

## MASTER

### A system dynamics model for the adoption process of electric vehicles from a consumer perspective

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Eindhoven, May 2011

**A System dynamics model for the  
adoption process of electric  
vehicles from a consumer  
perspective.**

by  
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A Thesis Submitted to the Faculty of the Eindhoven University of Technology  
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## **Abstract**

Substituting electric vehicles for traditional ones could reduce local pollution and greenhouse emissions from the transportation system. These benefits come at high costs to the owner of the electric vehicle in terms of price, limited driving range, and high refuel (recharge) times. In addition, the usability of an electric vehicle is hampered by the lack of an infrastructure for recharging. Such crucial elements are the result that this ‘new vehicle’ hardly sells itself to potential customers. This paper outlines in a system dynamic model the adoption process of electric vehicle from a consumer perspective and analyses the adoption effect related to these crucial elements. Data used for this research project is conducted by a survey and represents the Dutch passenger vehicle fleet.

## Preface

The report you are about to read presents the results of my graduation project of the master Innovation Management at the Eindhoven University of Technology (TU/e). The building company named Ballast-Nedam, provided me with the challenging job to find out how the development process of the electric vehicle evolves in the upcoming years. At the first moment, I realized this is a very interesting and upcoming technology in the 21<sup>st</sup> century and therefore I decided to go for it. Then the first hurdles started to arise and arise and arise and arise and arise... till that single moment, when I got the idea how to gather my data and transform this is a useful system dynamics model. During this process with ups and downs support from the environment is exactly the right thing you need... and.....

.....therefore, I would first like to thank friends and family for their support and understanding. They formed a firm base and helped me make important choices during my life, and were a valuable recourse during my study career. Second, I would like to thank Kim van Oorschot, my university supervisor, for her support during the whole project. Thank you for the trust, cooperation and support in my work. Besides, I would like to thank my supervisors at Ballast-Nedam, Job van de Sande, Ruud Kos and Erik Kemink, for their support concerning the content of the project. Third, I want to thank my fellow students Chase, Martijn and Jeroen. They were a valuable source for good discussions and debates during the many projects we jointly did. With them, I developed new ways of reasoning that proved to be useful during my graduation project.

Last but not least I want to thank my Brothers' laptop. While halfway the research project my own laptop let me down. Fortunately, I decided to purchase a hard disk before starting the master thesis project and with the help of several backup nothing was lost.

Rests me nothing else than to wish the reader a pleasant time reading my thesis.

Tim Bongard  
Eindhoven, May 2011

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## List of Abbreviations

	Abbreviation
<b><i>Companies</i></b>	
Ballast-Nedam	BN
Boston consulting Group	BCG
Energy research centre of the Netherlands	ECN
International Energy Agency	IEA
Rheinisch-Westfälische Technische Hochschule	RWTH
Toegepast Natuurwetenschappelijk Onderzoekscentrum	TNO
<b><i>Terms</i></b>	
Business to Consumer	B2C
Causal loop diagram	CLD
(Full) Electric Vehicle	(F)EV
Hybrid Electric vehicle	HEV
Internal Combustion Engine	ICE
Internal Combustion Vehicle	ICV
Multi-level perspective	MLP
Original equipment manufacturers	OEM
Plug-in Hybrid Electric Vehicle	PHEV
Stock and flow diagram	SFD
Zero Emission Vehicles	ZEV

## **Executive summary**

Media reports of today mention that millions of electric and plug-in hybrid vehicles make their introduction in the not too distant future. Many original equipment manufacturers (OEMs) proclaim the start of a 'mass' introduction in the year 2011 e.g. GM, Mitsubishi and Renault-Nissan. Respectively, they introduced the Tesla Roadster (first commercial electric sports car), a family car called the iMEV and the Nissan leaf. Triggering the start of the adoption process of the electric vehicle stimulated governments worldwide to set goals for an future electric vehicle fleet e.g Netherlands [1 million by 2025 [Lower House of the Dutch Parliament, 2009]], Germany [1 million by 2020], Canada [500,000 vehicles by 2018] (RETD, 2010). Achieving these goals requires intensive developments in the battery technology, which is related to important elements such as the driving range, purchase price and charging times. Additionally, investments have to be made into the development of a recharge-infrastructure network.

Personal transportation is a crucial element of modern-day society. Technology transitions such as the transition from steam engines to internal combustion engines involve several influential actors. Environmental damages are results of the use of internal combustion engines. Nevertheless, the total system of personal transportation of which the car is part of is running into problems. The depletion of oil is the important one and the resources are to a large extent located in politically unstable regions, which makes it possible that issues about the supply of oil will arise before resources are actually depleted. Because of these political and environmental pressures personal transportation is forced to change over time, one solution is the evolvement of the electric vehicle. Depletion of oil recourses and toxic emissions in urban places can to some degree be solved by introducing the electric vehicle in large numbers. Yet, it is by no means clear when the mass introduction of electric vehicles will take place. Hence the research question of this master thesis:

*'How will the adoption process of electric vehicles develop in the future, and in particular, what key elements influence this adoption process'*

Many institutions present fuzzy results concerning forecasting the development process of electric vehicles. Scenarios are hardly predictable due to the high number of unknown influencing elements, at different aggregate levels in the socio technical system. The top-level or macro-level is defined as the area with 'hardness', because this level includes cities, factories, electric infrastructures and highways. These deep structured elements slowly change and contain factors, such as; 'oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, and environmental problems' (Geels, 2002, pp. 1260). Elements are able to shift the technology in another direction. In example, recharge infrastructure investments might accelerate the usefulness of the electric vehicle, subsidies can be given by the government or emission rules become stricter. Together these macro elements simultaneously increases the attractiveness of electric vehicles and do influence the speed of the adoption process. All together the general trend for electric vehicle deployment is clearly more positive than in the past, unforeseen macro events can be a setback in developments that are not taken into account in most forecasts.

Besides these macro elements also some main competing technologies will improve (e.g. more efficient combustion engines or the introduction of the fuel cell), that might delay or disrupt the transition to electric vehicles. However, from an innovation perspective electric transport has just left the R&D stage and is now in the position to demonstrate its abilities on a larger scale (see figure A). Modelling such adoption process and predict the moment of 'mass adoption' depends on macro elements but also on the products fit with preferences and selection criteria of customers. Ultimately, the success of innovations depends on the acceptance<sup>1</sup> of consumers (Hauser et al., 2006). Willingness to adopt an electric vehicle is for a large part related to the battery properties; battery cost, maximum driving range and recharge time. Automakers worldwide are joining with battery producers to improve the overall performance of the vehicles and are for that reason also a major player in the development process. It seems clear that to get a better picture of the development process the adoption behaviour needs to be looked at more closely (RETD, 2010).

In this master thesis report an analysis is performed about the adoption behaviour of the Dutch population related to four<sup>2</sup> key elements in the electric vehicle<sup>3</sup> development process. Conducting a survey under 388<sup>4</sup> respondents provided their degree of acceptance and combining these values with the expected technology developments an adoption curve is provided by the use of system dynamics modelling program. In figure A, the early markets indicate the start of the mass adoption phase (commercialization) and the occurrence of this moment is an important issue for Ballast-Nedam<sup>5</sup>. In the case of electric driving Ballast-Nedam may benefit from projects concerning the development and placing of the grid-based electric systems. Foreseen a mass adoption is useful for the company's strategic decision making unit.

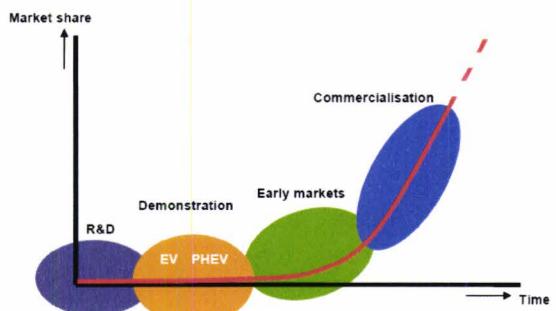


Figure A: electric vehicle adoption process

*'Compared to ICVs, current electric vehicles (EVs) still have disadvantages that make them less attractive. Current battery technology, (1) not allowing unlimited driving ranges, (2) relatively long recharging times and (3) high initial purchase prices are some of the EVs' major disadvantages. In addition, the usability of an EV is hampered by (4) the lack of an infrastructure for refuelling (recharging)'*

Gärling and Thøgersen, 2001

<sup>1</sup> Willingness to adopt an innovation = accepting an innovation (depends on the adoption behaviour)

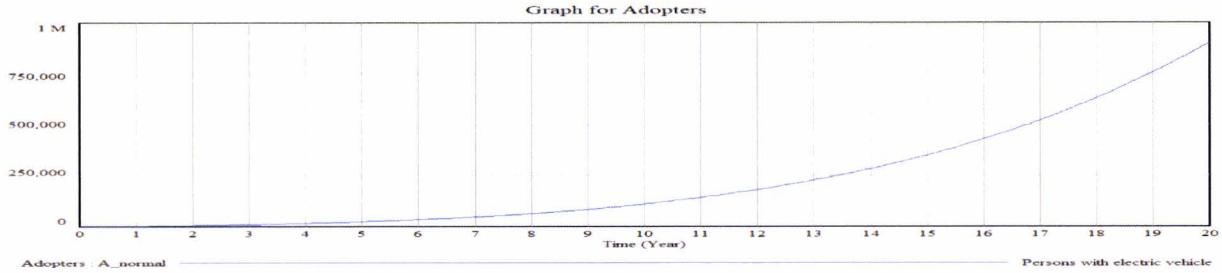
<sup>2</sup> Maximum driving range, purchase costs, recharge infrastructure network, recharge time

<sup>3</sup> Full electric vehicle (no hybrids are taken into account)

<sup>4</sup> N=388 represents the Dutch passenger vehicle fleet.

<sup>5</sup> Ballast-Nedam is a building concern and also the initiator of this research subject.

These four crucial elements defined by Gärling and Thøgersen (2001) form the basics of the total model. The results of this research indicate an total amount of approximately 1 million full electric vehicles of by the years 2030, based on the basic scenario input values and assumption made in this research project.



Above, an exponential growth of the population of Adopters, characterized by a slow but steady growth in the beginning (year 2010-2019), and a large growth in the end (year 2020-2030) is depicted above. The graph shows an early market phase' around the year 2020 and the reason for this is the fact that at that time of moment the specifications of the crucial elements are met with most of the consumer. In this report the reader will be provided with information about the gathering of data by conduction a survey, the selection of the most crucial elements, academic literature about socio-technical systems and technology transition. Furthermore, the reader will be introduced with the adoption and diffusion literature applied on the electric vehicle case. At the end the elements used in the model are extensively discussed and show that price is seen as the most important decision element at the purchase moment.

# **1. Introduction**

## **1.1 Area of research**

### **The world situation**

In these days of the 21st century the energy demand is still increasing. Unfortunately, a part of this energy is produced by fossil sources, such as; oil, natural gas and coals (RETD, 2009). The depletion of these sources is besides the pollution of the air, the major environmental concern of the future. However, the transportation sector plays a fundamental role in this process, and a lot of countries in Europe are occupied with sustainable development policies. For instance, the white book on transports illustrates that the transportation sector is responsible for 30% of the total European Union (EU) energy consumption and this is approximately 71% of the total EU oil use. Moreover, the road transport is responsible for 84% of the CO<sub>2</sub> emission in Europe (Armenia, 2010). This is the reason why there is some political pressure on this sector to become more sustainable. Solutions have to be created, those that can contribute to the solution of these problems especially the depletion of oil reserves. Moreover, the electric vehicle can be one of the solutions and is also beneficial when CO<sub>2</sub> emission reduction is demanded in urban areas. Well, the Netherlands is a perfect ‘playground’ to start pilot projects concerning the electric vehicle (EV). This is because of several benefits embedded in the Dutch location, for instance there are on average short travelling distances, it is densely populated, there is a well constructed road infrastructure and there are governmental financial stimulations for sustainable technologies.

### **The electric vehicle**

The year 2011 is for many companies expected as ‘the year’ of the electric vehicle. Every year new electric cars will be introduced with the result that nowadays dozens of different types of electric vehicles are built. However, there is a distinction between two types of electric vehicles. The first are the so-called plug-in hybrids (PHEV), which combine an electric drive system with a conventional engine and can run on electricity and fuel. Secondly there are full electric vehicles (FEV)<sup>6</sup> which only use electricity from the grid. A few FEVs are introduced already in the Netherlands and even more will be introduced in 2012 and 2013 [1] [2].

From this on it is assumable that the adoption process of the electric vehicle is in its early phases, which makes this an interesting situation for companies. This is because further adoption of the electric vehicle will create new business opportunities in different types of sectors. Before I explain more about the adoption process of the EV which is also related to this research topic, a general introduction is given about the electric vehicle. The very first electric vehicle was built in 1842 in Scotland, with the use of a rechargeable lead battery. Around the beginning of the 19 century, EVs were in the peak of its success. Besides the steam and the ICV, the electric vehicle was very popular and accounted for one third of the vehicle fleet built in those times (Gärling and Thøgersen, 2001). After that, oil was one important copious energy source and in those times better affordable than electricity, more investments were put into the development of ICVs and as a result the ICV made its

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<sup>6</sup>Also referred to as battery-electric vehicles or pure electric vehicles.

lead in the world. Around the 1950s people invented the semiconductor and this stimulated the attention for the electric vehicle. Because of this invention, more technical possibilities came available and were positive for the battery performance. About a decade later in the 1967s a very first emission regulation for vehicles was introduced in California and after that the whole world followed. This stimulated the attention for the electric vehicle again and until the present, several attempts to improve the emission regulations have been taken place.

Nowadays, California still has the leading position in low emission regulations. Automobile manufacturers today are forced to reduce the greenhouse gas emissions of the vehicle fleet and increase the sales of zero emission vehicles (ZEV) (Walther et al. 2010). Next to these regulations which have social benefits, a major technical drawback against an immediate mass adoption of the electric vehicle exists. This is for instance the expensive and not fully optimized battery technology, which allows only a limited driving range. Furthermore, the usability of an EV is held back by the lack of an infrastructure for recharging and in addition the recharge time is high in comparison with an ICV (Sperling 1995). Nonetheless, these technical drawbacks do not influence the adoption process of the electric vehicles on their own. Also elements<sup>7</sup> in the socio-technical system play an important role in the transition process to the electric vehicle.

## 1.2 Company description

Ballast-Nedam (BN) belongs to one of the top five Dutch building concerns. In 2009 BN realized a return more than 1.4 billion euro. On average BN covers approximately 4000 employees, which are located at different departments. These departments can be found in the concern structure depicted below. At the top two divisions are located; building, and development and infrastructure. The point is to have a decentralized entrepreneurial focus in their business units. The course is set up by these two divisions for four different internal companies; BN Concessies, BN Beheer, BN Bouwmaterieel and BN Prefab. My research project is set up by BN Concessies, which are responsible for the development of long term concession projects (Publiek-Private samenwerking [PPS-]). Their core activities are contract management, project management and financial engineering. It is important for BN to gather new information and ideas from external sources. Moreover BN concessions is interested in the developments of the following sectors; accommodation, transport, energy, care, education and leisure time.

## 1.3 Research objectives and context

Ballast-Nedam (BN) has already its focus on the transport sector and provides the infrastructure for the road transport, like complete projects such as; auto ways, natural gas stations, bridges etc. However, in the case of electric driving BN may benefit from projects concerning the development and placing of the grid-based electric systems. This infrastructure system is needed to be able to recharge the electric vehicles across the country. However, the future developments of the electric vehicle sector are still unknown. Analysis about theories and practices associated with the adoption

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<sup>7</sup> Element is defined as an aspect, rule or variable that influences the development of the adoption process of electric vehicles (technology transition process). See also the socio-technical configuration figure in appendix 3.1b (Geels, 2002).

process of the electric vehicle can provide useful future insight. Therefore it is important to know when the mass adoption of the electric vehicle evolves and what kind of essential factors influence this adoption process. Being able to answer this, I established the first general research question of this research project:

RQv1<sup>8</sup>: '*How will the adoption process of electric vehicles develop in the future, and in particular, what elements influence this adoption process'*

Unfortunately it is impossible to analyze all the influential elements in a limited amount of time, so to forecast the adoption process (technology transition) of the electric vehicle, an approximation is provided. Set up research boundaries is a requisite to provide a rigorous research. Academic literature about technology transition distinguishes five different types of regimes each with its own rules. Three of them are selected to make a *first focus* in this research project; (1) the technical & product regime, (2) the policy regime and (3) the user & market regime (Geels, 2004). In the case of the electric vehicle, respectively, the technical specifications of the battery, subsidy programs from the government and user preferences about the new technology are examples of rules in regimes that do influence the adoption process. According to Geels (2004, pp. 916), '*the conceptual perspective of the technology transition to the electric vehicle is fairly complex. Can it be made operational for empirical research? The proof of the pudding is in the eating, i.e. use the perspective for empirical analyses of dynamics of socio-technical systems.*' Meaning there is an abstract representation about technology transitions. Nevertheless, a more empirical version of this process is required and in this research an attempt is made with the assist of a modelling program, 'system dynamics'. This program is a 'method that challenge us all how to move from generalizations (abstractness) about accelerating learning and system thinking to tools and processes that help us to understand complexity, design better operating policies, and guide change in systems (concrete) from the smallest business to the planet as a world' (Sterman, 2000, pp. 4). However, using such a modelling program requires the availability of data. Therefore, a *second focus* of this research project is realized by focusing on the adoption process from the consumer perspective. This again narrows down the research boundaries and makes it possible to collect data by surveys. As a result, the general research question can now become more specific:

RQv2: '*Which crucial elements from a consumer perspective influence the adoption process (purchase moment) of the electric vehicle'*

This question resulted in a selection of elements that are the most deciding in the purchase moment of the electric vehicle. Additionally the magnitude on the adoption process of a certain element is answered by the following research question.

RQv3: '*To what extent do these elements from a consumer perspective influence the adoption process (purchase moment) of the electric vehicle'*

---

<sup>8</sup> RQvx: state for Research Question version x.

Based on the data from the conducted survey the willingness to purchase an EV is analysed and linked to the developments of the key elements in the adoption process of the electric vehicle. After the selection and collection of elements and data, the bass diffusion model is utilized as fundament for the final adoption model. This is a growth model applicable for the timing of consumers' first purchase of a new product and is used as forecasting tool for the diffusion of innovations<sup>9</sup> (Mahajan et al., 1990). The research context concerns the passenger electric vehicle market in the Netherlands, with only the focus on *full electric vehicles*. This focus is made with the purpose to do a better research on the four selected elements, such as; purchase price, recharge time, maximum driving range and recharge infrastructure, which influence the adoption process of the electric vehicle. Since a hybrid vehicle does not have the problems with the recharge infrastructure and maximum driving range at the first hand and therefore the selection is made for the full electric vehicle.

At the end, the *main objective* of this research is to provide a fundamental adoption model of the electric vehicle, including values based on literature and survey data. With this model, different scenarios are simulated to evaluate the impact of the elements that influence the adoption process.

## 1.4 Structure of report

First the abstract representation of technology transitions in relation with the adoption process and the innovation diffusion theories are given in chapter 2. In which also a distinction between the abstract and concrete manner of the electric adoption process is provided. In chapter 3 the research method and design is described which entails the process steps of system modelling. The description of the dynamic modelling including the basic model and the related technical elements are elaborated in chapter 4. The fifth chapter represents the data collection and the results. In chapter 6 different types of scenarios are elaborated and discussed. Finally the conclusion and recommendations of this research with managerial implications are given in chapter 7.

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<sup>9</sup> Innovation is defined as an idea, practice, or object that is perceived as new by an individual or other unit of adoption (Rogers, 2003)

## **2. Literature review**

### **2.1 Introduction**

The world is asking for sustainable technology solutions all to reduce the environmental pollution and depletion of fossil resources. One of the biggest contributors of this pollution process is the passenger transport sector and accounts for almost 8 million vehicles in the Netherlands (BOVAG, 2010). However, there is pressure from the world and also the European Union to become sustainable. Now in the 21<sup>th</sup> century a new technology is trying to evolve, and is also becoming commercial attractive. This is the ‘shift’ from ICVs to EVs in the automobile sector which is still in its early phase of development. These types of ‘shifts’ in technology we call ‘technology transitions’ and these transitions are described in an abstract form in the academic literature by (Rotmans et al., 2001; Geels, 2002; Geels & Schot, 2007). In this chapter, I first introduce some theory about; socio-technical systems, multi level perspectives and technology transitions. This provides the reader with background knowledge about the process of *technology transitions*. Secondly I provide the reader with theory about the diffusion and adoption of innovations. This is necessary to understand the underlying theory of the consumer responds to innovations (Hauser, et al. 2006). In the second part of this chapter I link the theories with the electric vehicle case.

### **2.2 The abstract view of technology transitions**

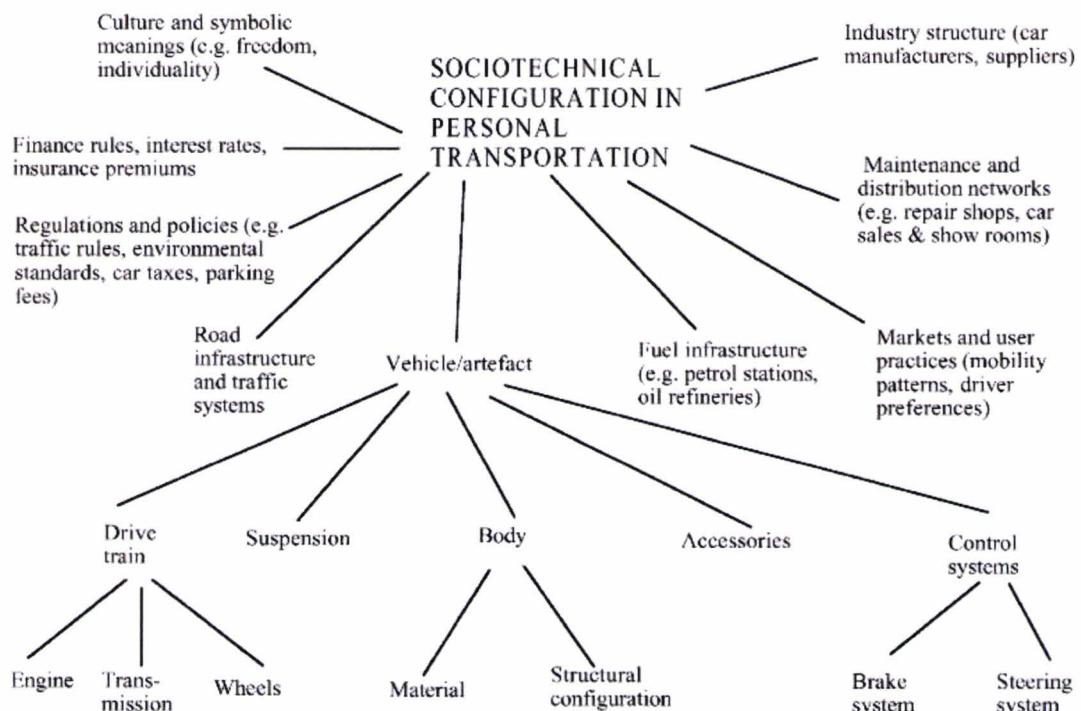
#### **2.2.1 Socio-technical systems**

In the past many transitions have occurred, for instance Geels (2005) investigated the dynamics of transitions with a historical case study in which horse-drawn carriages in the 1860s made a transition to automobiles in the 1930s. In another study, Geels (2002) empirically illustrated with a qualitative longitudinal case-study the transition from sailing ships to steamships (1780-1900). In which mechanisms of technology transitions are described. Technology developments are an important element in transitions, however, they do not stand alone. Societal functions are also significantly important in this process. Societal functions are defined by Geels (2005) as communication, housing, health care, *transportation*, supply of resources and supply of energy. Moreover, these societal functions do not evolve by themselves and a cluster of elements embedded in socio-technical systems are crucial to build them. This raises the question, what is a system? To answer this question, we first need to differentiate between a *product* and *technology*. According to Lovelock and Gummesson (2004) a product can also be referred as a good, service or an idea. On the other side, a technology is something more. Rogers (2003) defines technology in two components: '(1) a *hardware* aspect that consists of the tool that embodies the technology in the form of material or physical object and (2) a *software* aspect that consist of the information base for this tool.' Additionally, technology is defined in many different ways, the most common is ‘manufactured items’ that are made by human beings, including processes and procedures required to make these items. This definition is also reflected in the term “socio-technical system of manufacture”, that includes the manufacture equipment and from time to time this process is involved with people operating the equipment (Scharf, 2003). Moreover the complete working system of technology

includes inputs such as; people, machinery, resources, processes, and: the legal, economics, political and physical environment. Moreover, as well elements similar to, techniques, methodology and know-how are involved in a socio-technical system (Scharf, 2003). Apprehend the difference between a product and a technology, in which the latter one represents more complexity because of the extra elements involved. Well defined representations of four technical hierarchies are specified by Disco et al (1992);

- *Level 1: 'components* (e.g. materials, nuts and bolts, resistors and condensers, radio vacuum tubes) that do not 'perform' by themselves, but have to be assembled to do their job;
- *Level 2: devices* (e.g. a pump, a switching circuit, a sensor) that are assembled sufficiently to show their primary effect;
- *Level 3: functional artefacts* (e.g. a machine, a bridge, a radio), that work by themselves;
- *Level 4: systems* (a plant, an electricity network, road infrastructure, radio broadcasting plus receivers plus organizations to produce radio programmes) that fulfil a socio-technical function'.

All these technical elements on different level are required to perform a certain task and together with the involvement of *human activity (society)* this generates a *socio-technical system*. Societal functions like personal transportation are embedded in a huge basket of elements, which manipulate in a certain manner the diffusion of a technology. Rip and Kemp (1998) analyzes technology as 'configurations that work' while the term 'configurations' refers to the alignment between a heterogeneous set of elements, in addition 'that work' indicates that the configuration fulfills a social function. Figure 2.1 depicts a modern socio-technical configuration in land-based personal transportation.



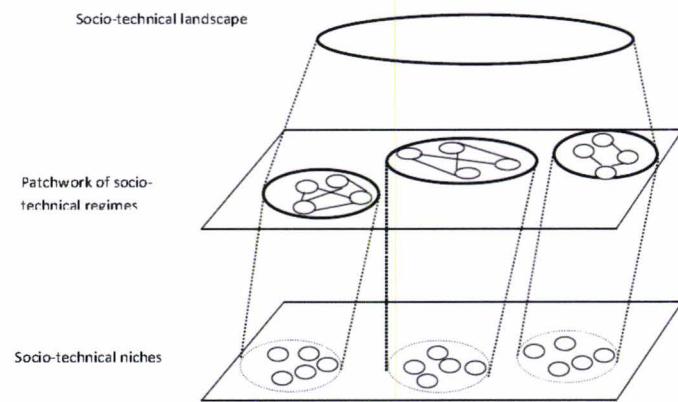
**Figure 2.1: Elements of the socio technical configuration in personal transportation. Source: Geels (2002).**

Elements in the configuration are connected and aligned to each other and this makes a technology transition a difficult and unpredictable process. As defined by Geels (2002, pp. 1258), 'radically new technologies have a hard time to break through, because elements in the socio-technical system such as; regulations, technology, infrastructure, user practices, maintenance networks and supply networks are aligned to the existing technology.'

Furthermore, these elements and linkages are established by the activities of social groups. Like the road infrastructures and car regulations, those are built by building concerns in assignment of transportation departments of the government. In addition, the users, media and societal groups create a certain symbolic and cultural meaning about a certain technology (e.g. fossil fuel car) through their interactions. Moreover, there is also technical knowledge of engineers embedded in these cars, while the car manufacturers produce the manufactured articles. Furthermore, Industry structures are the outcome of mutual positioning and strategies of car manufacturers and their suppliers, and the daily use of a technology by user groups will create user patterns and mobility patterns (Rotmans et al., 2001; Geels, 2002). The groups involved in these socio-technical configurations are aligned and co-ordinated to each other. Additionally, this creates complexity for the diffusion of a new technology (e.g. electric vehicle) which is involved with the elements in a *socio-technical system* in contrast to a new product adoption (e.g. laptop). Since an electric vehicle is concerned with, for instance, emission rules, subsidies, safety rules, infrastructures etc. All together, this makes it a big challenge to forecast the technology adoption process of an electric vehicle.

### 2.2.2 The multi-level perspective and technology transitions

Understanding a technology transition in its most abstract representation requires an introduction of the multi-level perspective (MLP). This perspective provides a conceptual representation of the complex dynamics during a socio-technical change (Rip and Kemp, 1998; Geels and Kemp, 2000; Rotmans et al., 2001). The change in elements concerning a technology transition is described as follows. The MLP distinguishes three levels (figure 2.2). The landscape-level, or *macro-level* is defined as the area with 'hardness', because this level includes cities, factories, (electric) infrastructures and highways. These deep structured elements slowly change and contain factors, such as; 'oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, and environmental problems' (Geels, 2002). Furthermore, the landscape developments can put pressure on the regime (mid-level), making new routes or impossible to continue in the existing socio-technical configuration.

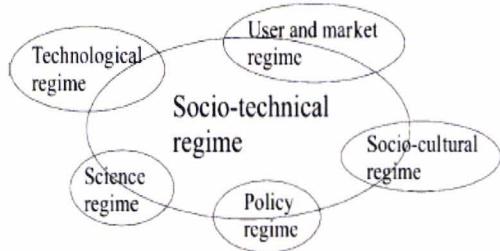


**Figure 2.2: Multi-level-perspective.**

Source: (Geels, 2002)

The elements in a socio-technical system are stabilized by a set of rules and are embedded in a technological regime. 'A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems all of them embedded in institutions and infrastructures' (Rip and Kemp, 1998, pp. 388). The

*meso-level or the socio-technical regime*, reflects a consistent configuration of a number of elements that facilitates the existing system, categorized in five regimes (figure 2.3); the technological regime, the users and market regime, the socio-cultural regime, the policy regime, and the science regime. Each regime encompasses its own set of rules, which are shared by actors. Relevant actors in the socio-technical configuration of the personal transport sector are the consumers, governments, the car industry (original equipment manufacturers, OEMs), the oil industry, and lobby groups. Together these actors embedded in regimes encompass rules, examples are given by Geels (2004) in table 1:



**Figure 2.3: Meta-coordination through socio-technical regimes. Source Geels (2004).**

**Table 1: example rules in different regimes. Source: Geels (2004)**

Type of regime	Examples of rules in different regimes
Technological and product regimes	Technical standards, product specifications (e.g. emissions, weight), functional requirements (articulated by customers or marketing departments).
Users and market regime	Property rights, product quality laws, liability rules, market subsidies, tax credits to users, competition rules, safety requirements, user practices, user preferences, user competencies, selection criteria.
Socio-cultural regimes (societal groups, media)	Symbolic meanings of technologies, ideas about impacts, cultural categories, cultural values in society or sectors.
Policy regimes	Formal regulations of technology (e.g. safety standards, emission norms), subsidy programs, procurement programs, policy goals, interaction patterns between industry and government (e.g. corporatism), institutional commitment to existing systems.
Science regimes	Formal research programmes (in research groups, governments), rules for government subsidies, criteria and methods of knowledge production.

Finally the lowest level of the multi-level perspective is the niche-level, in which new radical innovations or technological alternatives emerge. The existing regime technology (e.g. internal combustion engine) can be replaced by an alternative technology which starts to develop in niches. In general, the socio-technical regimes are forced to change their elements to become more aligned with the new technology (e.g. electric vehicle) and landscape pressures (e.g. emission regulations), with a technology transition as result (Rip and Kemp, 1998; Geels and Kemp, 2000).

In sum, the total process of a technology transition is depicted in figure 2.4. This figure is based on the famous s-curve used in marketing and the technology evolution literature (Hauser et al. 2004; Christensen, 1998). ‘Understanding the rate, shape and dynamics of technological evolution is necessary to make wise decisions about the technology and timing with which to enter markets’ (Hauser et al. 2004, pp. 696). Understand, the process of an technology transition by following the figure below from the niche-level (on the lower left ) were radical innovations occur and mature into the socio-technical regimes<sup>10</sup> when this new innovation is accepted by the rules and ultimately disrupted by another new Socio-technical regime (on the top right).

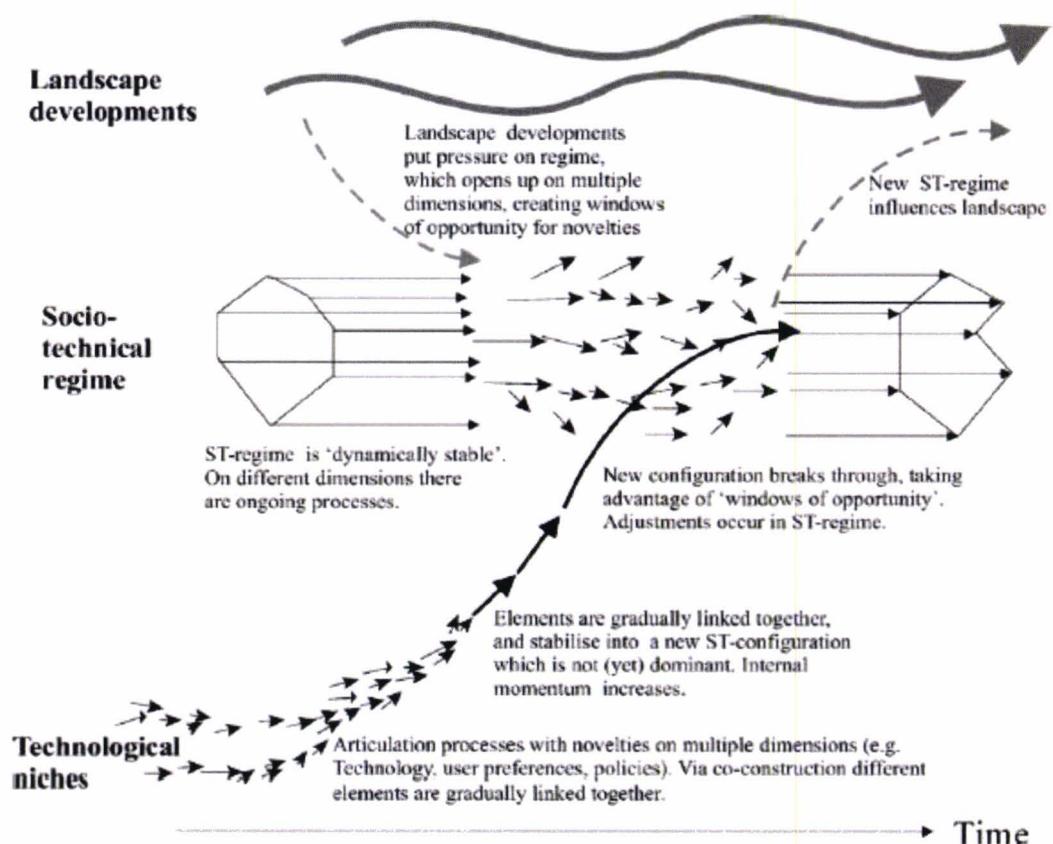


Figure 2.4: A dynamic multi-level perspective on technology transitions. Source: Geels (2004)

Up to now, the process of a technology transition is discussed in an abstract manner. Providing a useful view about the dynamic and complex technology transition process of personal transportation and the involved elements. In the next section, theories about the diffusion of innovations (adoption at the aggregate level) and the consumer innovativeness (adoption at the individual level).

<sup>10</sup> See figure 2.3 the five different types of regimes

### 2.2.3 Innovation diffusion- and adoption process

First it is important to know what is meant with innovation. 'Innovation is defined as an idea, practice, or object that is perceived as new by an individual or other unit of adoption'. Secondly it is important to identify diffusion, 'this is the process in which an innovation is communicated through certain channels over time among members of a social system<sup>11</sup>' (Rogers, 2003, pp. 5). The diffusion literature focuses on the aggregate level of adoptions, in which the individual level of adoption is based on the consumer responds to innovations and is merely focused on the 'mental, behavioural and demographic characteristics', related to the user preferences and selection criteria (Hauser et al., 2004). On the one side the adoption of an innovation is defined in the bass diffusion model. This is the basic logistic innovation diffusion model and defines the adoption process between users and potential users (Bass 1969, Sterman 2000). On the other side there is the innovation diffusion model (Rogers, 2003). The latter one describes how an innovation diffuses, with groups of consumers that adopt a new technology and the adoption of an innovation. These two types of approaches are also influenced by different variables that have effect on the rate of adoption.

'The *Rate of adoption* is the relative speed with which an innovation is adopted by members<sup>12</sup> of a social system. It is generally measured as the number of individuals who adopt a new idea in a specific period' (Rogers, 2003 p221). This relative speed with which an innovation is adopted depends on the degree an innovation (e.g. electric vehicle) is accepted by the society or in specific the individual (e.g. consumer, potential adopter). Therefore, obtaining a good match between product characteristics and potential customers' needs and wants is crucial for gaining market acceptance of a new product. New products are commonly not accepted at once by potential customers some resistance exists. The start of the process of adoption is already discussed previous section as the evolvement of a technology transition, which initiates with a niche (Schot et al., 1994; Kemp et al., 1998). Characteristics of the individuals in such a niche do have a fit with the current technological specifications and are therefore indented to adopt a certain product at first. According to Schot et al. (1994) and Kemp et al. (1998), the first group of adopters create a grip in the market, from which 'learning processes related to the core product itself and to supporting technologies and institutions accelerate' (Gärling and Thøgersen, 2001, pp. 56). Additionally, regimes of the socio-technical system, such as, social groups and, political and institutional networks get involved with the first group of adopters. A huge amount of actors become involved each with its own influence on the adoption process.

Therefore, it is of strategic importance to accurately measure the potential customer willingness to adopt<sup>13</sup> Goldsmith and Hofacker (1991). Accordingly, Goldsmith and Hofacker (1991) defined 'product specific innovativeness'<sup>14</sup> as a tendency to learn about and to adopt innovations within a specific domain of interest. They suggest that even if it is possible to construct a measure of a global innovativeness, at least the measure of willingness to pay for adoption should be concretized regarding a specific product concept.

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<sup>11</sup> Notice the socio-technical system and its complexity as discussed in previous sections

<sup>12</sup> In this case the potential adopters for the electric vehicle.

<sup>13</sup> The willingness to adopt an electric vehicle is analysed by the conducted survey in this research project. This concerns research question RQv3.

<sup>14</sup> Innovativeness is not part of the research, therefore I would suggest Rogers (2003) and , Goldsmith and Hofacker (1991) for further research. However, useful data for future research on these topics is provided by the survey.

## 2.3 The electric vehicle case

In this section the theory from the literature is applied on the electric vehicle case. Furthermore, research question RQv2 is answered and discussed. At the end a short overview and the purpose of this chapter is provided.

### 2.3.1 Theories applied on the electric vehicle case

Regarding the conventional vehicle specification that influence the customer willingness to adopt, electric vehicles currently available usually have a higher purchasing price and a shorter range than conventional power trains Walther et al. (2010). According to (Brownstone and Train, 1999; Train and Winston, 2007) the electric vehicles are in the early phases of the adoption process less competitive and therefore it is important to analyse when the specifications of the electric vehicle actually do met the consumer needs.

At this point in time the competitively increases in comparison to the conventional vehicles, which simultaneously increases the rate of adoption. Understand from previous discussed theories that the adoption process depends on the consumer acceptance or willingness to adopt, when modelling such an adoption process, what key specifications of the electric vehicle have to improve or change in order that an electric vehicle becomes equal or even more attractive as a conventional fossil fuel vehicle. Electric vehicles differentiate in several aspect compared to an conventional fossil fuel vehicle, such as the design or the issue it produces no noise. However, these are not the most decisive elements to concern when purchasing an electric vehicle. Electric vehicles are dependent on the *recharge stations* from which only a few have been placed up to now.

'As the smaller driving range means more refuelling processes, the infrastructure coverage appears to be even smaller from the customers' point of view' (Walther, 2010, pp. 242), and in the case no recharge infrastructure no attractiveness evolves and no fit with the consumer needs, which result in a low adoption rate. Furthermore, from the perspective of the potential adopter, the EV technology is a new system, which mainly removes one of the many non-market disadvantages of traditional ICVs (local emissions) (Gärling and Thøgersen, 2001) and reduces significantly the depletion of oil reserves. However, a major disadvantage is the use of coal - and nuclear plants for generating the primary energy of the electric vehicle (RETD, 2010).

This latter statement is important for the adoption process when mass adoption occurs. An scenario may exists that in the case a mass adoption of electric vehicles occurs, not enough renewable energy will be available to recharge the electric vehicle and the government is forced to raise electricity prices or even set limits for the amount of electric vehicles on the road. According to Geels (2002), this is one example of an element in the landscape level and such scenarios should also be taken into account in further research of the adoption process<sup>15</sup>. '*Compared to ICVs, current electric vehicles (EVs) still have disadvantages that make them less attractive. Current battery technology, (1) not allowing unlimited driving ranges, (2) relatively long recharging times and (3) high initial purchase prices are some of the EVs' major disadvantages. In addition, the usability of an EV is hampered by*

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<sup>15</sup> Equal scenarios concerning the transition process to the electric vehicle are discussed in the RETRANS report. (RETD, 2010)

(4) the lack of an infrastructure for refuelling (recharging). On the other hand, fuel for EVs is inexpensive, electric motors last significantly longer than internal combustion engines' (Gärling and Thøgersen, 2001, pp. 54) and 'EVs require significantly less maintenance and repair than ICV due to having only one moving part in the electric motor' Weber (2009). Additionally, the high fixed costs of an EV is commonly the *main reason* to reject (Borenstein, 2008). 'This cost grows linearly with the size of the battery pack, or the maximum range of the car. Still, this cost premium for EVs is compensated by the low cost of electricity compared to gasoline' (Werber, 2009, pp. 2465). However, a major benefit is the well-to-wheel efficiency of the electric vehicle, which is at least on average 2.6 times the efficiency of a conventional fossil fuel car (Unnasch and Browning, 2000).

Concluding, the citation above by Gärling and Thøgersen indicates the four key elements<sup>16</sup> of the adoption process and these are the most decisive in the adoption process. Because these four elements have by far the most negative effect on the attractiveness on the electric vehicle, this in comparison with the specifications of the conventional fossil fuel vehicles of today. Therefore, these elements are important to use in the adoption model, since these are the specifications of an electric vehicle which have to be fit at first with the needs of the potential adopters.

The model used in this research encompasses the adoption process for the consumer perspective. However, this chapter also highlight the involvement of a socio-technical system, in which more elements (or rules) embedded in different types of regimes play an important role at the three different levels of perspectives. Moreover, not only the renewable energy scenario is an issue, also production capacity limitations and lithium resource depletions (RETD, 2010) may have their impact on the adoption process in future time, or the improvement of other innovations like bio fuels or fuel cells. Therefore is from importance for long-term perspectives to understand the total picture of this adoption process and not only the consumer perspective.

Furthermore, this chapter provided an overview of the total transition process of a technology and ended with a specific focus on the most decisive elements in the adoption process from a consumer perspective:

RQv2b: '*Which crucial elements from a consumer perspective influence the adoption process (purchase moment) of the electric vehicle'*

*Answer on RQv2b:*

*'Compared to ICVs, current electric vehicles (EVs) still have disadvantages that make them less attractive. Current battery technology, (1) not allowing unlimited driving ranges, (2) relatively long recharging times and (3) high initial purchase prices are some of the EVs' major disadvantages. In addition, the usability of an EV is hampered by (4) the lack of an infrastructure for refuelling (recharging)'*

Gärling and Thøgersen, 2001, pp. 54

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<sup>16</sup> These four elements are used as the key elements of the adoption process in this research project

### **3. Research method**

#### **3.1 The birth of this research project**

The passenger road transport sector is one of BN business activities. Additionally, BN is also familiar with the techniques and know-how related to alternative fuels, such as natural gas. Together this formed knowledge, rules and practices about distinctive infrastructures. This knowledge advantage creates new ideas and those may be used for long term projects, for example in the electric driving sector.

However, why should BN be interested in the electric driving as a business opportunity? This is exactly the key question that should be answered. As is known, BN has already its focus on the transport sector and provides the infrastructure for the road transport, like auto ways, natural gas stations, bridges etc. However, in the case of electric driving, BN may benefit from projects concerning the development and placing of the grid-based electric systems. This system is needed to be able to recharge the electric vehicles across the country. The projects regarding the placing of these recharge points creates work opportunities (financial benefits) and are therefore of interest for BN. In spite of that BN has the knowledge and resources to perform these projects but they do not know what the future perspectives will bring. The very next question that arises is about the future developments of the electric vehicle sector. When and how much shall the electric vehicle sector expand? This unfortunately depends on a bunch of elements<sup>17</sup>.

Modelling such an ‘adoption’ process would be a first step to create better insights and knowledge, which is valuable for the establishment of the companies’ long-term strategies. After a first meeting with BN the first general research question of this research project is established:

RQv1<sup>18</sup>: *‘How will the adoption process of electric vehicles develop in the future, and in particular what key factors or elements influence this adoption process’*

<sup>17</sup> Element is defined as an aspects, rules or variable that influences the development of the adoption process of electric vehicles (e.g. a technology transition process). See also the socio-technical configuration figure in (Geels, 2002) or appendix 3.1b.

<sup>18</sup> RQvx: states for Research Question version x.

### 3.2 The purpose of system dynamics

It is not easy to model the diffusion process of a technology. However, system dynamic (SD) is an appropriate tool to model the macro-, meso-, but also the micro- elements of a technology adoption. Note, that 'SD is used for the analysis of policy and strategy, with a focus on business and public applications. Furthermore, SD is a perspective and set of conceptual tools that enable us to understand the structure and dynamics of complex systems' (Sterman, 2000). This modelling technique provides more concreteness to the abstract description of technology transitions as is defined in the literature by Geels (2002).

*'System dynamics is a method that challenge us all how to move from generalizations about accelerating learning and system thinking to tools and processes that help us to understand complexity, design better operating policies, and guide change in systems from the smallest business to the planet as a world'* (Sterman, 2000, pp. 4)

'Applications of system dynamics include: Transportation policy and traffic congestion; Business cycles; The design of supply chains in business and other organizations; The diffusion of new technologies; The use and reliability of forecasts; Project management and product development' and many others (Sterman, 2000 pag. viii). The total process of system dynamics covers the gathering of information, from which important variables are selected and causal relations defined in a causal loop diagram. Once the validation of these causal relations is finished, a second stock and flow model can be constructed including the dynamics (time included) of the situation.

### 3.3 An overview of the five research design steps

To create a system dynamics model, an structured approach is required to provide a rigour and relevant research. Sterman (2000) proposes such a structured approach by defining steps for the modelling process, see figure 3.1. Important is that all steps are iterative and therefore, during the whole process updates are made. The model used in this research project is a dynamic model and because of the survey data and other variables that have to be added in later, repeating these steps multiple times is therefore a crucial issue.

This process of modelling consists of five steps and starts with the *problem articulation* and defines the purpose of the model. In this research project the model is used to project the adoption process of adopters, which represents the Dutch potential buyers of an electric vehicle (e.g. the Dutch passenger vehicle drivers). In a time horizon of 20 years the adoption process is depicted which is influenced by four crucial elements from the consumer

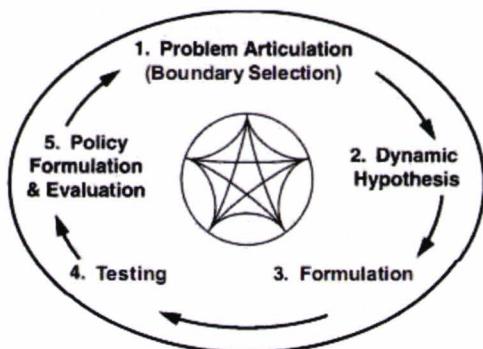


Figure 3.1: design steps defined by Sterman (2000)

perspective. Moreover, the time horizon of 20 years is set to be sure to capture the ‘mass adoption phase’ of the electric vehicle.

Subsequent to the definition of boundaries and area of research, the second step defines the *dynamic hypothesis*, which entails the explanation of the dynamic elements in the model. The modelling of an technology transition or an adoption process of electric vehicle, encompasses a lot of influential elements at different levels of perspectives. Crucial is to incorporate the most decisive elements of the adoption process. Therefore, a first approach is made to overview all important endogenous and exogenous elements of the process. Afterward, the most decisive elements have to be selected. In appendix 3.1a an overview is given which answers research question RQv1, this is discussed in the third step (formulating step). From the literature in chapter 2 the four crucial elements in the adoption process from a consumer perspective are defined; driving range, price, recharge infrastructure network and recharge time. Furthermore, the survey results provide the answer on RQv3, and incorporated the willingness to adopt of consumers.

*Formulation step:* The first sub step is the actual *modelling of problematic dynamics*, based on the boundaries and the dynamic hypothesis (see chapter 4). Afterwards the second sub step is the formulation of the causal loop diagram (CLD) (see section 3.4.3). This diagram depicts the main variables and feedback loops and shows the overall structure of the model and the relationship between the different loops. Moreover, at this moment the model is almost complete, with the final and third sub step the stock and flow diagram adds the actual dynamics to the model (see Chapter 4). In this model all the different stocks, flows, endogenous and exogenous variables are modelled.

As fourth the *testing step* in the design process is applied to detect flaws or unrealistic situations in the model and starts when the first formula in the model is written. It is important that every variable corresponds to a meaningful concept in the real world; just copying historical data is not appropriate. However, on the electric vehicle case historical data is scarce and for this reason a survey is conducted to gather reliable data from 388 Dutch respondents. The variables used in the model are based in the bass diffusion concept as defined in Sterman (2000) and other academic literature. Furthermore, the rest of the variables indicating the four crucial elements are selected by using reports and academic literature. At the moment that all variables, equations and values are placed in the model then the simulations can start and compared with historical data or in this case with other predictions. The values and variables used in the first model are presented as the base case situation, from this situation several scenarios can be modelled and leads to the final step.

*Policy formulating step* can be used to create to-be situations such as the implementation of new policies, strategies or decision rules. Chapter 6 discusses several types of scenarios, such as the impact of the driving range increase and the effect of word of mouth on the period of mass adoption. Moreover, the effect of subsidies is presented and, the recharge infrastructure and time influence of the early phases of the adoption process.

Upcoming sections present the design steps in more detail applied on the electric vehicle case.

### 3.3.1 Problem articulation

The first step of the design process is the boundary definition of the problem. This is an important step in the modelling process. During the orientation phase, the literature provided a lot of elements that are involved with the adoption process. For instance there are elements embedded in the landscape level, as well as in the regimes on the meso-level which are interrelated to each other (Geels, 2004). These interrelationships between all those elements make the situation of the adoption process very complex. Therefore the very first problem of this research is to be able to model this complexity. Notice that the purchase of an electric vehicle (adoption) is related to a socio-technical system in which oil prices determine the price of gasoline and that advertisement about sustainable transport may have its effects too.

Furthermore, examples of the technical feasibilities of the battery like, driving range and recharge time do have also a certain extend of effect on the adoption process (Gärling and Thøgersen, 2001), and also direct elements such as; design, comfort, price, reliability, image, safety, maintenance costs and consumption may have its influence on the adoption process. These are all examples of elements in different levels of context that actually do influence the future adoption process of an electric vehicle.

As is stated in previous section the time horizon (e.g. 20 years) should be defined in such a way it encompassed a frame with the most important variables, at the right level of detail so that the overall trend of the adoption process still can be described. Therefore the consumer perspective is defined as research approach and functions as a research boundary. This focus indicates that the researcher thinks as a consumer. From this a selection of elements that do restrict or stimulate a person to purchase an electric vehicle will be included.

This way of thinking is to create focus and helps to overcome the complexity of all elements involved with the adoption process and it also makes the modelling process easier. The focus on the consumer makes it possible to use the bass diffusion model that starts with the potential consumers (or potential adopters) and let them diffuse into actual consumers (after adoption). During this adoption process the most important elements that do influence the diffusion from potential to actual consumers are modelled. First, the direct<sup>19</sup> elements and in future research the indirect<sup>20</sup> variables can be included.

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<sup>19</sup> The elements on the individual levels that can be noticed from the product self (e.g. design, color, price, reliability, safety, driving range, recharge time etc.)

<sup>20</sup> The elements on higher level (e.g. oil prices, economical crisis, policy rules, infrastructure etc.)

### 3.3.2 Dynamic Hypothesis

Formulating the dynamic hypothesis is the start of the actual model. It is essential to split the very first RQv1 into two (RQv2 & RQv3) more detailed research questions, from which RQv2 has a special focus on the crucial elements. The second research question RQv2 will provide a model with a basket of elements that do influence the adoption process of the electric vehicle (RQv2a). Additionally, this research question answers also the *crucial elements from a consumer perspective* (RQv3b).

*RQv2a: Which elements from influence the adoption process (purchase moment) of the electric vehicle.*

*RQv2b: Which crucial elements from a consumer perspective influence the adoption process (purchase moment) of the electric vehicle.*

The question RQv3 is about the hard data that can be found. The previous question selects the most determined elements of the adoption process. However, in question RQv3 the extent (the degree of willingness to purchase an electric vehicle or in theoretical terms, the degree of willingness to adopt an innovation) of the crucial elements are defined. Note, that there is the possibility that assumptions have to be made, according to the values used in the model. However, the degree willingness is not assumed, because these values are base on survey data which represents the Dutch passenger vehicle fleet.

*RQv3: To what extent do these elements from a consumer perspective influence the adoption process (purchase moment) of the electric vehicle.*

### 3.3.3 Formulating a simulation model

The first step in the formulation phase is to identify the variables that are relevant to the model. A result is the already designed causal loop diagram (CLD) (appendix 3.1a). This CLD will not contain all the details but will give an overview of the main dynamics and should be used to get a good overview about the processes and their interactions. Moreover, this CLD is reviewed by the supervisors at BN and TU/e to make sure all the essential dynamics are captured. When the CLD is updated and approved in these reviews, then the final SFD structure can be started in Vensim. Vensim is a software program able to model and simulate system dynamic models. Furthermore, it has a wide range of analysis and simulation tools to compare output, and even create a management flight simulator (Sterman, 2000). The elements or variables from the CLD are also used for the stock a flow diagram. Here from, it is important in the modelling process to assign the units of the different variables. Which demands that this will be done precisely, otherwise lots of rework can evolve. Chapter 4 discusses extensively the elements and described the SFD of the model. The assigning of

the units is formally part of the testing step, but will be executed as the model is being build to prevent problems with the consistency of the model (Sterman, 2000)

### 3.3.4 Testing

The testing phase starts as soon as the first equation is written down (Sterman, 2000). This means that the last part of the formulating phase will overlap with the testing phase because a lot of the equations will be entered on the spot, along with the units. This process will go on until the model is ready for its first run. The first test is to compare the output of the model to any historical data on the projects. There should be a fit with this data. If this is not the case, the model should be redesigned to fit the data as accurate as possible. However, in the case of the electric vehicle no historical data is available. Therefore, predictions and data from other recently executed studies and surveys are used as reference.

Besides giving reliable output with realistic parameters, the model should be tested for sensitivity and robustness. The sensitivity of the model behaviour and policy recommendations should be assessed in light of the uncertainty in assumptions, both parametric and structural (Sterman, 2000). Depending on the assumptions used in the eventual model, sensitivity tests will be designed to assess these assumptions and validate them. Robustness of the model and the output will be tested by entering extreme values for some of the variables and this is also in line with the scenario testing. For instance, the battery performance will set to infinity, then the problem with driving range is eliminated or the infrastructure network is gone. In the latter case no one wants to purchase an electric vehicle. The other way around, a mass adoption situation will start. This could probably also be the case when a subsidy for an electric vehicle increases heavily. Based on these different aspects of the model all the subsystems will be tested for robustness to ensure the validity of the model. Dependent on the outcomes of these tests the model will be altered and retested to ensure validity and robustness. After this is achieved the base case results will be analyzed.

### 3.3.5 Policy Design and Evaluation (scenarios)

This final step of the process uses the base case situation as reference for the additional scenario as presented in chapter 6. A few out of the box scenarios are created and represent a realistic situation. These are probably not realistic for direct implementation, but this way of intervening can provide valuable insights in underlying dynamics. By comparing the results of the scenarios to the current policy the effects of proposed policy changes can be examined. The redesign of the policies at Ballast-Nedam should not only be about changing values of some of the parameters in the model but they include the creation of entirely new strategies, structures, and decision rules. At the end of the research I will recommend policy changes that would benefit Ballast-BN which can be implemented after the research period. It will not be possible to fully redesign policies and decision rules due to the time constraints of this master thesis project. The scenarios tested in this research project are extensively elaborated in chapter 6. This chapter highlights the most important possible situations and provides insight for the assumptions made in the model.

## 3.4 The research phases

### 3.4.1 Starting phase

A starting point for this research was the report (RETD, 2010) published by three reliable research institutions ECN, RWTH and TNO. This report created a solid knowledge fundament and made it possible to gather more specific information about the electric vehicle and also the transition process. Additionally, this resulted in a literature study about the theoretical representation of technology transitions, including a description of socio-technical systems and multi-level perspectives, and the adoption and diffusion of innovation literature both topics were valuable for the master thesis project. These topics were briefly described in Chapter 2.

### 3.4.2. The definition phase

This master thesis process encompasses two parts, first a deep research in the academic literature and second the application of the academic literature in practice. Academic literature explains that the success of innovation diffusion depends on the acceptance of a consumer (adoption) (Rogers, 2003; Hauser, 2004). Moreover, there is an distinction between the adoption and diffusion of an innovation. ‘Diffusion is indentified as the process in which an innovation is communicated through certain channels over time among members of a social system<sup>21</sup>’ (Rogers, 2003, pp. 5). The diffusion literature focuses on the aggregate level of adoptions, in which the individual level of adoption is based on the consumer responds to innovations and is merely focused on the ‘mental, behavioural and demographic characteristics’, related to the user preferences and selection criteria (Hauser et al., 2004). On the one side the adoption of an innovation is defined in the bass diffusion model. This is the basic logistic innovation diffusion model and defines the adoption process between users and potential users (Bass 1969, Sterman 2000). On the other side there is the innovation diffusion model (Rogers, 2003). The latter one describes how an innovation diffuses, with groups of consumers that adopt a new technology and the adoption of an innovation.

Additionally, the dynamics and complexity of the ‘diffusion’ of a technology is described as a ‘technology transition’ in Geels (2002; 2004; 2007) and Kemp (2004). Technology transitions occur in both, the aggregate level of adoption as well in the individual level of adoption. For instance, the transition from fossil fuel to electric driving is determined by the consumer willingness to adopt an electric vehicle (individual-level) influenced by their characteristics, and also by rules embedded in regimes<sup>22</sup> (aggregate-level) (Hauser, et al 2004).

Subsequently, the literature stresses for more *empirical research* on these technology transitions since there are only abstract representations of this process. ‘An integration of both streams of research, the individual and aggregate adoption, might allow for more insightful models with superior predictions’ (Hauser, 2004, pp. 693). ‘The conceptual perspective of technology transitions is fairly complex. Can it be made operational for empirical research? The proof of the pudding is in the eating, i.e. use the perspective for empirical analyses of dynamics of socio-technical systems’ (Geels, 2004). For that reason, a fundamental model that compasses the dynamics of the adoption process would be a solution for this conceptual perspective in the academic literature. Still, the

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<sup>21</sup> Notice the socio-technical system and its complexity as discussed in previous sections

<sup>22</sup> The five types of regimes are discussed in chapter 2

actual problem is to forecast the development of the adoption process of electric vehicles, which depends on numerous influential elements embedded in different levels of aggregation. Additionally, another problem to overcome is to make clear which and to what extend these elements are key decision factors in the persons purchasing moment of an electric vehicle. In other words, note that this is not only about the price, shape or performance of an electric car in specific. There are also elements like, (European) standardizations, beneficial rules (e.g. free parking), oil prices, technological developments and investments, media influence (advertisements, word of mouth) and recharge infrastructures that influence the purchasing process of an electric vehicle<sup>23</sup>. Also electric driving is something new which involves an element like 'inertia' (Geels, 2002 p.1258). Meaning there is some risk involved with the purchasing of an electric vehicle, which resists people to change their buying behaviour. This is because of the newness (unawareness of new technology) and this newness is also another issue of this research, because less information (explicit data) is available and most of the other research in the electric driving area is still based on assumptions. Therefore at this point of time many assumptions have to be made in the fundamental model, which can be replaced by data from additional surveys in future times. Additionally, performing a survey to potential consumers about new technology may also be risky, because of the unknown factors involved. However, using data from surveys might create better insight about the adoption process and therefore is only useful as supplement for the many assumptions made in the first model.

Concluding four crucial elements influence the decision to adopt. Resulting from the literature, these four crucial elements are the limited driving range, the high purchase price and the recharge time all of them are related to the battery performance. Additionally the influence of the recharge infrastructure is decisive. Moreover, the willingness to adopt is analysed by conduction an survey, here from the cumulative amount of respondents per question is depicted in adoption graphs and used as input values for the final dynamic model.

### 3.4.3 The phase of modelling

During this research process a fundamental stock and flow adoption model is built. This model also has the ability to be extended with other variables and more concrete data when these are available in future times. However, the first hurdle in the information search process is the analyses of most decisive elements that are described in a few information sources and are embedded in a dynamic research topic which develops very fast. In other words, the first step is to find as much as possible elements that actually are of concern in the adoption process of the electric vehicle. A first attempt is made in the causal loop diagram (see appendix 3.1a), resulted from the orientation phase by evaluating European reports and diverse websites. This causal loop diagram is used as tool (guide) to provide a clear description of the literature currently available. This diagram is used as discussion concept and is updated during the whole research process (iterative).

This causal loop diagram distinguishes three different types of focus: the regulation and policy approach, the technological approach and the customer preference approach, respectively, the policy regime, the technology regime and the user and market regime. Each of these regimes are

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<sup>23</sup> These macro elements and scenarios are extensively discussed in the RETRANS report. (RETD, 2010)

represented by a different colour and indicates the focus of a causal relation. These three types of regime focus are selected on the basis of 5 types of socio-technical regimes described in the academic literature by (Geels, 2004) and section 2.2.2.

### 3.4.4 The demarcation phase of this research project

The three regime categorizations are used with the purpose to create a research demarcation. After discussions with BN the focus is set for the user and market regime, in which rules like 'user preferences and selection criteria' are embedded (Geels, 2004). The most influential elements of the adoption (purchase) moment from the customer perspective will be modelled. This is done, because it provides the ability to gather data by conducting a survey regarding the Dutch People response to the electric vehicle. Moreover, it also creates a specific research focus which is needed to create a rigorous model.

Furthermore, the most influential elements are found and validated by the academic literature. However, these elements do change over time and makes the technology transition a dynamic process. Therefore, a second model will be defined known as the 'stock and flow' model described in Sterman (2000). This model includes time and makes it possible to model the dynamics of the process. Graphs and simulations can be run with this software program. Subsequently, this is an operationalisation of the causal loop diagram.

The bass diffusion model in figure 3.2 is used as starting model. This is a growth model applicable for the timing of consumers' first purchase of a new product and is used as forecasting tool for the diffusion of innovations (Bass, 1969).

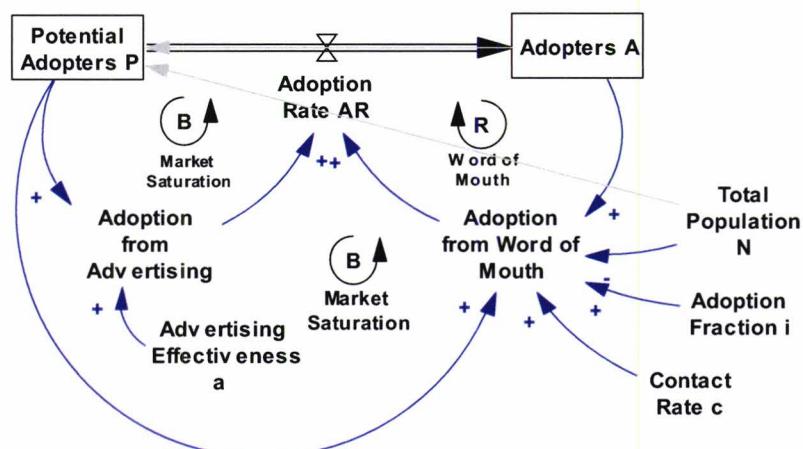


Figure 3.2 Bass diffusion model. Source: Software disk (Sterman, 2000)

This model is set up by use of the software program 'Vensim', which is a modelling, program used by Sterman (2000) to analyze complex systems in the world, also named as *system dynamics*. This software program is used as the modelling method of this research project.

## 4. Dynamic Modelling

### 4.1 Introduction

In this part the construction of the system dynamics model is explained. The total model (figure 4.1 & appendix 4.1a) exist of a basic model part which is based on the bass diffusion model (explained in 3.4.4). Besides this, there is a second part that describes the four main variables of the electric vehicle adoption process. These four elements are defined in chapter 2 as the crucial elements of the adoption process, three are related to the battery performance; the *price*, *driving range* and *recharge time* plus there is the influence of the *recharge infrastructure*.

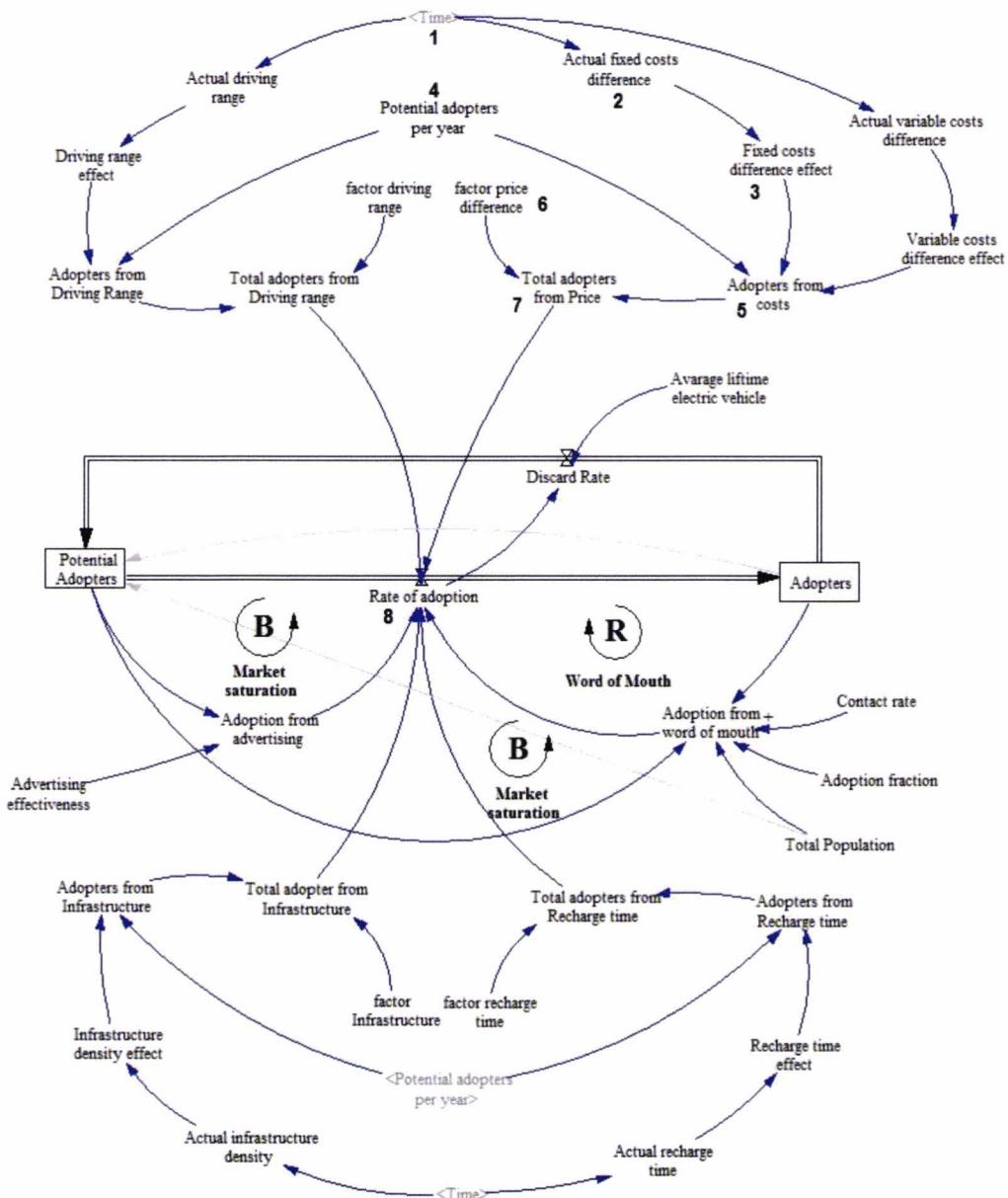


Figure 4.1: total model of the electric vehicle adoption process

Moreover, the prediction of the electric vehicle adoption process can be achieved in many different ways. Walther et al. (2010), for instance investigates the market introduction of alternative power train technologies. In this research the ‘co-evolutionary development of power train technologies corresponds infrastructure coverage, vehicle types offered, and customer behaviour are adjusted to the low emission vehicle regulations’. Walther et al. (2010, pp. 239) used data from the California Air Resource Board (CARB, 2010), in which vehicles are categorized on their air pollution.

The model used in this research is based on technical and survey data. Chapter 4 focuses on the technical data of the variables and chapter 5 on the adoption behaviour of the consumers. Respectively, the technical data used in the model is based on literature and some assumptions, and the adoption behaviour is analysed by a survey. This survey is used because no other data set was available, and therefore a method is devised to collect data about the Dutch passenger vehicle drivers. Together, the technical data in chapter 4 and the adoption behaviour data from the survey in chapter 5, together with the effect of advertising- and word of mouth cause this the ‘rate of adoption’.

In short, the function description of the total model is given below. The sequence of variables is allocated by the numbers in the model:

1. On top the *time* variable (nr. 1) is used to simulate time steps of a year and projects these steps to the *actual-x* variables (nr. 2);
2. The *actual-x* variables (nr. 2) contain a graph that plots the future developments of the driving range, fixed and variable costs, infrastructure density and recharge time. These future developments are base on literature and are connected to the *effect-variables* (nr. 3). (the actual variables are discussed in chapter 4)
3. The *effect-Variables* (nr. 3) contain a graph based on the survey results. Here, the future developments of the *actual-x* variables (nr. 2) are related to the willingness to adopt an electric vehicle. (e.g. when the driving range per full recharged battery increases with 100km then the amount of adopters increases with 5%). (the effect-variables are discussed in chapter 5)
4. The variable, *the potential adopters per year* (nr. 4) indicates the amount of new registered passenger vehicles per years. The average amount of the past 10 years account approx. 480.000<sup>24</sup> vehicles (Bovag, 2010, p17);
5. Together the *effect-variables* (nr. 3) and the *potential adopters per years* (nr. 4) produce a fraction [%] of the potential adopters per year (nr. 5). This fraction is based on the willingness to adopt and the future developments of the elements (see point 3);
6. Each element includes a *weight-factor* (nr. 6) which is examined by the survey and allows differentiating the four elements from each other in importance. Both the weight-factor (nr. 6) and the fraction of adopters (nr. 5) result in the *total adopters from x* (nr. 7).

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<sup>24</sup> According to the survey results; 30% of the respondents is *in doubt* to purchase an electric vehicle as their next car; 15% of respondents are *pretty sure* to buy an EV as next first car and 9% is *completely certain* to buy an EV as the first car (see appendix 4.1 c). Hereby the assumption is made that 9% of the annual 480,000 ( $0.09 * 480000 = 43200$  potential adopters per year) new cars registered are used as standard value in the model.

7. The *total adopters* from x (nr. 7) represent a percentage of the rate of adoption. All four key elements plus the adoption from advertisement and word of mouth together account for 100% of the rate of adoption (nr. 8).

See that step 1 till 7 are de same for all four elements, with a small modification for the price element which is split up in fixed and variable costs. The middle part of the model is the same as the bass diffusion model and is discusses in the next section. Moreover, the upcoming sections will discuss the model in detail, beginning with the basic model part and ending with the four elements.

## 4.2 Basic model description

'The bass model is a significant and useful extension of the basic logistic model of innovation' (Sterman, 2000). The bass model assumes that potential adopters of an innovation are influenced by two types of communication channels: Mass media and interpersonal channels. 'It is a predictive model that seeks to forecast how many adoptions of a new product will occur at future time periods, or on the basis of pilot launches of a new product, or from managerial judgments made on the basis of the diffusion history of analogous products' (Rogers, 2003). Subsequently, another significant contribution of the bass model is to provide a mathematical formula for predicting the rate of adoption. The key elements (see fig. 4.2) in the bass diffusion model are, '(1) adopters due to mass media messages, (2) adopters due to interpersonal (word of mouth) communication channels, and (3) an index of market potential for the new product' (Bass, 1969).

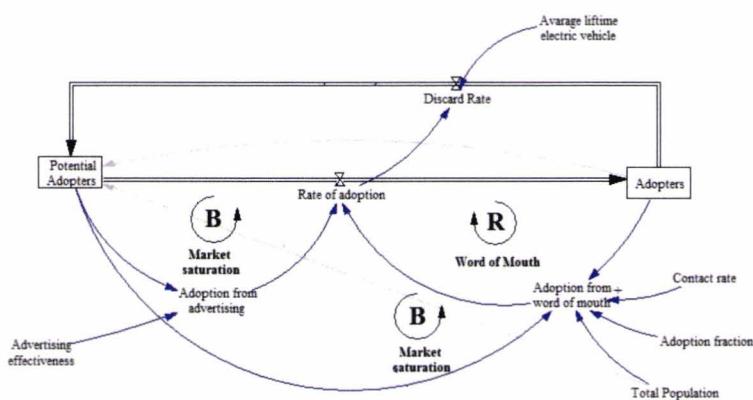


Figure 4.2: The basic model plus discard (bass diffusion model)

### 4.2.1 Potential adopters → Actual adopters

This model starts with the potential adopters, which are the current passenger vehicle drivers and account for approximately 7.8 million drivers, exclusive the 1 million commercial vehicles (Bovag, 2010). The population value used in the model is 8.5 million, this is because there are an increasing number of vehicles in the Netherlands and there for the assumption of an average of 8.5 million is made. However, this increasing number of driving population functions as limitation for the total adopters and can be modelled in future research. Regarding the survey, the selected respondents

$n=388^{25}$  is enough to represent the 7.8 million Dutch ‘passenger vehicle’ driving population. The potential adopters in the stock become adopters when they purchase an electric vehicle and this is mentioned as *the rate of adoption*. The diffusion and adoption of new products often follows an S-shaped growth pattern (Sterman, 2000; Hauser 2006).

In the basic part of the model the word of mouth and the advertisement effect are of concern. The word of mouth is the positive feedback or reinforcement loop (e.g. social exposure and imitation) that generates the initial exponential growth, for instance the more people purchase an electric vehicle the higher the possibility that someone comes in contact with an owner and is triggered to adopt. Furthermore, the external sources of awareness and adoption are usually interpreted as the effect of advertising which is a balancing loop (Sterman, 2000). This balancing loop results in the saturation of the market and limits the growth of the adoption process. Once all the potential adopters purchased an electric vehicle then no potential adopters exist, the market is saturated.

#### 4.2.2 Advertisement & Word of mouth

The adoption from advertisement depends on the advertising effect and is used as starting point for the model. The assumption is made that each year  $2.5e^{-5\%}$  (8.5 million drivers \*  $2.5e^{-5\%}$  = 213 EVs) of the residual potential adopters purchases an electric vehicle as the result of advertising effects. This value is based on the 206 sold vehicles in the past three years (source: RDC). These 206 drivers are the first adopters that purchased an EV which are probably triggered by advertisement effects (websites, pilot projects etc.) [3]. This value used for the advertising effect might be realistic on the fact that the electric vehicle is an unknown and expensive product. This newness keeps potential adopters from purchasing the electric vehicle.

Moreover, in chapter 6 different scenarios are given related to the advertising effect. This will show the influence and can be used. Moreover, historical data from the electric vehicle is not available. Therefore, making the model more reliable will require data from surveys, focus groups, test markets and so on, and this can help to estimate the advertising effect in future research.

The adoption by word of mouth<sup>26</sup> contains three variables, first the contact rate which represents a value of 20 people based on 80% of the respondents (see appendix 4.2a). The second variable indicates the adoption fraction<sup>27</sup> which is assumed on 0.01, see section 6.2 for further explanation for the adoption fraction value as used in the model. The final variables indicated the total passenger vehicle population of the Netherlands. This variable creates an upper limit for the adoption model.

#### 4.2.3 Discard rate

‘The bass diffusion model is often described as first-purchase model because it does not capture situation where the product is consumed, discarded, or upgraded’ (Sterman 2000). This means the other way around, from adopters to potential adopters for instance because of the battery lifetime or dissatisfaction. In the model the battery lifetime is modelled and has the value of 15 years.

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<sup>25</sup> The selected respondents are calculated with a standard formula and represent the 7.8 million drivers (see section 5.1.1).

<sup>26</sup> Adoption by word of mouth is driven by the contact rate between potential adopters and active adopters and the fraction of times these interactions will result in adoption. The word of mouth effect is small if the number of active adopters relative to the total population size is small (Sterman, 2000).

<sup>27</sup> The fraction of times a contact between an active adopter and a potential adopter results in adoption. ‘The person’s cogency’ (Sterman, 2000).

'Given the high costs of batteries, it is preferable that the battery life equals or exceeds the vehicle lifetime (10 to 15 years / 100,000 – 200,000 km). Whether this is the case for lithium-ion batteries, and how this is affected by the use of the battery, is still to be determined in practice' (RETD, 2010). However, this part of the model also allows for future research of other kinds of discard situations. Think about the hydrogen introduction, improvements in fossil fuel vehicles or other pressures from the 'landscape level' (Geels, 2002, pp. 1260), such as a war or an economic crisis.

### 4.3 The four technical elements

The four technical elements; *price [fixed costs and variable costs]*, *driving range*, *recharge time* and *infrastructure* are mentioned as the most decisive in the mass adoption process of the electric vehicle (Gärling and Thøgersen, 2001). This is because these elements do differ at most with the current conventional fossil fuel vehicles. In this section the future developments and facts about these four key elements are discussed. Moreover, this section covers a lot of detailed data that is essential to clarify the values and graphs as used in the model.

#### 4.3.1 The driving range

The maximum driving range of an EV is largely related to the performance of the battery. The improvement in lithium-ion battery technology allows driving ranges on average around 200 km<sup>28</sup> and in special case even more. However it is not yet entirely clear if the technology of the lithium-ion is the breakthrough for mass introduction of the electric vehicle (RETD, 2010).

ING produced a report in cooperation with other important reports from Boston consulting group (BCG), Deutsche bank, HiTeq, McKinsey and Roland Berger, and point out the future driving range developments with an expectance driving range of approximately 200 km till 350 km in the year 2020 (Figure 4.3 & appendix 4.3b). However, these numbers are predictions and reliable because of the important players involved.

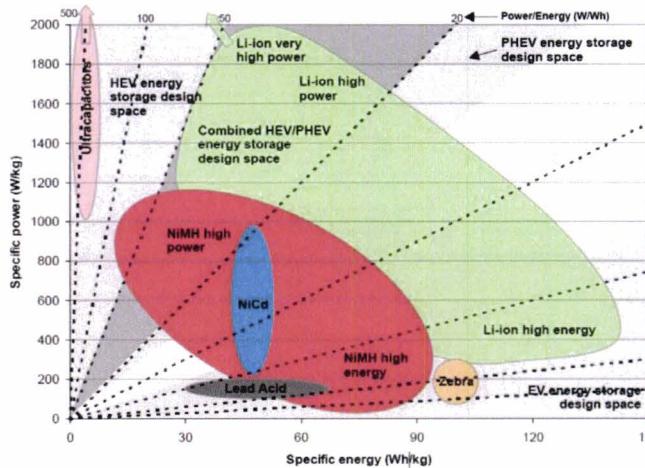
	2010	2015	2020
Massa (kg.)	200	200	200
Energiedichtheid (Wh/kg.)	100	150	200
Capaciteit van de accu (kWh)	20	30	40
Accukosten (€/kWh)	600	400	300
Totale kosten (€)	12.000	12.000	12.000
Actieradius (km.)	100 tot 170	150 tot 250	200 tot 350

Bron: INC Economisch Bureau op basis van diverse rapporten (BCG, Deutsche Bank, HiTeq, McKinsey en Roland Berger).  
Opmerking: 8 kWh aan accucapaciteit is nodig voor een stadsrit, 20 kWh voor woon-werkverkeer. Ter vergelijking: de Nissan Leaf (2010) heeft een accucapaciteit van 24 kWh.

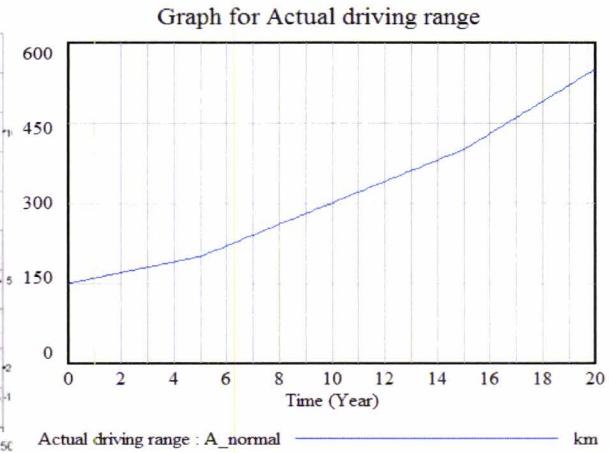
**Figure 4.3: Battery performance future perspectives. Source: ING report (2010)**

<sup>28</sup> 'The energy density of Li-ion is about 150 Wh/kg. Assuming an electricity consumption of 150 Wh/km a 200km range would thus require at least a 200kg battery pack. In practice, however, most vehicles only use 80% of the available battery capacity to avoid battery degradation. A 200 km range thus requires about 250 kg of batteries. In light duty vehicles a 10% weight increase generally leads to about 6.5% increase in the vehicle's energy consumption. Given an electric vehicle of 1250 kg empty mass with 200 km range and an energy consumption of 150 Wh/km, doubling the battery capacity increases vehicle mass to 1500 kg. This increases energy consumption to 170 Wh/km, so that the range of the vehicle with double battery capacity is just over 350 km, 75% increase' (RETD, 2010).

Figure 4.4 shows the different feasibilities of the battery performance for both full electric and hybrid vehicles see also appendix 4.3a for extra information about battery specifications. Furthermore, this figure indicates some shaded design areas for battery development possibilities. As can be seen from this figure, the specific energy design area limits at 150 Wh/kg, this is comparable with the value in figure 4.5 in which ING forecast the battery performance for the year 2015.



**Figure 4.4: Comparison of specific energy and power for a range of battery types. Source: (BERR, 2008)**



**Figure 4.5: Actual driving range perspective**

Remember the total model description in section 4.1, in which the total model is explained. In the function description at point 2, the *actual variable* is mentioned and indicates the future developments of an element. Above in figure 4.5 the future developments of the driving range is estimated based on several reports and expresses on the x-axes the years with the starting point of 0 (year 2010) and ends with 20 (year 2030). The starting actual driving range modelled is 150 km and predicted for year 2015 on an average of 200 km. Furthermore, in the year 2015 and 2020 the driving range is respectively set on 200 km and 300 km, this is the average calculated range from table ING. The years 2020 and further are assumed to develop following the curve line.

#### 4.3.2 Price

The actual purchase price of an electric car is in general twice that of a comparable fossil fuel car (e.g. gasoline or diesel). 'The purchase price of the Mitsubishi EV (MiEV) is more than twice that of a comparable conventional vehicle (reportedly €32,000, same as Nissan leaf €32.839 Euro)' (RETD, 2010). This price will go down, but how fast will this happen. The mass adoption effect and battery R&D are key players in the price reduction. Moreover, the general public is not willing to pay this amount of money for an EV. The early adopters such as the government and fleet operators might be willing to purchase an expensive EV. However, subsidies and tax deduction can relax the market introduction. Finance state secretary Jan Kees de Jager introduced the 'bijtelling' to 10% for electric vehicles and the exemption from BPM for these cars will be extended until 2018 (Source:

Rijksoverheid). Next, the fixed price of the electric vehicle will be discussed which is mostly determined by the battery costs, see an overview in appendix 4c.

### Fixed price

The high purchase price of an EV is mainly caused by the high battery prices and low production volumes. 'This cost grows linearly with the size of the battery pack, or the maximum range of the car. This cost premium for EVs is still compensated by the low cost of electricity compared to gasoline' (Werber, 2009, pp. 2465). Over time the electric vehicle costs are expected to decrease as the result of ongoing R&D, learning effect and mass production. According to the International energy agency (IEA) the battery costs by the year 2015 could be estimated at US\$300-600/kWh [€212-424/kWh] (IEA, 2009). According to McKinsey (2009) there is a battery costs reduction possible around 5 and 8 % per year, till the time horizon of the year 2030. Moreover, today Li-ion batteries on the market cost between 1000 and 2000 €/kWh (BERR, 2008). In extreme long term future predictions the costs of batteries can be estimated at 200 – 300 €/kWh. However, the longer the time horizon more uncertainty is involved with the predictions. This latter prediction indicates an current battery cost of €20,000 - €40,000 per vehicle and €4,000 - €6000 in future times. Finally, ING (figure in 4.3) indicates a battery costs reduction of 50% in ten years, from 600 to 300 €/kWh respectively the year 2010 - 2020. These facts indicate the price developments of batteries. Concluding that in the year 2010 the price of a battery is around 600 €/kWh and will decrease to 359<sup>29</sup> (41% reduction) in 2015. Moreover the estimations on the very long term (year 2020) is approximated on 275 €/kWh<sup>30</sup> (55% battery cost reduction over 10 years) and together these predictions are plot as the actual fixed cost difference figure 4.6. Assuming that the fixed costs of an EV is €10000,- more expensive as an comparable fossil fuel vehicle and will decrease in price following the battery development predictions, with a reduction of 55% in 10 years, resulting in a price difference of €5900 and €4500 for respectively the year 2015 and 2020. The long term predictions till the year 2030 are assumed by extending the line in a linear direction. According to Sterman (2000), innovation diffusions and growth of new products are intended to follow an S-shaped curve in some situations. Growth of products can reduce the price as result of mass production benefits. On the other hand the depletion of the raw materials (e.g. expected for lithium, see also section 6.6) can increase the price of batteries. For this reason a linear extension of the line is assumed, however, in the case lithium can be substituted by another raw material (e.g. silicon) [3] an S-shaped curve cannot be excluded.

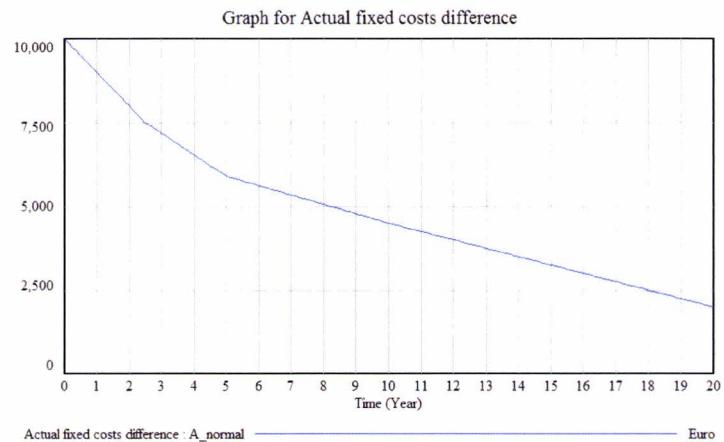


Figure 4.6: The actual fixed cost difference

<sup>29</sup> Assumed: for the year 2015 an estimate is given (€212-424/kWh) on average 318 kWh [IEA 2009]. This in comparison with the estimates of ING (€400 kWh) gives: 359 kWh.

<sup>30</sup> (200 -300 €/kWh) on average 250 €/kWh compared with ING (300€/kWh), gives 275€/kWh

## Variable price

EVs benefit from the lower cost of electricity compared to fossil fuels. Additionally there are also other 'external' factors that do influence the variable costs difference between an EV and ICE vehicles. Such as the rising oil prices which could make ICE vehicles less attractive and supports a transition to electric vehicles. Moreover, the maintenance costs are lower, but the battery devaluation as result of recharge cycles and the effect of environmental temperature have their own impact too. Moreover, there are subsidies (10% 'bijtelling' and no BPM) that should stimulate the early introduction of the EV. In figure 4.7 the upper half of the total model is depicted, in which both the fixed and the variable costs are modelled. Previously the fixed costs are discussed and represent the first quantity of the total *adopters from the price*<sup>31</sup>. The second quantity is determined by the variables cost and the average of both is taken.

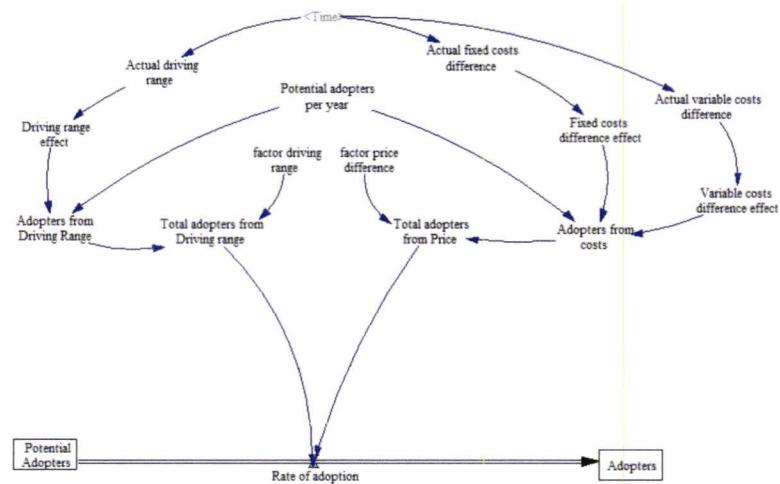
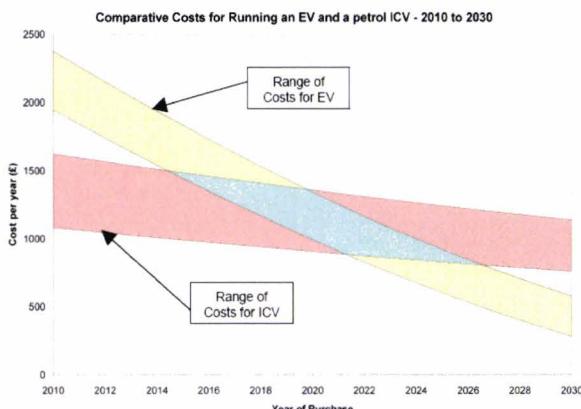


Figure 4.7: top part of the total model with two elements [driving range (left), price (right).]

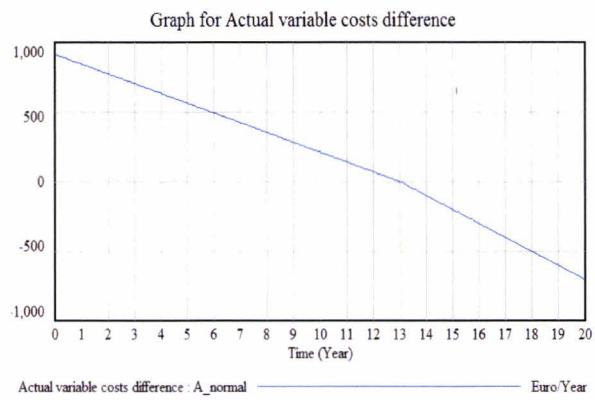
Subsequently, the actual variable costs (costs per year) exist out of different values. There is the influence of oil and electricity prices, subsidies, maintenance costs, R&D influences and devaluation of the battery through recharge cycles. Moreover, the subsidies are the best values to manipulate in these variable costs. Therefore the government can be an important player in the transition process to the electric vehicle scenario's according to the variable costs are given in chapter 6.

The devaluation of the battery is estimated at 0.50 – 2.00 € per kWh used from the battery. These costs of the battery lifetime reduction are determined on behalf of 1000-2000 lifetime cycles and the current battery price of 1000 - 2000 €/kWh (RETD, 2010). However the Department for Business, Enterprise and Regulatory Reform (BERR) constructed an estimate of the variable price comparison of the EV and the petrol ICV, see figure 4.8. Furthermore, to make a fair comparison the battery devaluation as result of the maximum cycle times is taken into account. The figure below points out the comparative variable costs and how they change over time, based on the assumptions in appendix 4.3d.

<sup>31</sup> Adopters from price, formula:  $((\text{Potential adopters per year} * \text{Fixed costs difference effect}) + (\text{Variable costs difference effect} * \text{Potential adopters per year})) / 2$



**Figure 4.8: Comparative costs for running an EV and a petrol ICV. Source: BERR (2008)**



**Figure 4.9: Actual variable cost difference**

The energy cost of ‘fuelling’ an EV using off peak electricity is approximately *one seventh* the cost of fuelling a comparable ICV. The off peak electricity price in the UK is 5pence/kWh and the day-time price is 20pence(23cents)/kWh and this is the same as in the Netherlands (23cent/kWh). In the Netherlands the ‘fuel’<sup>32</sup> costs per 100km of an EV are approximately *one third* in comparison with the refuelling of a comparable ICV. This accounts the same for the UK in peak times. Concluding that the electricity and gasoline costs are comparable with the costs in the Netherland and this validates the use of the diagram above (BERR, 2008).

Furthermore as result of the battery developments in the future the costs of battery devaluation will fall significantly and therefore the EV running costs become lower in future times in comparison with ICV<sup>33</sup>. In figure 4.8 the bandwidth indicates the higher (daytime) and lower (night) electricity prices. As can been seen the overlap shows the competitive area of variable costs between the EV and ICV, which is somewhere between 2015 and 2026. However, the diagram gives an global representation of the variable costs development and shows an crossover in the year 2023 at the variable cost of €1300,- (€1483,-). Moreover these values are used for designing the graph (figure 4.9) for the actual variable costs difference in the model. The differences in costs are defined by taken the average of the bandwidth, see below the data used with respectively, the year, the average variable costs of an ICV and EV, and the difference expressed with the delta.

[2010: £1400 ICE, £2200 EV  $\Delta$  £912,-] [2023: £1300 ICE, £1300 EV  $\Delta$  £0] [2030: £1100 ICE, £480 EV  $\Delta$  -£707]

<sup>32</sup> An EV (Nissan leaf) drives 6.6 km per 1kWh and in the Netherlands 1kWh cost about 23 cents (day time). So, driving a distance of 100km costs around €3,45. (e.g. Nissan leaf; 24kWh with driving range of 160km, see appendix3.3b ING subscript). This in comparison with the ICV including the assumption of €1.60 per litre gasoline and driving ratio of 1:16 gives the costs per 100km around €10,-.

<sup>33</sup> Increasing oil prices can increase the running costs of an ICV in future times.

#### 4.3.3 The recharge infrastructure network

Availability of charging infrastructure is essential for the market introduction of electric vehicles. The infrastructure is necessary to increase the competitiveness of the electric vehicle up on the conventional vehicles. Moreover the different charging alternatives, for instance the fast charging stations and the locations (infrastructure density) influence the electric vehicle's range and charging times, which additionally affect the possible market share. A high density of infrastructure charging points and fast recharge times (< 5min) requires a lower maximum driving range in comparison with a low density and slow recharge times. This concludes that the better the recharge infrastructure coverage and recharge time the less important the driving range could become and the larger the potential market (potential adopters). Both the adoption effects of the driving range and the recharging time are described in respectively section 5.2.1 and 5.2.4.

Yet, the number of recharging points in the Netherlands is 1774 [4], this includes the recharge points for scooters, vehicles, bicycles and boats. Further the electric car recharge point foundation e-laad, established<sup>34</sup> already 251 recharging points with a request for 537 additional recharging points for the coming year. Still, this is by far not the amount of fuel stations in the Netherlands which accounts for 4207 stations Bovag (2010), see appendix 3.3e.

Additionally, each fuel station covers multiple refuelling points and with the assumption that the average refuelling points per station is about 3, an estimate can be made of 12000 refuelling points in total for the Netherlands. Therefore it is reasonable (not necessary) to place at least the same amount of electric recharging points to satisfy the current consumer perceptions about recharge/-fuel possibilities. Moreover, the development of the recharging infrastructure is related to the adoption process of the electric vehicle. In the case of the electric vehicle, it can be described as 'the more recharging stations there are, the more attractive electric vehicles become. Attractiveness in turn leads to demand and sales, which expands the installed base of electric vehicles' (Walther, 2010). For this reason the government places recharge points, in the hope that this stimulates the evolution of a total recharge infrastructure network in the Netherlands and simultaneously the adoption process of the electric vehicle. Take for example the province Zeeland that initiated a total coverage of recharge points in their province with 75 recharge points [5].

Furthermore, there has been an agreement about the development of total recharge infrastructure coverage. Together the grid owners (netwerk beheerders), energy suppliers (Energie-Nederland) and a leading group of cooperating municipalities agreed on February 18, 2011 that electric vehicle drivers from throughout the Netherlands do not have to worry about an empty battery, meaning that enough recharge stations will be realized this year. These charging points will be installed in at least 10 areas, including Amsterdam, Rotterdam, Utrecht and the province of North Brabant. All loading points allow electric drivers to charge their vehicle with one standardized pass system [6].

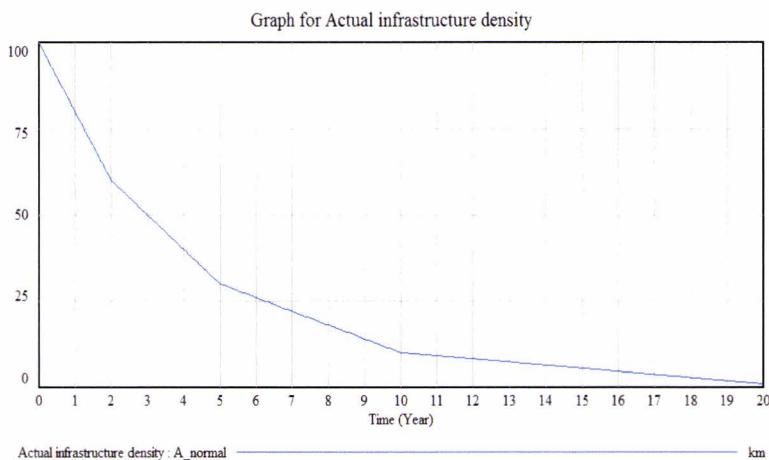
According to this section, it is assumable that a total coverage in the Netherlands requires at least 10000 recharge stations (e.g. approx. 12000 fuel stations). Hence, this is an appropriate amount for the early stages of the adoption process, later on there are too many electric vehicles and this increases the chance on congestion at recharge stations as result of the high re-'fuel' times. Further

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<sup>34</sup> Date: April 2011

readings about recharge infrastructure solutions and scenario's can be found in the Power choices report, 'Pathways to Carbon-Neutral Electricity in Europe by 2050'.

The system dynamic model used in this research see appendix 4.1a, the actual infrastructure density is expressed in distance between two recharge points, with a range between 0 and 100 km. A total coverage is estimated at 10000-12000 recharge stations and this is the same as the amount of fuel points in the Netherlands and is comparable with a 10 km distance between two recharge stations (e.g. current fuel station density). Furthermore, in the beginning of the year 2009, there was an intension to create a total coverage of recharge infrastructure (10000 stations) in the year 2012. [7]. However, this is far too optimistic, because following the rules of the government, e-laad has only the ability to place at maximum one recharge point per 10000 residents in a municipality. This means that in the Netherlands with a population of 17 million people a maximum of 1700 recharge points is allowed for e-laad. All together, it is unlikely that 10000 recharge points are placed in 2012. Therefore, the assumption is made that the target of 10000 recharge stations or a cross country density of 30 km between two recharge points<sup>35</sup> will be achieved in 2015. Therefore figure 4.10 depicts the actual infrastructure density with on the y-axes distance between two stations and on the x-axes time in years.



**Figure 4.10: Actual infrastructure density**

#### 4.3.4 Recharging time

In overall an electric vehicle requires a battery capacity of 40kWh or more to drive a 200 km range (RETD, 2010). However in the beginning of 2011 the Nissan leaf made its entrance in the Netherlands with the following technical specification. One type of charging is slow charging and requires a power of 3,7kW (230 V/16 A), this is corresponding with the average power per house. This indicates that it will take about 6,5 - 7 hours to recharge the Nissan

##### Fact sheet Nissan Leaf

Accu: lithiumion, 24 kWh

Oplaadtijd: 7 uur (230 V/16 A)

Bereik: 180 km (NEDC)

Motor: 80 kW – 280 Nm

Lx B x H: 4.450 mm x 1.770 m x 1.550 m

Prijs: +32.829 euro

##### Specification sheet Nissan leaf.

<sup>35</sup> These points indicates the possibility to recharge every 30 km without the possibility that congestions occur at these recharge points (it is possible that a cluster of multiple recharge points are placed in a small area, this however accounts for one recharge point).

leaf in your garage. In the case of three phase charge station there is an recharge power about 22kW (440 V/32A), these types of recharge points are commonly used in large homes, offices and firms. According to these specifications the recharge time of the Nissan leaf can be reduced to approximately 1 hour.

Still this could be a problem when recharging an electric vehicle in public places. However, this type of fast recharging could be ideal for a quick recharge en route at public places. Besides the two types of recharging possibilities there is also another which is mentioned as a fast charging station. This type of recharging has the option to recharge with 50-250 kW (400-600V/125A [DC]). However it also has some disadvantages, because these recharge stations are heavy a large (expensive), meaning that there is no possibility to place this type of recharge station into the electric vehicle. Additionally, this makes it complicated to recharge the electric vehicle at home. Another issue is the maximum of 80% a battery can be recharged with a fast recharging station, further recharging will damage the battery heavily. [8] [9].

Charging the battery (max. 80%) with a fast charging station takes about 25 min (50kW used at the Dutch railroad) and in future times when the battery is commercially prepared for charging with 250kW it will require approximately 5 minutes to recharge, which is comparable with the refuelling time of a fossil fuel tank. Nonetheless, the exact impacts of fast charging on battery lifetime and charging efficiency is still to be determined (RETD, 2010).

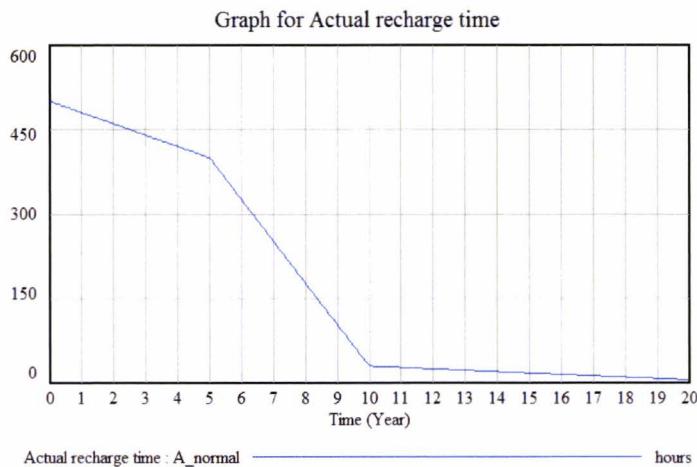
There is much uncertainty about the development of a fast recharge infrastructure in the Netherlands. According to various web sites [10] [11] 25 fast recharging stations will be placed this year (2011) in the Netherlands and this is far not enough to cover the Netherlands. In previous section it is mentioned that at least 10000 recharge stations are required for a decent coverage in the Netherlands. Furthermore, it is assumable that there is an decent slow charging infrastructure in the Netherlands by the year 2015 (see section 4.3.3). Covering the Netherlands with an fast recharging infrastructure requires an investment which is much more. Notice the price difference in charging stations; slow stations costs about 3000-4000 Euros and the costs of a fast charging station is about 50000 Euros. [12]

Therefore the figure 4.11 below represents the development of the actual recharge time<sup>36</sup>, which is based on the facts mentioned in this section. The assumption is made that the difference in costs and size of fast recharging stations delays the placement, with the result that total fast recharge coverage will be achieved in the year 2020.

Further improvement of the recharge time is speculated on the facts that there is a range possibility to use a charge station with a power of 250kW and assuming that the battery technology will allow this in future times. Concluding that there is a total coverage with slow recharge stations (6-7 hours, 3,7kW[at home]) in the year 2015, and a total coverage of fast recharge stations (30 min, 50kW) in the year 2020. In line with the technical possibilities to recharge with 250kW a model assumption is made that in the year 2030 a total coverage is achieved in the Netherlands to recharge an electric vehicle within 5 min.

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<sup>36</sup> This is the maximum time needed to recharge an EV at that point in time at *public places* all over the Netherlands.



**Figure 4.11: Actual recharge time (the line represents a total coverage)**

#### 4.3.5 Weight-factor

According to step 6 in section 4.1, the weight-factor manipulates each of the four elements in the model. This factor is examined by the survey and allows differentiating the four elements from each other in importance. The results of the survey are given in appendix 4.3f, and indicate that the fixed price is the most important factor in the decision moment to purchase an electric vehicle and this is also confirmed by a survey ‘groene mobiliteit’ conducted by Bosch (Bosch, 2009). The percentages in table 1 of appendix 4.3f are used in the model. These are for price 56%, driving distance 24%, recharge infrastructure 9% and 7% for the recharge time. Concluding the maximum driving distance is also an important factor. However, when asking for the second decisive element in the purchase process (appendix 4.3f, table 2), three elements (price, recharge time, infrastructure) are intended as equally important. The reason for these results and the relationships between these elements could be analysed in future research.

## 5. Data collection and results

### 5.1 Survey design

The survey used for this research is conducted with the purpose to gather information about the adoption effect (moment of purchasing) related to the four elements in the model. After collection this data is transformed in useful adoption behaviour graphs. The survey assesses the consumer willingness to adopt an electric vehicle in relation with the four key elements. Questions used to exam the adoption behaviour in relation to the four key elements and the weight factors are depicted in appendix 4.1b. Respondents are asked to give an acceptable value on the scrollbar (e.g. acceptable minimum driving range distance with one full charged battery). The cumulative percentage of respondents at a certain value are plot as adoption behaviour graphs, supplementary information is given in this chapter. The target group of this research is the Dutch passenger road transport, which constitutes approximately 8 million vehicles (BOVAG, 2010). From which a selected group is taken with an age between 18 and 75 years, and in possession of a driving licence. The survey is split up in different types of questions. One part exams the effect of the four main elements plus a weight-factor, respectively, the driving range, purchase price, recharge infrastructure network and recharge time which is used for this research.

A second part is concerned with general questions related to the technical knowledge and characteristics of the respondents, which globally measures their innovativeness. Yet, some data about the characteristics and technical knowledge of the respondents is given in chapter 7 of the full output report<sup>37</sup> of the survey. For future research a more specific measure of this innovativeness can be analysed. This latter explanation gives the possibility to categorize the respondents on their sense to innovation adoption, which is in relation to their adopter characteristics (Rogers, 2003; Hauser, 2006). This is done, because it is known that early adopters and the early majority differ in their approach to a new technology (Rogers, 2003).

#### 5.1.1 Sample size

The minimum required sample size of the survey is calculated at n=386, see formula (right). In which the population (N) represents the Dutch passenger road transport and constitutes approximately 8 million vehicles (BOVAG, 2010). The standard deviation (z) is set on 1,95 with a 95% confidence, this can be calculated with a statistic table as is defined in (Montgomery and Runger, 2007). Increasing the precision of the confidence percentage would require a sample size almost as double. A more precise calculation is costly and ineffective because of the many assumptions made in the model. Furthermore, the (p) represents the percentage chance someone gives a certain answer. For a market research an error margin (F) of 5% is commonly used.

$$n \geq \frac{N \times z^2 \times p \times (1-p)}{z^2 \times p \times (1-p) + (N-1) \times F^2}$$

<sup>37</sup> The full survey output report (file) is in possession of Ballast-Nedam. Title: 'Elektrisch rijden in de toekomst'

## 5.2 Statistics

In this section the results of the conducted survey are discussed and statistics provided by another survey (Bosch, 2009)<sup>38</sup> are used as reference material. In chapter 4 the technical specification of the four elements of the system dynamics model are discussed and have been related to the survey outcomes that will be discussed in this chapter.

### 5.2.1 Driving Range

The graph in figure 5.1 conducted from the survey indicates the cumulative percentage<sup>39</sup> of potential adopters per year, which will purchase an electric vehicle in relation with the maximum driving range of an electric vehicle. The most remarkable from this graph is that an extra 57% of the adopters is achieved when the driving range develops from 255 km (10%) to 465 km (67%). Moreover this driving range development starts in year 2018, according to the driving range estimations in section 4.3.1. As such the most intensive amount of adopters as result of the driving range will occur in the time line from 2018 till 2028. Furthermore, the current maximum driving range is around 160 km, this is by far not enough and will only be accepted by 3% of the survey respondents. The graph on right is used as input for the driving range effect variable in the total model. According to the ADAC (heft 8, aug 2010) and Bosch (Bosch, 2009) one third of the passenger vehicle drivers hopes for a driving range more than 500 km, this is remarkably the same respond as measured by the survey in this research.

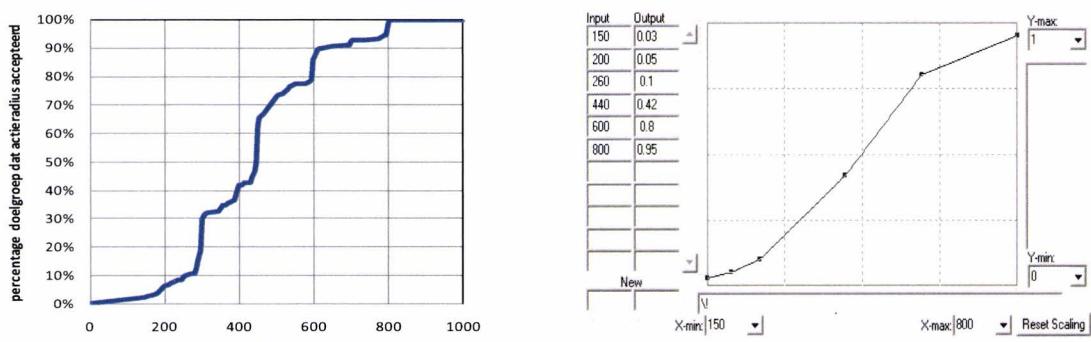


Figure 5.1: results of driving range response from survey (left) and the same results projected in the Vensim model (right).

### 5.2.2 Price

Fixed price difference and the variable price (or yearly price) difference between an EV and a ICV is brought into relation with the respondents. The graphs (figure 5.2 & figure 5.3), respectively indicate the percentage of potential adopters per year, which will purchase an EV in relation with the fixed price and variable price difference compared to an ICV.

<sup>38</sup> In this representative study 1000 Dutch and Belgium vehicle driving respondents were asked.

<sup>39</sup> The graph is the result of the cumulative percentage of respondents related to a certain value (answer), form the survey data set a graph is created by the use a calculation program (excel).

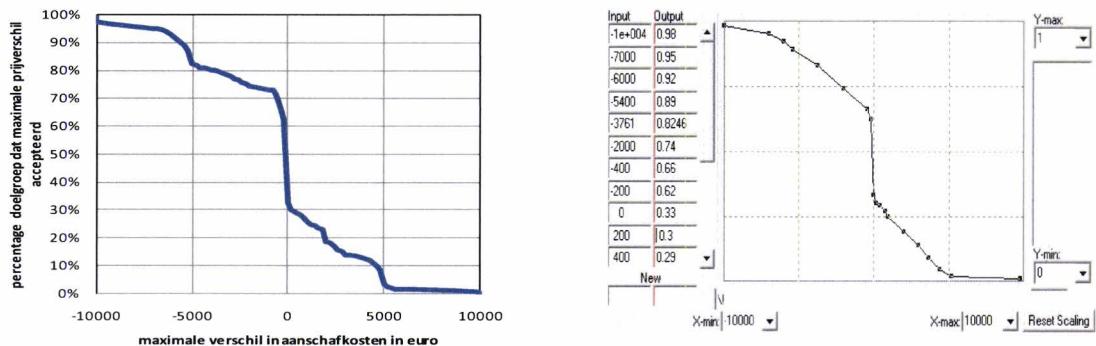


Figure 5.2: results of the fixed price response from the survey (left) and the results in the Vensim model (right).

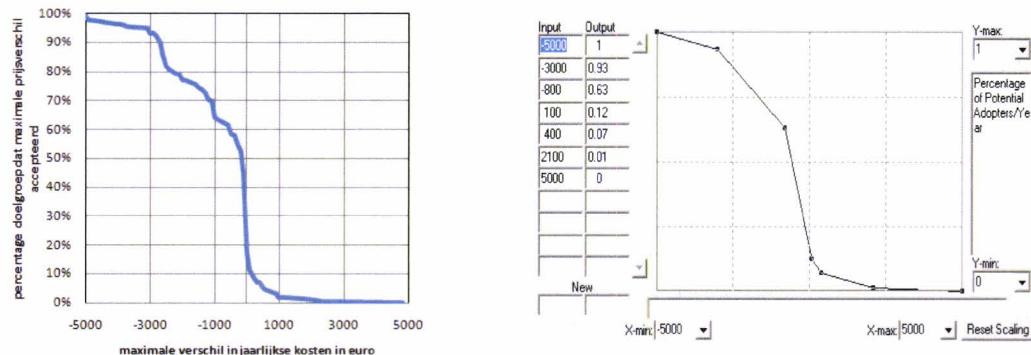


Figure 5.3: results of the variable (yearly) price response from the survey (left) and the results in the Vensim model (right).

Remarkable in both graphs is the steep decline on the zero price difference line. Large numbers of the Dutch passenger drivers are expected to accept an EV when the fixed and also the variable price are equal to the ICVs price of today. However, according to the estimates in section 4.3.2, a zero fixed price difference between an EV and ICV is not to be expected in future times, because of the slow battery price reduction.

*'Governments are therefore advised to provide a temporary financial relief for the additional vehicle cost to end-consumers. This can take the form of a fiscal incentive, such as reduced registration tax, subsidy on the battery cost (€/kWh) or the stimulation of alternative business models e.g. via battery leasing'[RETD, 2010].*

Furthermore, the variable costs difference influences the total cost of ownership and the variable costs for an EV are expected to be zero in year 2023 (see section 4.3.2). After the year 2023 an EV owner is expected to save costs in comparison with a ICV. Moreover, a windfall for the industry is that 69% accepts a higher purchase price as the lowering variable costs made a compensation (Bosch survey, 2009). Concluding, the total cost of ownership need to be brought to an equal level as for the ICV. Adopters (purchasers) do have the tendency to value incentives at the time of purchase (fixed costs) higher than incentives during the use of a product (variable costs), this is called 'consumer myopia' (Frederick, Loewenstein & O'Donoghue, 2002). So, mechanisms focussing at reducing the

fixed price are more effective for the adoption process compared to the variable costs reduction of EVs.

Concluding from both figures above, higher fixed costs are indeed accepted by a larger part of the respondents as with the variable costs. The results indicated a 30% acceptance for higher fixed costs compared to a 10% acceptance for higher variable costs. In the scenario analyses in chapter 6 the influence of subsidies and other costs reducing instruments up on the adoption process are discussed.

### 5.2.3 Recharge infrastructure network

One important fact is that the daily driving distance in the Netherlands comparable is with the current maximum driving distances of an EV. Notice that the maximum driving distance of an EV about 160 km entails (e.g. Nissan leaf) and the daily average driving distance in the Netherlands indicates that 91% of the Dutch drivers drive less than 150 km a day. Furthermore, in future perspectives when there is the fast recharge infrastructure with 50kW/h, drivers only have to recharge 30 min every 150 km they drive. Meaning only 9% of the Dutch passenger vehicle fleet have to recharge once every daytrip (appendix 5.2a). Moreover, on average Europe's mean travelling distance every day is 25 - 30 km [13] and in the Netherlands the passenger vehicles drive about 44 km a day (CBS) (Enexis, 2009).

The problem about the maximum driving distance is related to people using their car for long distances (e.g. holidays). Although, there is still a huge market share left that covers the demand specifications for driving the average daily distance. Availability of fast charging station makes it possible to use the EVs for driving longer distances and therefore reduces the 'range anxiety' of consumers (RETD, 2010, pp. 20; Saqib, 2010). According to some field trials in Sweden and France, the fast recharge infrastructure was hardly used because the experience is that 'EV users will not stop to charge but will rather charge where they stop' (RETD, 2010). The practical function of fast recharging provides less importance as the psychological one. Figure 5.4 below indicates the accepted recharge infrastructure density. Approximately half of the respondents accept a distance of 40 km between two recharge points.

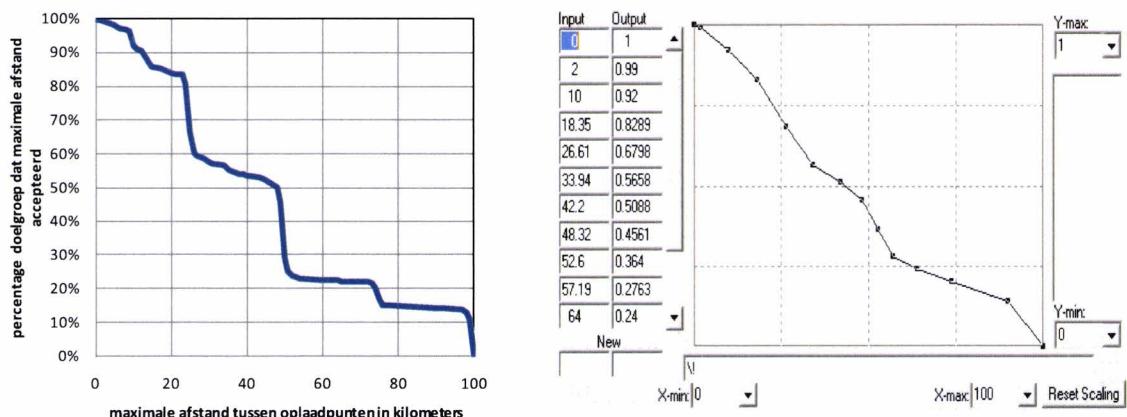


Figure 5.4: results of the variable infrastructure density response (left) and the results in the Vensim model (right).

According to section 4.2.3, the estimation is made that in about 3 years an infrastructure is established which entails a maximum distance of 40 km between two recharge points. Another remarkable point is an increase of 60% in adopters when the distance decreases from 50 km to more or less 20 km. This decrease in distance takes place in the time scale 2013 to 2018 following the estimations mentioned in section 4.2.3. Concluding that there is also a higher adoption rate per km increase between charge points in small distances (future situation), compared to the higher distances (current situation). So, faster adoption will occur in the future times as result of a higher infrastructure density.

#### 5.2.4 Recharge time

Recharging an EV takes a while when using the power capacity at home. In section 4.3.4 the technical possibilities and future estimates are given. The results from the survey (figure 5.5 & 5.6) below indicate that people accept a larger recharge time at home compared to recharging in public places. However, it is reasonable that respondents do not have an accurate sense about the recharge time. But, some remarkable points can be analyzed from the survey results. One of the most remarkable points is the high increase of adopters in the case of public charging as result of time decrease in recharge times > 100 min (see. figure 5.6). Moreover, this is not the case when charging at home, it points out that the respondents are less sensitive for lowering the charging times at home.

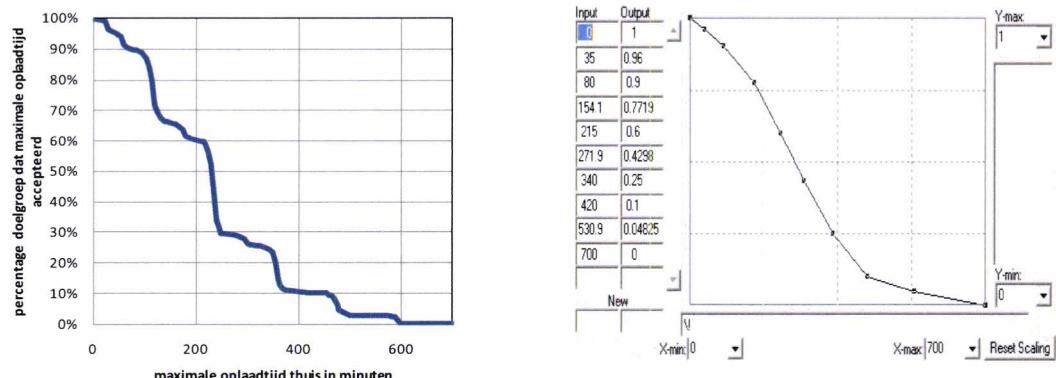


Figure 5.5: recharge time (at home) response (left) and the results in the Vensim model (right).

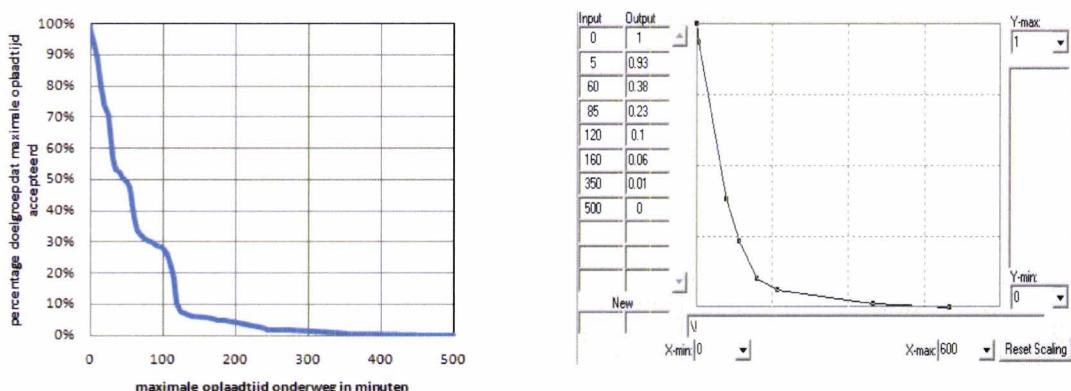


Figure 5.6: recharge time (in public) response (left) and the results in the Vensim model

Furthermore, there are different types of recharge power station each related to a specific recharge time (see section 4.3.3). The development of a fast recharge station infrastructure may have a major impact on the amount of adopters. According to section 4.3.4, in which the figures indicates the actual recharge time developments and the responds on the public recharge time, it is reasonable to conclude that a fast recharge time of 30 min in public accounts for an acceptance of 57% from the respondents, this is assumed to occur by the year 2020. Charging times lower as 30 min will result in a tremendous increase in adopters. This is concluded from the steep response line in figure 5.6 which indicates a remaining 43% of adopters in a time range of 30 min. Concluding that recharge time improvements (>30min) account for a sort of ‘mass adoption’ situation and will occur from the year 2020 and further. However, in the scenario analysis in chapter 6 the adoption effect as result of fast charging times is tested.

## 6. Scenario & test analysis

In this chapter some scenarios and tests with extreme value changes in the model are given. Testing the model is requisite to detect flaws. Therefore some variables in the model are set to extraordinary high and low values.

### 6.1 Basic scenario

The basic scenario is based on the values explained in chapter 4 and 5. Upcoming scenarios use the same values for the model as in the basic situation except from the variable that is tested or changed to simulate a particular scenario. Outline of the values used in the basic model are given in appendix 6.1a. The basic model uses the public recharge time as input, because charging at home is already available for almost everybody and therefore the effect of fast charging which is a future option for public charging can be analysed. Together all basic values result in the Graph for adopters<sup>40</sup> (figure 6.1). Figure 6.1 shows an exponential growth of the population of Adopters, characterized by a slow but steady growth in the beginning (year 2010-2019), and a large growth in the end (year 2020-2030). The reason for this ‘boost’ is probably the fact that most of the remarkable points in the adopter graphs as discussed in chapter 5 are around year 2020. Driving range improvements from the year 2018 cause a heavy increase in adopters. Variable costs difference is expected to become zero in the year 2023, which also accounts for a major increase in adopters. Furthermore, the fast recharging network expected in about 10 years creates an additional major amount of adopters. According to the basic model more than 100.000 full electric vehicles is expected in 2020, based on the data from the survey, literature and the assumptions made in chapter 4 and 5. Apprehend that the simulation is given for a time horizon of 20 years, and that the first 10 years are based on the most reliable data and that the longer forecasts incorporate an increasing amount of uncertainty.

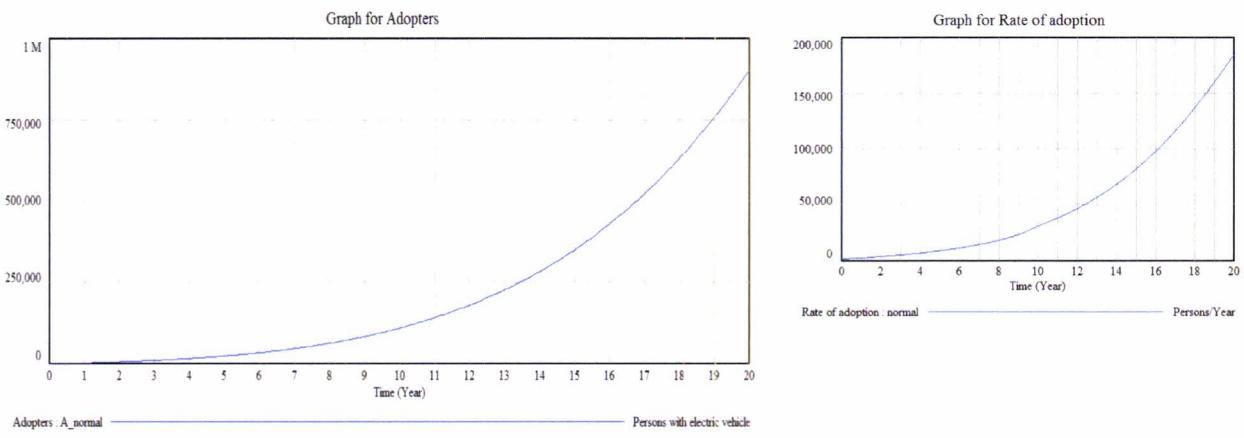


Figure 6.1: The graph of Adopters, basic model. Right the total adoption and left the rate of adoption

<sup>40</sup> According to the survey results; 30% of the respondents is *in doubt* to purchase an electric vehicle as their next car; 15% of respondents are *pretty sure* to buy an EV as next first car and 9% is *completely sure* to buy an EV as the first car (see appendix 4.1c). Hereby the assumption is made that 9% of the annual 480,000 ( $0.09 \cdot 480000 = 43200$  potential adopters per year) new cars registered are used as standard value in the model during the whole time line. Furthermore, in appendix 6.1b two graphs are presented that indicate the of both, respondents that are pretty sure and completely sure to purchase an EV as their next car.

## 6.2 Scenario situations

Scenario situations are useful to create insights for the model and to make the assumptions more reliable. For instance the recharge time in public is assumed to be less than 30 min by the year 2020. However this development depends on many other variables, such as the government, technical possibilities or financial issues. Therefore this section tests different situations of different variables from which the assumptions made in chapter 4 & 5 can be analysed.

The first scenario encompasses the effect of word of mouth, in which the intensive effect as result of the mass adoption is discussed. Secondly, the price which is the most important element of the model is simulated and the effects of subsidies on the adoption graph are shown. As third the driving range effect is modelled in a scenario and incorporates the issue when the battery performance increases heavily. The fourth and the last scenario, analyses the assumptions made in the model concerning the development of the infrastructure and the recharge time. Additionally, the results of the scenarios are discussed in detail per sub section and at the end of this chapter a conclusion of all scenarios is given that incorporated linkages between the scenarios and provides an realistic overview.

### 6.2.3 Word of mouth

Adoption by word of mouth is driven by the contact rate between potential adopters and active adopters and the fraction of times these interactions will result in adoption (Sterman, 2000). The adoption fraction is assumed to be 0.01 and this indicates the fraction of times a contact between an active adopter and a potential adopter results in adoption, which is 1 adopter per 100 contacts. Moreover, the value for the adoption fraction is commonly estimated from sales data, but in the case of the electric vehicle this is not possible because of the lack of sales data. Therefore, the assumption value 0.01 is tested by creating different scenario situations. In figure 6.2 (left) a high, normal and low adoption fraction, respectively 0.1, 0.01, 0.001 is simulated. Moreover in the case that one in ten (0.1) contacts results in a new adopter, then the maximum amount of potential adopters of 8.5 million is already reached in 2011 and this a very unrealistic situation. Therefore, an approximation (figure 6.2 [right]) to a realistic number is simulated and shows the extreme sensitivity of the adoption fraction effect. Concluding the effect of word of mouth is low in the first years and very intensive at the end phases of the adoption process.

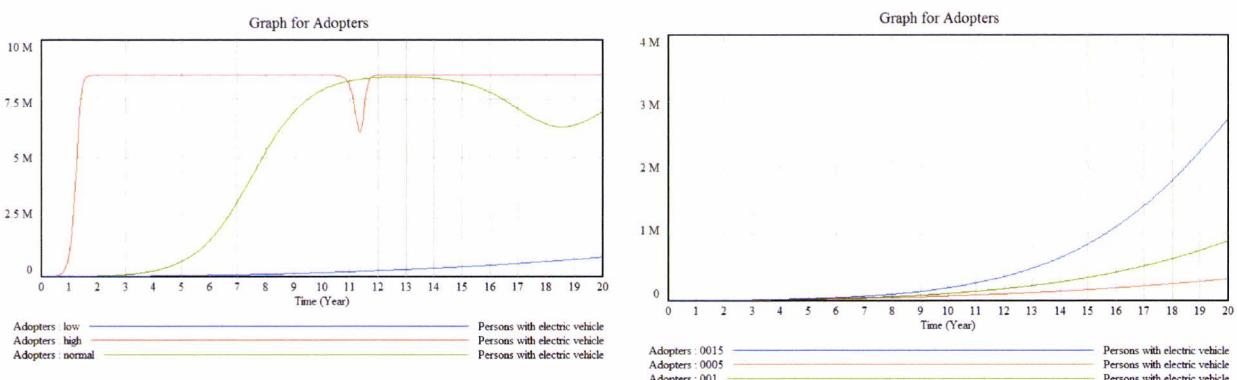
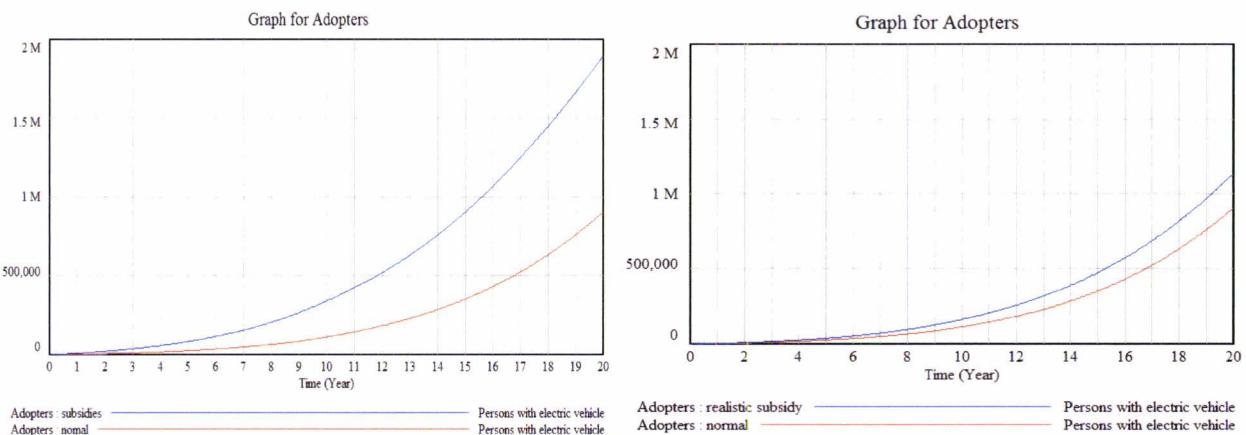


Figure 6.2: adoption fraction effects, high, normal ,low (left) realistic approximation (right)

Remarkable is the dip in the graph when simulating with a high adoption fraction. The reason for this is the delay in the model that is used for modelling the lifetime of the battery. The lifetime of the battery is set on 10 years and this is exactly the time span that the dip occurs after the start of adoption. Furthermore, the degree of the 'dip' depends on the speed of adoption.

#### 6.2.4 Price difference effect

The price difference between an EV and a ICV is the most crucial element that potential adopters keep from their decision to purchase an EV. According to the adoption graphs in chapter 5 the area around a zero price difference has the most effect on the adopters. In contrast to the driving range, the price difference can be artificially influenced through subsidies given by the government. Therefore the subsidy scenario is given, in which different amounts of subsidies are analysed. Creating a zero price difference for the fixed and variable costs requires respectively the subsidies 10.000 euro and 1000 euro, which are initiated in year 2010. In figure 6.3 on the left the effect of the subsidies is depicted. Reasonably the amount of adopters increases and concluding from this scenario, the 'boost' is shifted to the left in the region of 2016. Moreover, this high amount of subsidies is not realistic and therefore another scenario with only a subsidy of 5000 euro on the fixed price is given in the first 8 years. The 5000 euro is based on the average BPM of an normal passenger vehicle and the 8 years are based on the subsidy rule of the government, which is set until the year 2018 [14].



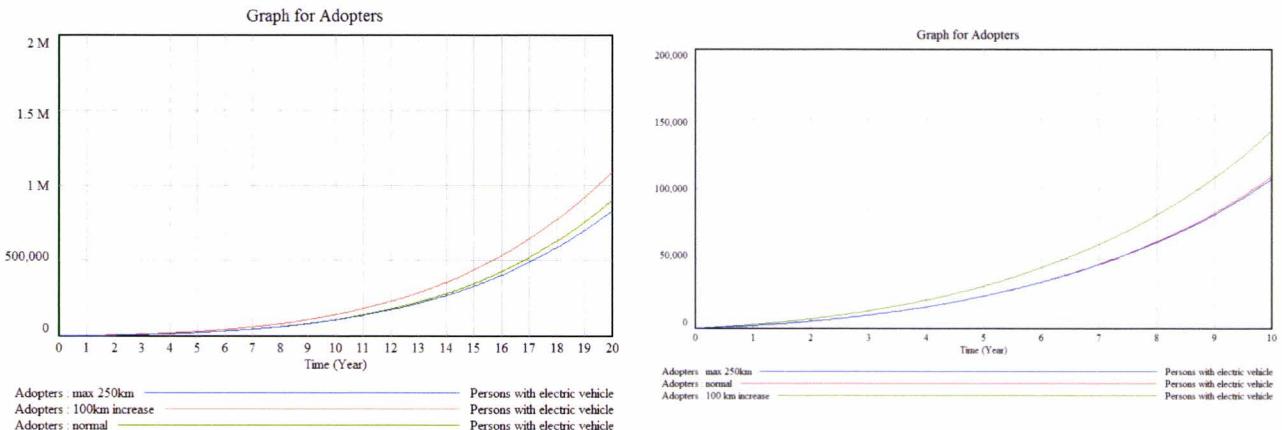
**Figure 6.3: The adoption effect of subsidies unrealistic (left), realistic situation (right)**

Remarkable from the two price scenarios depicted in the figure above, is the major increasing effect of subsidies as result of approaching the zero costs difference line as is discussed in section 5.2.2.

#### 6.2.5 Driving range effect

According to the facts in previous chapters the maximum driving range in 2020 is estimated at 300 km and the most potential adopters are expected to purchase an EV with a driving range of 255 km and further. However the current maximum driving range is about 160 km. Analysing the effect of the driving range therefore requires at least an increase of 100 km ( $160 \text{ km} + 100 \text{ km} = 260 \text{ km}$ ). Two

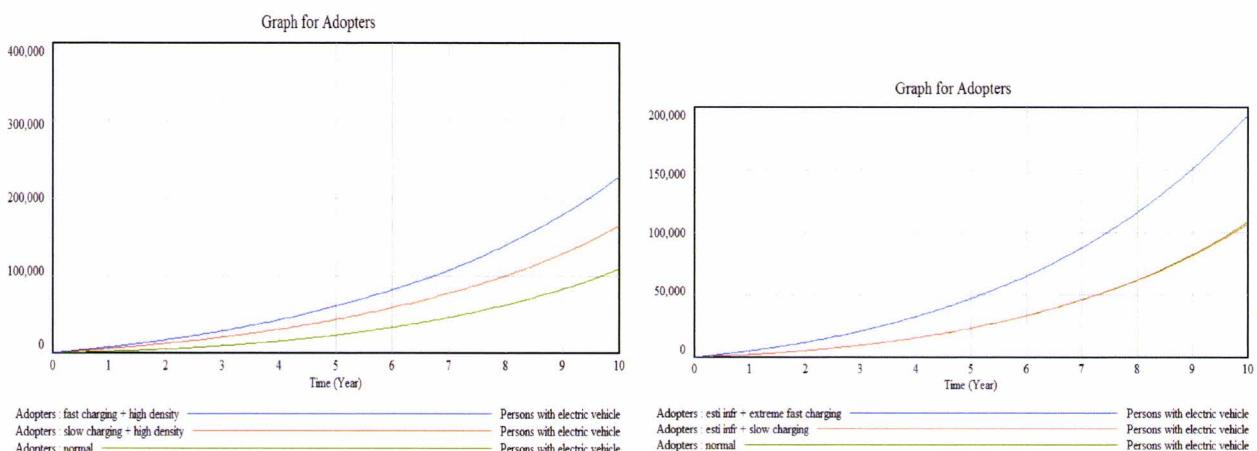
scenarios are given, one with the driving range increased with 100 km over the whole time line and the second with a maximum range of 250 km for the whole time range. The latter one indicates a technological limitation of batteries. The simulations shown in Figure 6.4 show a small adoption effect in comparison with the effect of the high subsidy in the previous scenario. However, these are comparable with the realistic subsidy rule of 5000 euro as explained in previous scenario.



**Figure 6.4:** the driving range scenario effect, 20 year time scale (left), 10 year time scale (right)

### 6.2.6 Infrastructure network and recharge time effect

In this section the infrastructure network and the recharge time effects are measured. There are two scenario's given, the first encompasses an early (year 2010) total coverage of a slow (8 hours) and a fast (30 min) recharge infrastructure with a density of 10 km. Secondly, an extremely fast (5 min) and slow (8 hours) recharge time is simulated with use of the estimated infrastructure as defined in chapter 4 and 5. This extremely fast charging scenario represents the battery switch technology which indicates that recharging is replaced by switching the battery within 5 min. The time range is set to 10 years, because this better shows the effect of the infrastructure and recharging times in the early phase of the adoption process.



**Figure 6.5:** first scenario (left), second scenario (right)

From these simulations, it can be concluded that the population of adopters increases as result of both a high infrastructure density and a fast charging time. Remarkable is the high increase of adopters as result of the extreme fast charging time (second scenario) with the estimated infrastructure. On the other hand, slow charging times (second scenario) have no effect on the adoption process. Furthermore, in the first scenario the slow charging with a high density of infrastructure increases the amount of adopters with at least 50% and in the second scenario the slow charging with the estimated infrastructure has no influence. This suggests that it is useful to increase the infrastructure density in the early phase of the adoption process when fast charging is not optional.

#### 6.2.7 Conclusion of the scenario simulations

Concluding from the scenarios<sup>41</sup>, the basis adoption model shows an exponential growth of the population of adopters, characterized by a slow but steady growth in the beginning (year 2010-2019), and a large growth in the end (year 2020-2030)<sup>42</sup>. The reason for this ‘boost’ is the fact that most of the remarkable points in the adopter graphs as discussed in chapter 5 are around year 2020. This indicates that the specification of the four elements fit with of most of the consumers’ needs. Concluding from all scenarios, the word of mouth effect has an extreme impact on the later stages (year 2020-2030) of the adoption process. Therefore, Ballast-Nedam is forced to place their infrastructure before the mass adoption occurs. Because at the moment of ‘boost’ in the year 2020 the consumer needs are met by the battery specification and it is reasonable that other companies foresee this and anticipate by previously place their infrastructure, while these infrastructure is the only element that is missing and therefore plays an important role in the years before the boost. According to the price scenario, high subsidies can heavily increase the amount of adopters. The more realistic situation of subsidies indicates a somewhat equal increase as is given in the driving range scenario. Given that a subsidy of 5000 euro in the first 8 years has the same effect on the adoption process as is reach with an increase in driving range of 100 km over the whole time line (20 years). Additionally the most potential adopters are expected to purchase an EV from 255 km and further. Another scenario related to the driving range simulates a maximum range of 250 km through technical limitations of the battery. Because of this the results show a bit lower amount of adopters on the long term perspective. An important aspect for Ballast-Nedam is the high sensitivity of price in the adoption process. Therefore, BN should keep control over the development of the fixed price of electric vehicles and the elements that influence this fixed price, such as; BPM reduction, subsidies, mass production, battery developments and so on. Keep control over the fixed price more important than keep control over the driving range developments. Because, an increase in driving range occurs slowly and is better to keep control over and the fixed price can for instance be changed in one day

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<sup>41</sup> Note that the scenarios show a value change of one particular element and that the rest of the values is given following the basic model value and assumptions.

<sup>42</sup> The first 10 years are based on the most reliable data and that the longer forecasts incorporate an increasing amount of uncertainty.

though the introduction of extra subsidies, the occurrence of effect on the adoption process is in the price situation much faster.

Chapter 4 defines the development graphs of the four crucial elements in the model, based on research reports the expectation for the maximum driving range and also the price developments in future times are discussed. However, the infrastructure network and recharge time developments are difficult to predict and based on several assumptions. For this reason the final scenario in this chapter test the assumptions about the recharge infrastructure network and the recharge time. See figure 6.5 and compare both lines; (left) slow charging + high density & (right) est. Infr. + slow charging. Concluding from this is that a high density of recharge points has a remarkable 50% increasing effect on the adoption process, compared to the normal estimated infrastructure with slow charging. Furthermore, battery switching takes about 5 minutes and shows in the scenario that it doubles the amount of adopters compared to the basic situation. This extreme effect is explained by the section 5.2.4, in which is declared that the largest part potential adopters, adopts when charging times are < 30 min. BN in this case, can play an important role in the development of the adoption process by placing fast charging stations. However, when other firms start placing fast charging stations then probably the adoption process accelerates heavily and the situation may exits that BN is too late to get in. Therefore, keep control over fast infrastructure density project of other firms and get in when just before it starts to become a serious fast recharging network.

## 7. Conclusion

### 7.1 Conclusion

#### *Intro (theoretical)*

The evolution of the electric vehicle creates projects concerning the development and placing of the grid-based electric systems. This infrastructure system is needed to be able to recharge the electric vehicles across the country and these projects are an interesting opportunity for Ballast-Nedam. Yet, the future development of the electric vehicle sector is still unknown. Analysis about theories and practices associated with the adoption process of the electric vehicle are provided in this report. It is known that many elements at different levels of perspectives do influence this process. According to the technology transition (Geels, 2002) and diffusion of innovation (Rogers, 2003) literature, the process of adoption initiates with a niche (Schot et al., 1994; Kemp et al., 1998). Here in such niche new ideas develop to useful technologies (e.g. the technology transition from fossil fuel vehicles to the electric vehicle). Characteristics of the individuals in such a niche do have a fit with the current technological specifications and are therefore intended to adopt a certain product at first. According to Schot et al. (1994) and Kemp et al. (1998), the first group of adopters create a grip in the market, from which ‘learning processes related to the core product itself and to supporting technologies and institutions accelerate’ (Gärling and Thøgersen, 2001, pp. 56). Additionally, regimes of the socio-technical system, such as, social groups and, political and institutional networks get involved with the first group of adopters. A huge amount of actors become involved each with its own influence on the adoption process. Some examples are the deep structured elements that slowly change and contain factors, such as; ‘oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, and environmental problems’ (Geels, 2002). Moreover, there are also influences on the lower levels of perspectives, such as; the consumer preferences, technical specification, subsidy programs, emission rules, technical standards, safety rules and so on. Being able to model all these influences creates a high amount of complexity, because all these different elements in the socio-technical system are aligned to each other. For this reason the focus is given on the consumer perspective. Academic literature shows a diffusion model that is used for modeling an adoption process from the consumer perspective. I used this bass diffusion model and simulated by using a software program the adoption process. This is a growth model applicable for the timing of consumers’ first purchase of a new product and is used as forecasting tool for the diffusion of innovations (Mahajan et al., 1990). However, new products are commonly not accepted at once by potential customers and some resistance exists. Therefore, it is of strategic importance to accurately measure the potential customer willingness to adopt Goldsmith and Hofacker (1991).

#### *Selection and describing the specification of the crucial elements (theoretical)*

I defined the consumers in two groups; the potential adopters, representing the Dutch passenger vehicle fleet and the actual adopters, representing the amount of consumers driving an electric vehicle. Moreover, the purchasing moment or in other words the transition from potential to actual adopters is influenced by four crucial elements related to the electric vehicle, in terms of *price*, *limited driving range*, and *high refuel (recharge) times*. In addition, the purchase moment of an electric vehicle is also influenced by the *lack of an infrastructure for recharging* (Gärling and Thøgersen, 2001). These four crucial elements are selected from the academic literature and I confirm that these are the most crucial because they differ at most compared to the specification of the conventional fossil fuel vehicles and therefore are the most decisive in the consumers' purchasing moment of an electric vehicle. However, the *Rate of adoption* which is the relative speed with which an innovation is adopted by members of a social system and is generally measured as the number of individuals who adopt a new idea in a specific period' (Rogers, 2003 p221), is an important aspect for developing an adoption model.

Therefore, once I defined the crucial elements from the consumer perspective and answered with this research question 2<sup>43</sup>, I started designing a survey in which the willingness to adopt an electric vehicle is measured from 388 respondents. These respondents represent the potential adopters<sup>44</sup>, from which I analysed the degree of acceptance regarding the four crucial elements. The cumulative answers per survey question given by the respondents are transformed into adoption graphs. From this on I made it possible to simulate the degree of acceptance per crucial element, this answers research question 3<sup>45</sup>. Further I defined the future technical developments of the four crucial elements and linked these with the adoption graph. This provided me the total adoption model of this research.

### *Model outcomes*

The basic adoption model as result of my creative thinking to transform survey data into useful data for the adoption model and by using academic literature provided an exponential growth of the population of Adopters, characterized by a slow but steady growth in the beginning (year 2010-2019), and a large growth in the end (year 2020-2030). The graph shows a boost around the year 2020 and the reason for this 'boost' or 'mass adoption' is the fact that at that time of moment the specifications of the crucial elements are met with most of the consumer needs. The adopter graph of the driving range indicated a remarkable point. Here the driving range develops from 255 km (10% of share of the potential adopters) to 465 km (67% share of the potential adopters), this indicates an increase in adopters of 57%, starting from the year 2018. Furthermore, the variable costs difference influences the total cost of ownership and the variable costs for an EV are expected to be zero in year 2023. After the year 2023 an EV owner is expected to save costs in comparison with an ICV. Another remarkable point is the increase of 60% in adopters when the distance between two recharge points decreases from 50 km to more or less 20 km. This decrease in distance takes

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<sup>43</sup> RQv2: 'Which crucial elements from a consumer perspective influence the adoption process (purchase moment) of the electric vehicle'

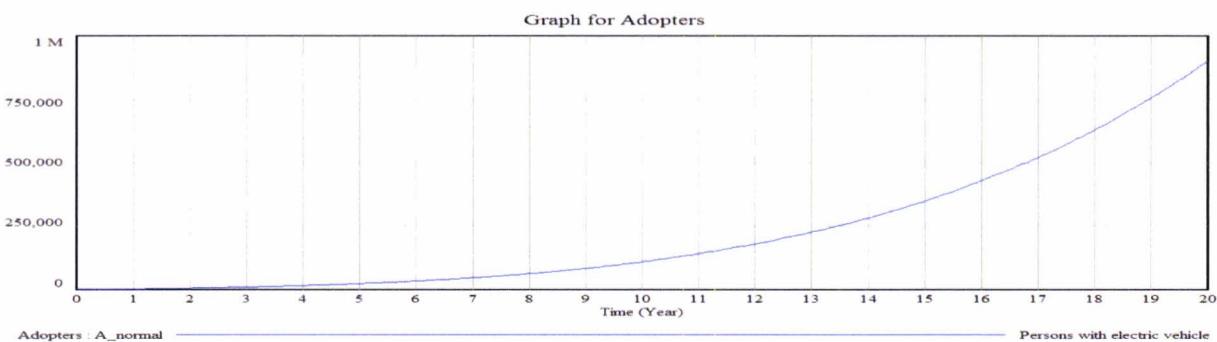
<sup>44</sup> The respondents represent the Dutch passenger vehicle fleet and accounts for approximately 8.5 million vehicles

<sup>45</sup> RQv3: 'To what extent do these elements from a consumer perspective influence the adoption process (purchase moment) of the electric vehicle'

place in the time scale 2013 to 2018. Additionally the recharge time developments are important to consider, while a large share of the potential adopters according to the time are intended to purchase an electric vehicle when the recharge times at public places are below 100 min. However, this is not the case when charging at home, it points out that the respondents are less sensitive for lowering the charging times at home. Furthermore, a fast recharges time of 30 min in public accounts for an acceptance of 57% from the respondents, this is assumed to occur by the year 2020. The placement of charging stations with charging times even lower than 30 minutes and will result in a tremendous increase in adopters. Concluding each crucial element has its degree of impact on the total adoption model. I suggest Ballast-Nedam to keep control over these fore crucial elements with especially a focus on the fixed price, because this is the most sensitive element and easy to influence by the government (e.g. subsidies).

### *Scenarios (managerial)*

Finally, I provided some scenario situations to test the model and assumptions made. Results from the scenario show the following interesting findings. First the basic adoption curve below to give an impression. Concluding a total amount of approximately 1 million full electric vehicles of by the years 2030, based on the basic scenario input values and assumption made in this research project.



Concluding from all scenarios, the word of mouth effect has an extreme impact on the later stages (year 2020-2030) of the adoption process. Therefore, Ballast-Nedam is forced to place their infrastructure before the mass adoption occurs. Because at the moment of 'boost' in the year 2020 the consumer needs are met by the battery specification, it is reasonable that other companies anticipate and previously place their infrastructure, while at that time of moment the infrastructure is the only element that is missing and therefore may have an important in the years before the boost. Furthermore, a realistic situation of subsidies (BPM exemption) indicates an increase in adopters. Another scenario related to the driving range simulates a maximum range of 250 km through technical limitations of the battery. Because of this the results show a bit lower amount of adopters on the long term perspective. An important aspect for Ballast-Nedam is the high sensitivity of price in the adoption process. Therefore, BN should keep control over the development of the fixed price of electric vehicles and the elements that influence this fixed price, such as; BPM reduction, subsidies, mass production, battery developments and so on. Keep control over the fixed price more important than keep control over the driving range developments. Because, an increase in

driving range occurs slowly and is better to keep control over and the fixed price can for instance be changed in one day though the introduction of extra subsidies, the occurrence of effect on the adoption process is in the price situation much faster. The infrastructure network and recharge time developments are difficult to predict and based on several assumptions. Scenarios indicate that a high density of recharge points has a remarkable 50% increasing effect on the amount of adopters. The battery switching scenario indicates a double amount of adopters compared to the basic situation. This extreme effect is the result that the largest part of potential adopters, adopts when charging times are < 30 min. Ballast-Nedam in this case, can play an important role in the development of the adoption process by placing fast charging stations. However, when other firms start placing fast charging stations then probably the adoption process accelerates heavily and the situation may exits that Ballast-Nedam is too late to get in. Therefore, keep control over other fast infrastructure density projects and get in just before it starts to become a serious fast recharging network.

#### *Limitations & future research*

The model used in this research only covers the consumer perspective, and not the perspective from the government or original equipment manufacturers (OEM). In my opinion these actor play also an important role in the adoption process, and therefore some future research on these perspectives might provide useful insights. Furthermore, limitations are the estimations and assumptions made regarding the four crucial elements and are important to update for this reason. Especially in these time lots of firms are involved with the electric vehicle and large investments are put into the R&D resulting that it is possible that in a short time battery performances will increase intensively. Moreover, in future research I would suggest to analyse the consumers innovativeness<sup>46</sup> (characteristics of the consumer) and also make an attempt to model the other effects of the elements in the socio-technical system, such as: battery production limitations, lithium resource depletion, oil prices, standardization of the grid system, electricity grid capacity (e.g. when mass adoption occurs), renewable energy limitation and rules, battery lifetime effects or even the effect of network externalities. Also, segmentation of market (e.g. business market) is interesting to analyse, or the company adoption behaviour.

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<sup>46</sup> Useful data for measuring the innovativeness is already gathered by the survey in this research. Hence, not all the data from the survey is used and could be useful for future research.

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