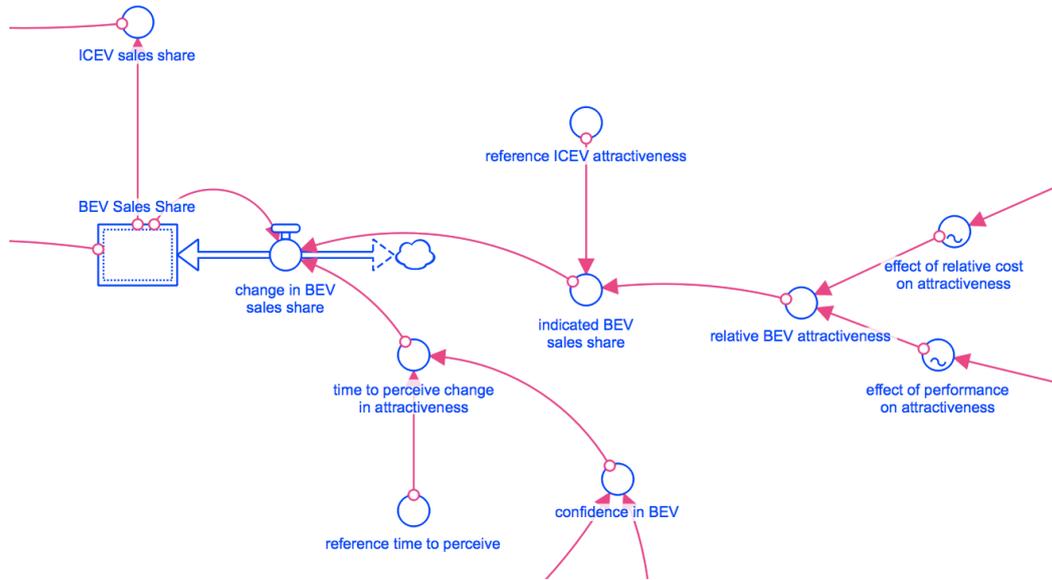 (relative_BEV_attractiveness + reference_ICEV_attractiveness)*

Figure 77. Original structure for indicated BEV sales share

The indicated sales share could have been alternatively defined by including relative confidence in BEV in the definition, as illustrated in the figure below (Figure 78). The variable time_to_perceive_change_in_attractiveness is now exogenously defined and constant. The equation becomes the following:

*Indicated_BEV_sales_share = relative_BEV_attractiveness * confidence_in_BEV /*

*(relative_BEV_attractiveness * confidence_in_BEV + reference_ICEV_attractiveness)*
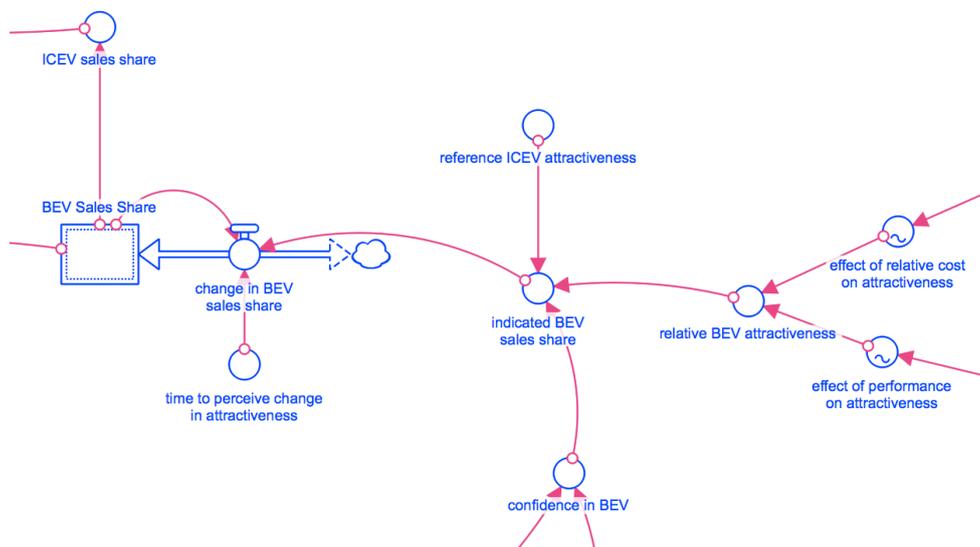

Figure 78. Alternative structure for the definition of indicated BEV sales share

This new structure includes the reinforcing feedback loop Word of Mouth in the definition of the indicated sales share. The simulations shown below, ceteris paribus, show that the

alternative definition causes two main differences: firstly, the sales share is higher the further in time we go, and doesn't converge towards a steady state as in the original behaviour; secondly, the actual sales share grows with a more continuous behaviour, less impacted by changes in attractiveness. Hence the Word of Mouth loop has a reinforcing effect on the growth in BEV sales. The actual sales share follows the indicated sales share with a constant delay time of 10 years; therefore, it is less reactive to volatility in BEV attractiveness.
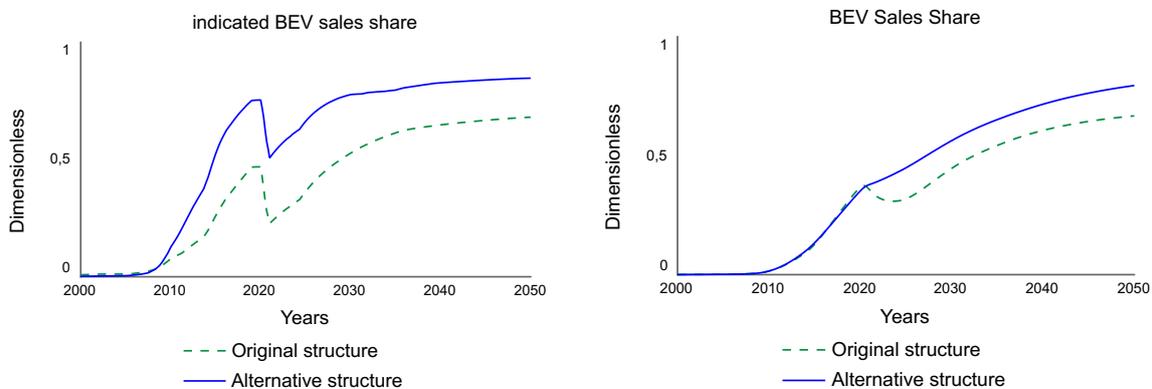

Figure 79. Indicated (left) and actual (right) BEV sales share under original and alternative model structure

The alternative definition of model structure for indicated sales share opens for a more important role of the Word of Mouth reinforcing loop and eliminates the endogenous definition of perception time. The effect of this is that sales are larger and accelerated in the long run. However, the present study takes the position that perception time on vehicle attributes can change over time, driven by exposure- as discussed in chapter 3.4. Hence, alternative model structures for indicated sales share bring a different interpretation of the dynamics of the system than the one advocated in this study. The structure test performed is considered to bring further validation to the choice of model structure.

B 5. Behaviour reproduction tests

There is a family of tests for behaviour reproduction, which examine how well the behaviour generated by the simulation matches with real-life behaviour: symptom-generation, frequency generation, relative phasing, multiple mode, and behaviour characteristic. The tests symptom-generation and multiple-mode have been selected here.

Symptom-generation stands for the recreation of symptoms that are of interest in the study. This is the growth in the BEV fleet in Norway and Sweden during the period 2000- 2016. This has been discussed in chapter 5.1, where the simulation was compared with historical data.

The multiple-mode test considers whether a model is able to generate more than one observed behaviour. In the present study, the same model has been applied to two different contexts corresponding to two national settings; specific variables and structure formulations have been contextualized, as presented in section 4.4. As presented in chapter 5.1, the model is therefore able to generate multiple observed behaviours with a satisfactory degree.

B 6. Sensitivity Analysis

Sensitivity analysis is based on the instructions given in Barlas (Barlas, 1996). The analysis aims at identifying the sensitive parameters within the model's structure and thereby assessing the robustness of the model. The sensitivity of the model shall match with the sensitivity of the real system. This is especially useful for model parameters that are qualitatively and not objectively assessed, as for example sensitivity parameters, delay times, and graphical functions. In this section, four main variables under the mentioned categories and from different model sectors will be analysed.

Sensitivity analysis 1

The weight vector for performance attributes has been estimated on the basis of literature review, in particular from consumer surveys (Sierzchula, Bakker, Maat, & can Wee, 2014; Thiel, Alemanno, Scarcella, Zubaryeva, & Pasaoglu, 2012). The weights could however be different from what has been chosen (see Table 5. Ranking of performance attributes and assigned weights). In fact, these weights will probably change over time, as different adopter profiles are considered.

In the following sensitivity analysis, six alternative weight allocations are explored, and the effect of this on BEV relative performance, relative attractiveness and sales share will be analysed. The denomination W will be used to describe the weight vector function, where the function dimensions are charging availability, travel range, lifetime, diversity and emission level, in this order. The five weights shall always sum up to one.

    Base case: W(0.4, 0.3, 0.15, 0.1, 0.05)

    Test 1: equal weight to all attributes. $W = (0.2, 0.2, 0.2, 0.2, 0.2)$

    Test 2: opposite ranking from base case. $W = (0.05, 0.1, 0.15, 0.3, 0.4)$

    Test 3: all weight to travel range and diversity, no importance to other attributes. $W = (0.0, 0.5, 0.0, 0.5, 0.0)$

    Test 4: all weight to emissions. $W = (0.0, 0.0, 0.0, 0.0, 1)$

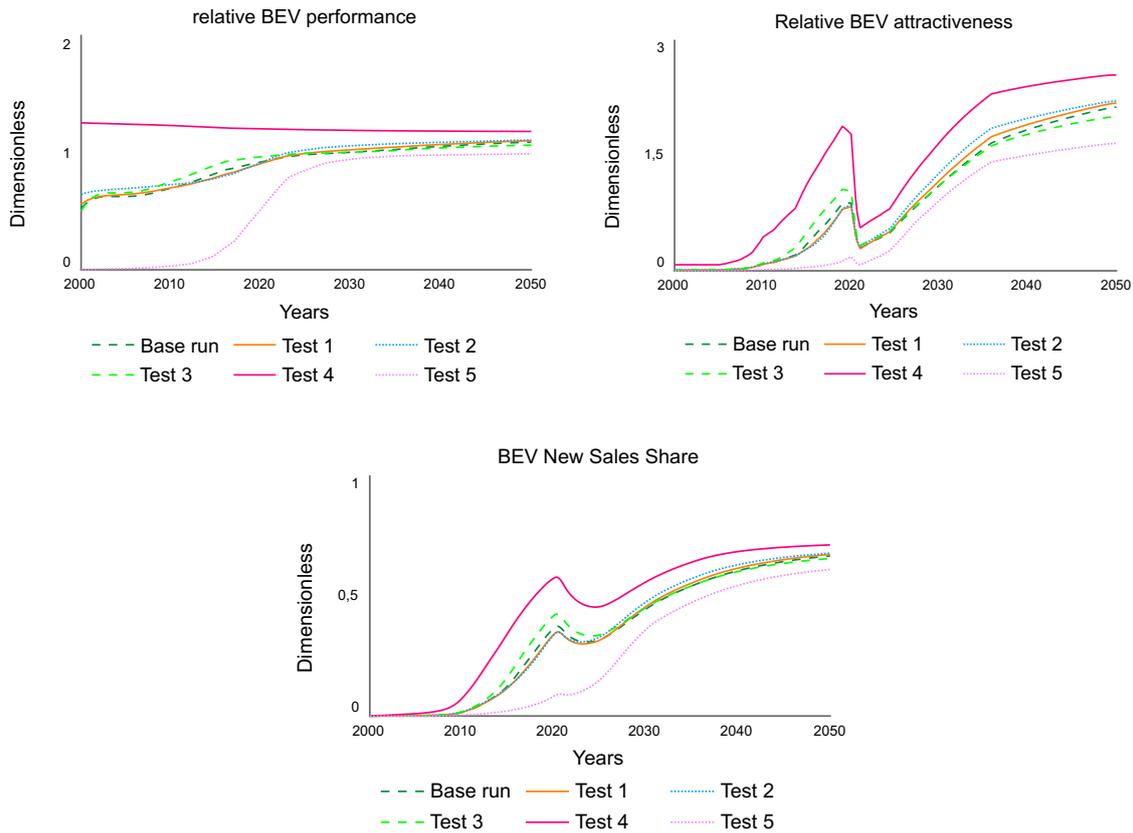**Test 5**: all weight to diversity. $W = (0.0, 0.0, 0.0, 1, 0.0)$

Figure 80. Sensitivity analysis on weights for performance attributes

It can be seen that allocating weights differently to the five weights can bring a large degree of variation in the relative performance, in particular if some of the attributes are ignored (as in the case of Test 4 and 5). The variation is smaller in the cases that all attributes are considered, even if different weights are allocated. Different values of relative performance translate in some degree of variation in the relative BEV attractiveness, which in turn defines BEV sales share. In the case that only emissions are considered as a parameter of performance, the sales share is higher at all times of simulation; if diversity is considered, the sales share is lower. It must be taken into consideration that the BEV diversity is an endogenously defined parameter, which is driven by confidence in a reinforcing loop (a Chicken & Egg dynamics); while emissions are exogenously defined. Hence, in Test 5, the sales share grows at an even slower rate because the reinforcing acts in a vicious direction.

It can be concluded that, as long as all attributes are considered in the weight allocation, the model is not highly sensitive to variations in the weights. It is when more than one attribute is ignored, that relative performance obtains considerably different values.

Sensitivity analysis 2

Little information could be found in the literature on the value of the time to build park&charge points. The value of 2 years is a personal assumption. This time depends not only on construction time but also on a range of uncertain factors such as planning time, availability of information about site of installation, time to receive permission to build, and more. Hence, the variability of this time can be large. In this sensitivity analysis, the time variable will be changed from 1 month to 15 years, and the effect on relative BEV attractiveness and BEV new sales share will be observed. It is expected that relative attractiveness will decrease, and so also sales share.
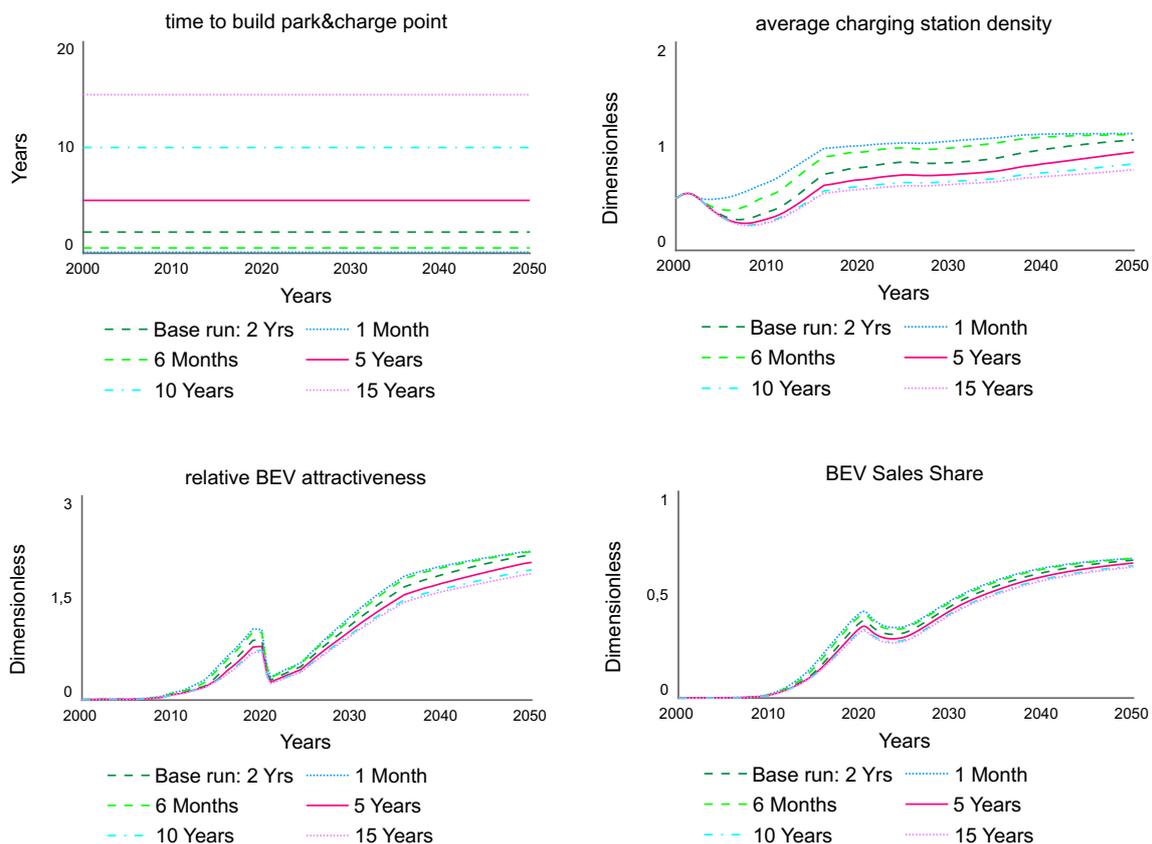

Figure 81. Sensitivity analysis on time to build charging points

The figures above show the effect of changes in building time on charging point density, relative BEV attractiveness and BEV sales share. The simulations show that the expectations are met: as the time needed to build a charging point grows, the density is lower, the relative attractiveness decreases, and the BEV sales share is lower. A longer construction time impacts therefore the confidence in the BEV, and this causes resources to construction to grow at a lower rate: the reinforcing loop Chicken& Egg in infrastructure loses momentum.

Even though the time to construct varies from 1 month to 15 years, the sales share does not show high sensitivity to this variation. This is in part due to the fact that BEV sales share is determined by both costs, performance and confidence; also, charging station density is one of 5 attributes determining performance. Hence the model shows response, but not high sensitivity, to changes in this time variable.

Sensitivity analysis 3

The last sensitivity analysis that will be presented here takes into consideration the graphical function illustrating the effect of relative BEV cost on BEV attractiveness. A parallel analysis can be done for the effect of relative BEV performance which will bring to similar results, and is therefore omitted here. Already in the scenarios, two alternative formulations of this function were explored (see chapter 5.4). In this chapter, the sensitivity of the model with respect to this variable will be analysed for six different effect curves. Different effect functions correspond to different levels of sensitivity, or reactiveness, that the consumer has to changes in relative costs. A consumer group may for instance be weakly influenced by marginal improvements in BEV costs depicted; another consumer group may instead be very reactive to savings in costs. These differences may be context-dependent, related to the spatial location or to the consumer group. The six different effect functions are depicted in Figure 82: Base run and Effect 2 correspond to the first group, while Effects 3, 4, 5 and 6 to the second, with different degrees of sensitivity. The indifference point (1, 1) is kept for all alternatives, as well as the S-shape, following Prospect Theory.

The figures below show the impact of different effect functions on relative attractiveness and on BEV sales share. The relative attractiveness grows as the effect function expresses higher and higher sensitivity to marginal changes. The BEV sales share shows a strong sensitivity to changes in effect functions in the long-run, and less so in the short-run. This is due to the fact that BEV sales share is defined by indicated sales share and confidence in the BEV; in the first years of the simulation, confidence is low, and hence sales share grows slower than indicated. In the long run however, the indicated sales share and actual sales share are very near, reflecting more directly the relative BEV attractiveness.

It is interesting to observe that the BEV sales share never reaches the value 1, given the model formulation and under the tested effect functions. As discussed in earlier chapters, this is due to how the indicated sales share is defined: the ratio of relative BEV attractiveness to the sum of relative BEV and ICEV attractiveness. The indicated sales share cannot reach exactly the value 1 unless relative BEV attractiveness achieves values near to infinity, which is unrealistic

and should therefore not be included in the model. An alternative to this is discussed in the structural test section (B 4): the definition of indicated sales share could be modified in different ways, applying alternative functions (such as the exponential function), or including additional inputs (such as BEV confidence).
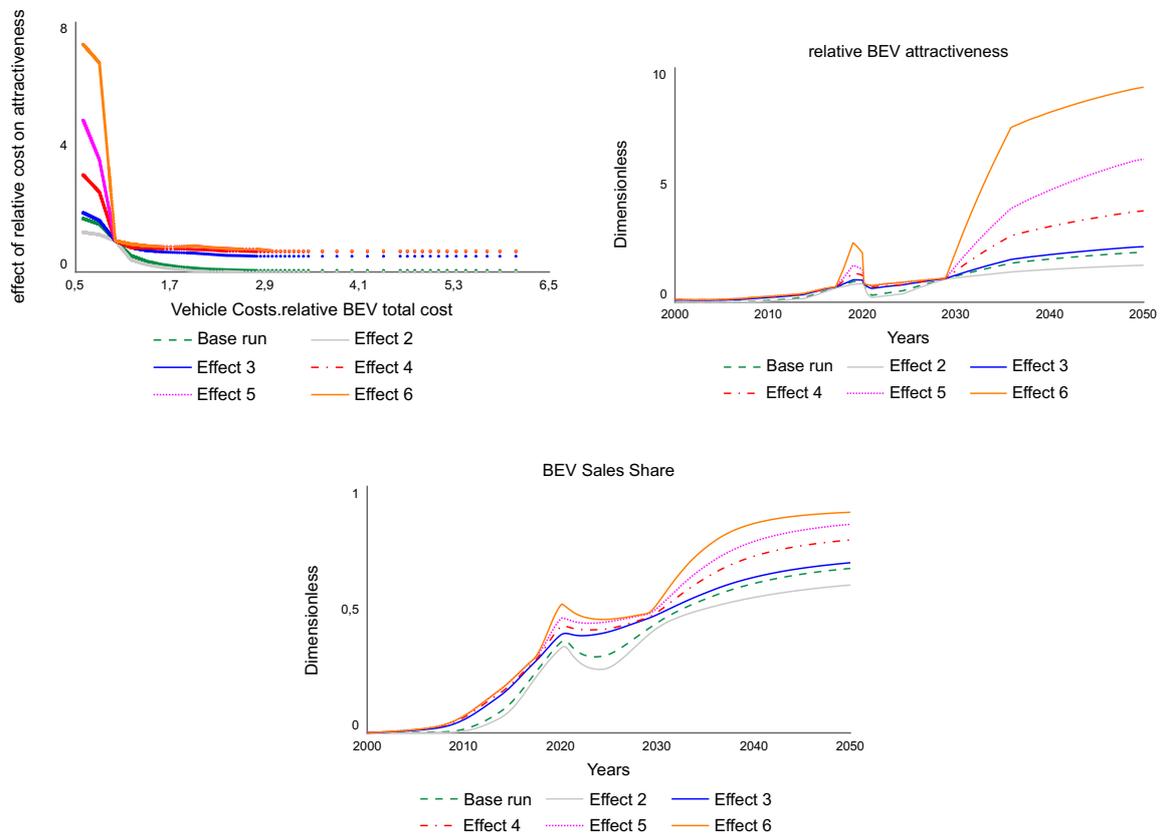

Figure 82. Sensitivity analysis on effect of relative BEV cost on BEV attractiveness.

Sensitivity analysis 4

The last parameter that is considered for sensitivity analysis is the graphical function of information campaign/media coverage. The variable is an important component of the reinforcing feedback loop Word of Mouth, because it "magnifies" the exposure from the BEV fleet. Potential buyers are exposed to the BEV through direct presence of BEVs in the streets, but also by newspapers, social media, research topics, television and similar. This is also a highly uncertain variable that is not based on empirical data, but on a qualitative assessment by the author. The fading nature of policies and media coverage is taken into consideration, as well as some a qualitative evaluation of the media coverage, based on found online sources. A factor that is not taken into consideration here is the fact that this variable can vary greatly across

space and across consumer groups: Drivers living in rural areas are probably less exposed to the media coverage on the BEV topic than an urban settler.

In this analysis, the graphical function for information campaign will be altered, and the effect of this alteration on the variables time_to_perceive_change_in_attractiveness and sales share is studied. Figure 83 shows the simulation results. It can be seen that the time to perceive does indeed vary considerably, spanning from few months, when the policy is at 1 throughout the simulation, to 70 years, when the policy is constant zero. The BEV sales share responds to this perception time accordingly: even though the indicated sales share does not change considerably from run to run, the speed at which the actual sales share converges towards this value is very different. Hence, in case of very low exposure, the BEV sales share in 2050 can be half the size of the sales share derived from very high exposure. The indicated sales share is different for each simulation because of the feedback effect of BEV sales share on confidence, which in turn impacts relative performance. However, the indicated sales share is not considerably influenced, as instead in the case that the effect function is changed (as is done in the sensitivity Test 3). The effect of varying the policy information campaign is dampening, rather than accelerating.
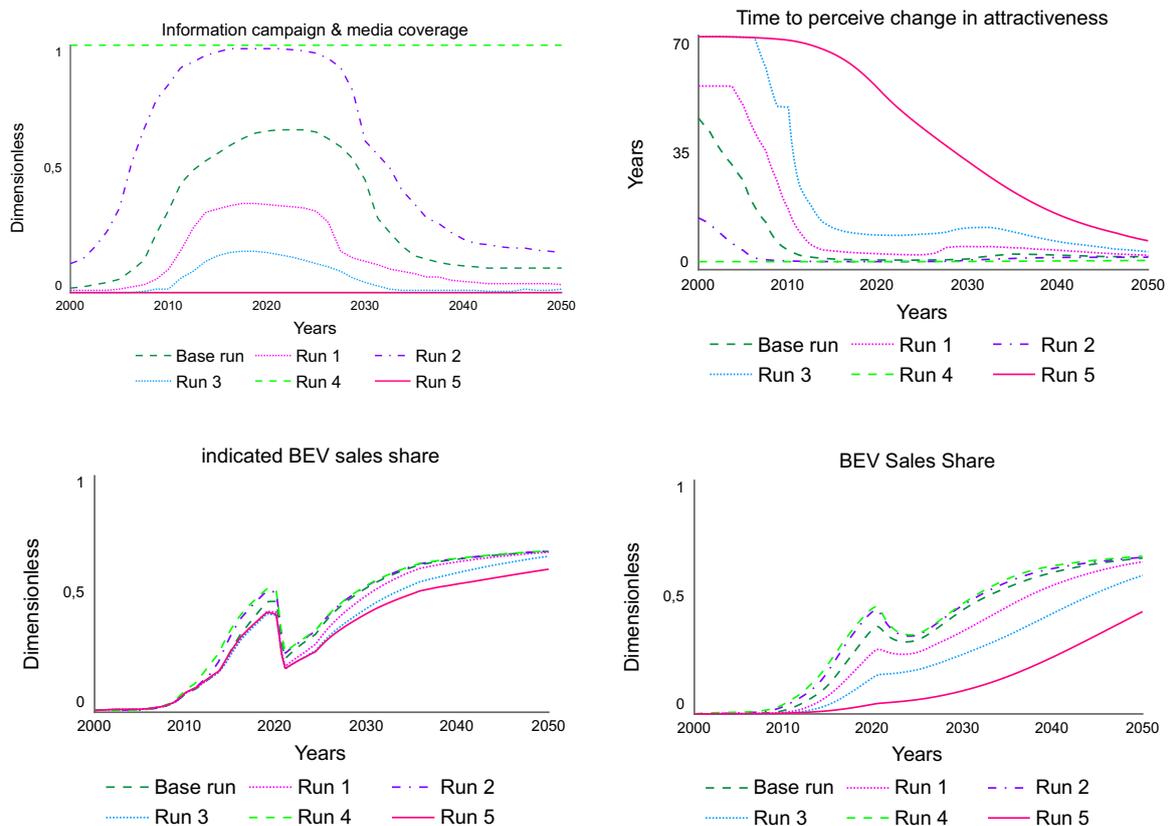

Figure 83. Sensitivity analysis on information campaign parameter

178

C. How green is the BEV?

The choice of electromobility as main strategy for a greener transportation merits careful consideration: light passenger EVs contribute to congestion, noise, and the number of accidents. A larger vehicle fleet, whether electric-driven or fossil fuel-driven, also demands more parking space in the urban areas, road construction and maintenance. Sustainable urban planning aims at developing a daily life where the use of public transport, bikes and foot covers most mobility needs of the citizens (Norwegian Department of Transportation, 2017). EVs, on the other hand, contribute to a range negative environmental impacts and sustainability challenges such as GHG emissions, decreased air quality and noise pollution. In addition, the transition needs to be sustainable and green over the whole production line, starting from the generation of power (Prud'homme & Koning, 2012). Switching to EVs means a higher demand on the power supply system. No substantial reductions in GHG or in oil consumption will be achieved until power generation is low carbon. This is nowadays so for countries with richness in renewable energy, such as Sweden and Norway. In the US however, as in much of the rest of the world, two-thirds of all electricity is generated from fossil fuels. Finally, the production of batteries for EVs contributes to the depletion of rare resources and represents a challenge in terms of recycling after last use. From a life-cycle perspective, the EV does not seem to bring extensive contributions to the transportation system of the future and may in fact counteract a shift towards more sustainable lifestyles.

There are, on the other side, many factors indicating that electromobility may bring considerable benefits in the long term. Cheap and clean electricity generation is expected to increase significantly in the short term due to rapid technological development and worldwide extensive incentives in solar and wind power (International Energy Agency, 2016). While emissions may not be significantly reduced from a life-cycle perspective, EVs do not present pipe emissions. Local air quality can therefore be improved, especially in high density urban areas (Krzyzanowski, Kuna-Dibbert, & Schneider, 2005). In the special case of the Norwegian EV policy, the government has estimated that, if the established targets are reached, emission cuts of 5 million tons of CO_2 per year will be possible from 2030. Resource scarcity can be tackled by major improvements in recycling systems and resource substitution.

Population growth and increase in per capita GDP will place growing demand for travelling and comfort. Total CO_2 emissions from the transportation sector are a combined effect of

vehicle efficiency, vehicle fleet size and travel range. Radical shifts in the way mobility works may also be considered, including demand reduction. However, radical modal shifts represent a scenario with a high uncertainty, and are therefore excluded from the present research.