ANALYZING ELECTRIC VEHICLE DIFFUSION SCENARIOS FOR ISTANBUL

by

Özlem Turan

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APPROVED BY:

Assist. Prof. Gönenç Yücel ………………

(Thesis Supervisor)

Prof. Gürkan Kumbaroğlu ………………

Prof. Aslı Sencer ………………

DATE OF APPROVAL:

to my family

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ABSTRACT

ANALYZING ELECTRIC VEHICLE DIFFUSION SCENARIOS FOR ISTANBUL

In this study, a dynamic simulation model for electric vehicle (EV) diffusion is constructed. The objective of this work is to investigate two main questions; what are the plausible diffusion patterns of electric vehicles for Istanbul under different scenarios developed considering both local and global socio-economic, governmental, technological factors and their interaction with each other? Secondly, what is the extent of the diffusion rate that can be expected in Istanbul after three decades? The model is validated by standard structure and behavior tests. After, various scenario and policy analysis are performed. The results show that fleet market share of battery electric vehicle (BEV) and hybrid electric vehicle (HEV) would likely reach around 19.76% and 20.77% respectively by 2042 in Istanbul. In addition, CO_2 reduction in the transportation sector would only reach around 17.32% in 2042. Moreover, both gasoline and electricity cost influence EV diffusion. However, their impact on EV diffusion is mainly related with a mobility cost gap between gasoline and electricity. Furthermore, technological improvement would lead BEV sales to increase. However, if battery technology cannot keep pace with or exceed CV technology, technological improvements would less likely create a significant raise in the BEV sales. Contrary to expectations, even if no technological improvements were progressed, BEVs would still likely succeed to penetrate around 10% of the market with its current technology within the 30 years. Moreover, a sufficient number of recharging points may lead to faster diffusion of BEV’s as well, causing higher fleet market share overall. Both marketing activities and word of mouth have a remarkable impact on rapid EV diffusion. Besides, increase in repurchasing rate may cause faster EV penetration. Subsidies would have a small impact on EV sales. Finally, applying the 3% private consumption tax (PCT) instead of the 37% PCT for HEV may increase HEV sales but does not show considerable change on HEV sales.

ÖZET

. ISTANBUL İÇİN ELEKTRİKLİ ARABA YAYILIM SENARYOLARININ ANALİZİ

Bu çalışmada, elektrikli arabaların (EA) yayılımı için dinamik bir benzetim modeli kurulmuştur. Çalışmanın amacı, iki önemli soruya araştırmaktır; yerel ve global sosyo-ekonomik, hükümetsel, teknolojik faktörler ve onların birbirleriyle etkileşimleri göz önünde bulundurularak geliştirilen senaryolar altında, elektrikli arabaların makul yayılım davranışları nelerdir? İkincisi ise Istanbul'da 30 yıl içinde elektrikli arabaların beklenen yayılım oranı nedir? Model, standart yapısal ve davranışsal testler ile doğrulanmıştır. Daha sonra, farklı senaryo ve politika analizleri uygulanmıştır. Sonuçlar, 2042 yılında, İstanbul'daki bateri elektrikli araba (BEA) ve hibrit elektrikli araba (HEA) yayılımının sırasıyla 19.76% ve 20.77% civarında olacağını göstermektedir. Ayrıca 2042 yılında, ulaşım sektöründe, CO_2 miktarında 17.32% civarında azalma olacağı görülmüştür. Bunun dışında, hem benzin hem de elektrik maliyetinin EA difüzyonunu etkilediği, fakat önemli etkinin aralarındaki maliyet farkına önemli derecede bağlı olduğu görülmüştür. Teknolojik gelişmeler BEA satışlarını artırmaktadır fakat bateri teknolojisi, konvansiyonel araçların seviyesine erişmeden ya da onları geçmeden, bu gelişmeler BAE satışlarında çok büyük bir değişiklik oluşturmazlar. Ayrıca, hiçbir teknolojik gelişme olmasa bile BEA var olan teknolojiyle pazarın %10'una nüfuz edebilir. Bunun dışında, yeterli şarj istasyonu sayısı yayılımı hızlandırmakta ve artırmaktadır. Hem pazarlama aktivitelerinin hem de insanların EA hakkında bilgi yaymaya yarayan davranışlarının EA yayılımı üzerinde büyük ve hızlandırıcı bir etkisi vardır. Araba değişim hızının artması daha hızlı bir EA yayılımına neden olabilir fakat para yardımı stratejileri elektrikli araba satışlarında çok etkili olmamaktadır. Son olarak hibrit araçlarda, %37 yerine 3% özel tüketim vergisi kullanılması, araç satışlarını artırabilir ama çok büyük bir değişikliğe neden olmaz.

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$\delta_{,j}$	Sales market share of i-type vehicle in all customers
$\delta_{i,j}$	Sales market share of i-type vehicle which belongs to group *j*
$u_{i,j}$	Total perceived utility of vehicle type *i* which belongs to group
w_{ikj}	Weight of utility *k* for *i* - type of vehicle which belongs to group *j*
$tu_{i,j}$	Time utility of *i* type of vehicle which belongs to group *j*
$\alpha(t)$	Value of the attribute at time t
E(t)	Denotes value of cumulative experience at time t
α	Denotes learning factor
nf	Denotes normalization factor
$pu_{i,j}$	Purchase price utility of *i* type of vehicle which belongs to group *j*
$ou_{i,j}$	Operating cost utility of *i* type of vehicle which belongs to group *j*
$ru_{i,j}$	Refueling cost utility of *i* type of vehicle which belongs to group *j*
$mu_{i,j}$	Maintenance cost utility of *i* type of vehicle which belongs to group *j*
$eu_{i,j}$	Emission utility of *i* type of vehicle which belongs to group *j*
V_{EV}	Total number of EV (sum of BEV and HEV) in Istanbul.
V_t	Total number of vehicle in Istanbul.

LIST OF ACRONYMS/ABBREVIATIONS

AFV	Alternative Fuel Vehicle
B	Balancing
BEV	Battery electric vehicle
CO_2	Carbon dioxide
CV	Conventional vehicle
Dmnl	dimensionless
ect	extreme condition test
EV	Electric vehicle
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
OECD	Organization for Economic Co-operation and Development
PHEV	Plug-in hybrid electric vehicle
R	Reinforcing
RQ	Research question
SNM	Strategic niche management
sms	Sales market share
TUBITAK	The Scientific and Technological Research Council of Turkey
WoM	Word-of-mouth

1. INTRODUCTION

Nowadays vehicles that are powered by internal combustion engines (ICEs), which transform the chemical energy of fuel to the thermal and mechanical energy, occupy major role in ground transportation industry all over the world [1]. The transportation industry produces high amounts of greenhouse gases and pollutant emissions. For this reason, internal combustion engine vehicles (ICEVs) can be seen as one of the major contributors to air pollution. ICEVs use petroleum-based fuels that increase the CO_2 level and other emissions in the air [2]. CO_2 is one of the major greenhouse gases that is emitted to the atmosphere through burning fossil fuels [3]. Fuglestvedt, Berntsen, Myhre, Rypdal, and Skeie indicate that 20-25% of the global CO_2 emission stems from the transportation sector which is potential cause of global warming [2]. From 1990 to 2001, different sectors in European Union reduced their global greenhouse gas emission rates. However, emission originating from transportation, particularly road transportation, increased about 21% during the same period [4].

40% of the global energy demand, including almost all of the fuel consumption of transportation system is supplied by conventional oil [5]. Heated debates started with the modern oil era in the mid-1800s in relation to the possibility of reaching the peak point of the global conventional oil[1]. This situation is a potential problem for the urban transportation system. Since reaching to peak point of oil means facing with a fuel shortage. In case of reaching to the peak point of oil production, reliance on oil will generate drastic global challenges in petroleum-based transportation sector such as unmet demand, high fuel prices, and oil black-market [5,6].

Emergence of environmental and energy related concerns have given birth to ongoing debates about how world can overcome global warming, air pollution, and limited oil problem. One of the suggestions is to replace fossil-powered internal combustion engine vehicles (ICEVs) with various alternative fuel vehicles (AVFs). Alternative fuel vehicles are vehicles that can run on fuels other than petroleum products such as diesel or

[1] Peak oil is the term used to describe the point in time at which the global conventional oil production rate will reach its maximum, after which the annual production will begin to decline permanently [6].

petroleum. Alternative fuel can be electricity, compressed natural gas, hydrogen, liquid natural gas, liquefied petroleum gas, and some biological materials like soybean or vegetable oil-based fuels [7]. Among all alternative fuel vehicle options, the most outstanding one is an electricity-powered one. Compared to other AFV types, electric vehicles are more preferable regarding the fuel cost, availability of the fuel, vehicle technology, and fuel efficiency [8-10].

Turkey has a recently growing interest in AFVs that is supported by both Turkish government and automobile industry that are particularly focusing on electric vehicles. The progress that is observed in the electric vehicle research and investments has already given way to some electric vehicle models in the Turkish automobile market. Therefore, this thesis focuses on electric vehicles rather than other types of alternative fuel vehicles in Turkey.

There has been a great deal of studies conducted about electrical vehicles' advantages and importance in recent years. According to OECD 2010 reports, 23% of world CO_2 emissions stem from the transportation sector. Thus, the decrease in carbon emission level can be expected with the increase in use of electric vehicles in an effective way [11]. The study of Argonne National Laboratory shows that the usage of EVs in Houston and Washington can help to decrease CO_2 emission by 26-64% and this variation stems from the difference in electricity generation method, vehicle-recharging time per day, and geographical location [2]. Furthermore the work of Geyer, Koehn, and Olsen underlies that hybrid electric vehicles release around 25% less emission gas compared to conventional vehicles [12].Moreover, many other studies support the previous argument regarding the EV's positive impact on the reduction of greenhouse gas emissions, specifically of CO_2 [13-18].

Limited crude oil reserves along with the high rate of oil consumption gave birth to studies [19-22], that show electric vehicles are effective options to reduce fuel consumption in transportation sector. Additionally, electric vehicles are regarded as one of the major long-term cost saving remedies with its fuel efficiency feature against the possible high oil prices in the future [23]. Christidis, Hernandez and Georgakaki specify that hybrid electric vehicles have 25% higher fuel efficiency compared to their conventional counterparts [24]. Moreover, some type of EVs may help overcoming the energy security problems that could develop from the dependency on imported conventional fuels [17]. Another point that should be mentioned is the cleaner and quieter environment that the battery electric vehicles provide compared to conventional vehicles [25]. In addition, electric vehicles are believed that they do not need as much maintenance as ICEVs do [26].

Although EVs seem as potential solutions for the environmental and energy related difficulties mentioned above, penetration of EVs to the market faces certain technical and social barriers. Immature battery technology, high price, high battery cost, and inadequate refueling infrastructure of EVs are main technical obstacles, while the social barriers can be listed as the lack of public knowledge on EVs, the hardships of acceptance of new technology. Research and developments about EV technology have been continuing all over the world to reduce the weak aspects of EVs. On the other hand, in order to eliminate the social barriers, governments have started regulatory policies to provide subsidies or to lower taxes on electric vehicles. Additionally, they have started adopting various marketing strategies to raise public awareness about EVs [27,28].

Turkey has become one of the countries that recognized the significance of electric vehicles and accordingly initiated research activities on EVs. The Scientific and Technological Research Council of Turkey (TUBITAK) is continuing feasibility studies and research on EVs that started in early 2000s. TUBITAK developed Electrical Vehicle Development Platform and accelerated the research and development, and feasibility studies on electric vehicles by the end of the 2012 [29]. Moreover, Renault, which is one of the global automobile companies that operates in Turkey, launched new battery electric vehicle models to the Turkish automobile market in 2011. In addition, Nissan, another global automobile company, has been planning to introduce its battery electric vehicle models to the Turkish market in near future. Moreover, Toyota and Honda, automobile companies, have been offering their hybrid electric vehicle models to Turkish customers since 2000s.

Turkish government made an important step towards eliminating the social barriers by reducing the tax on battery electric vehicle. Furthermore, Istanbul Metropolitan

Municipality (IBB) supports the construction of recharging points that is required for the infrastructure. There are already functioning charging stations located at some busy districts of Istanbul, such as in Çamlıca, İçerenköy, Bostancı, Kartal, Florya, Avcılar and Şişli. These developments are encouraging for the future of EV technology use in Turkey.

As a result, the aforementioned studies show that EVs appear as an important available solution for environmental and energy related concerns. However, the technological and social obstacles come with the EV technology cannot be disregarded. Therefore, research and developments about EV technology, and new EV-specific policy regulations should be carried out which would likely accelerate the adoption of EV by the potential customers. In this regard, penetration process of EVs in Istanbul will be analyzed considering all advantages and obstacles in the study.

1.1. History of Electric Vehicles

In recent years, due to environmental and energy related concerns, electrical vehicles are proposed for replacing conventional vehicles. However, they are not new technologies. Emergence of electric vehicles (EVs) goes back to as early as 1800s. First experimental lightweight electric cars were used in the USA, the UK and the Netherlands in the mid-1830s. With the developments in electro chemistry, Belgian Gaston Planté invented the first lead-acid battery cell that is still used in most electric vehicles and in all internal combustion engines. First electric vehicle was demonstrated with the lead battery of Planté in France by Gustave Trouvé in 1881. During the same era, in the USA and the UK, other similar electric cars were also developed. In 1901, Thomas Edison invented the nickel-iron battery that could store 40% more energy per weight compared to lead battery. However, the nickel-iron battery had a higher cost of production. Then, higher quality batteries such as nickel-zinc and zinc-air were invented. The period from 1880 to 1900 was the golden age of electric vehicles because most of the technological developments, which form the basis of modern electric vehicle technologies, took place in this period. In those two decades, new transportation options were explored with the intention of shifting from horse drawn carriage to the more advanced options; electric vehicles, steam engine cars, and internal combustion engine cars [25]. Although electric vehicles were effectively used at the beginning, after a while sales of vehicles with internal combustion engines (ICE) started to dominate the market particularly because of the rapid advancement of ICE cars, limitations of batteries, and the higher cost of electric vehicles [30].

In the golden age, new battery types, and the basic principle of hybrid cars were developed. It is worth mentioning that one of the inventors of the first hybrid vehicles was Ferdinand Porsche. Thousands of hybrid and battery electric vehicles were produced in the early 1900s. However, the concept of hybrid car did not become popular at the time mainly due to the high production cost of hybrid cars during the World War I up until 1990s. Around 1960s, there was a common debate on environmental pollution that the conventional cars were discussed as one of the main reasons [25]. In addition, price of oil increased rapidly in 1970s due to the Arab oil embargo. During that unlucky period of ICEs, electrical vehicles seemed as an appropriate solution to avoid the mentioned problems. Thus, number of experiments and research on electric vehicles were conducted in 1970s [30]. Moreover, in the early 1990s, hybrid once again became one of the important topics of policy discussions on cars. Some car manufacturers like Honda and Toyota launched their hybrid car models to the market during 1990s. These models succeeded to survive in the ICEV dominated market. Innovations and research and developments (R&D) about cost and performance of electric vehicle, and recharging infrastructure have been continuing since 1970s [31]. Although ICEV still dominates the automobile market and EV still needs to be improved to meet the current demands of customers, the diffusion of EVs has gradually but surely started all around the world with their recognition as a significant potential solution for the environmental and energy related problems.

1.2. Types of Electric Vehicles

Electric vehicles (EV) can be categorized under three major groups which are battery electric vehicles (BEV), hybrid electric vehicles (HEV), and plug-in hybrid electric vehicles (PHEV).

An electric vehicle that does not have an internal combustion engine and uses portable battery as the only energy source is called as a battery electric vehicle (BEV). BEVs use an electric motor instead of an internal combustion engine for the traction. BEVs are electricity-powered vehicles and they can be recharged externally. BEVs have zero tailpipe emission, high efficiency, and they operates silently [32,33].

A hybrid electric vehicle is a vehicle that has both an internal combustion engine and an electric motor/generator [34]. Hybrid vehicles cannot be recharged externally and they do not have portable battery. They are powered from both petroleum-based fuels and electricity. HEV uses efficiency improvement technologies such as regenerative breaking, and idle-off. Most of the HEVs use an electric motor as a generator that converts kinetic energy of the moving car into the electric energy in order to charge the battery while vehicle is decelerating. Moreover, some HEVs reduce fuel consumption by turning the ICE off when it is idle and restart it when needed. Even this process solely could save fuel around 5-8% [35]. HEVs are classified as series hybrid and parallel hybrid. A series hybrid vehicle uses ICE consistently at the highest efficiency point during frequent stops and starts. Hence, it provides lower fuel consumption in a city driving cycle. Besides, a parallel hybrid vehicle uses ICE at the highest efficiency point while car is going at a stable speed. Thus, it lessens the fuel consumption in the highway driving cycle [34].

PHEV is a kind of hybrid electric vehicle, which has a larger battery than a hybrid vehicle. It can recharge its battery with electricity from off-board sources like an electric utility grid [36]. PHEV uses two distinct powers which are chemical fuel (as HEV does) and electricity in the battery (as BEV does) [37]. PHEV has longer driving range and lower emission level compared to CV and HEV [38]. HEVs can be converted into PHEVs either by replacing the existing battery pack or by adding high-energy battery pack. High-energy battery pack stores electrical density that comes from external recharging, and from regenerative breaking, and then stored electrical energy is send to traction motor system [34].

HEVs could provide high fuel economy; nonetheless, they need petroleum to operate. On the other hand, PHEVs have fuel flexibility; they can utilize either electrical energy or petroleum depending on the demand of the vehicle driver and the level of battery charge. On the other hand, BEVs do not use any petroleum during operation; so, they have zero tailpipe emission, but the generation process of electricity may cause releasing CO_2

depending on the energy source. Furthermore, BEVs rely on immature battery technologies that are long charging times, high amount of battery cost, and limited driving ranges [36].

Comparative properties of CV, BEV, HEV, and PHEV are briefly given in Table 1.1.

Table 1.1. Comparative properties of vehicle types.

	CV	**BEV**	**HEV**	**PHEV**
Internal combustion engine	√		√	√
Electric motor		√	√	√
Portable battery		√		√
Usage of petroleum based fuel	√		√	√
Usage of electricity		√	√	√
External charging		√		√
Zero tailpipe emission		√		

2. PROBLEM DEFINITION AND RESEARCH OBJECTIVES

Electric vehicles have potential advantages related to environment and energy compared to their major counterparts CVs. HEVs and PHEVs have tailpipe emission less than CVs'. Moreover, BEVs do not cause any emission during their operation [19]. However, high amounts of emissions may be released during electricity generation. Amount of emissions arisen from electricity generation varies depending on the resource type used in generation and conversion technology. Therefore, in order to understand the impact of electric vehicle transportation on the emission rates and global environmental change, the emission arising both from energy generating process and tailpipe should be taken into consideration [2]. However, extent of CO_2 emission reduction changes depending on the demand for electric vehicles. In other words, the number of conventional vehicles that are replaced with electric vehicles and the rate of this change at a certain period of time are substantial when the total impact of EVs on environment is to be assessed [39].

Potential advantages of electric vehicles support the suggestion that proposes increasing penetration rate of EVs to the automobile market, which is dominated by the internal combustion engine vehicles [15]. However, compared to conventional vehicles, electric vehicles seem less likely to have the chance of having a remarkable share in the automobile market even in the long run. Inadequate infrastructure, immature battery technology, inadequate performance, higher purchase price, and lack of knowledge of people about EVs could be listed as the major obstacles. Nevertheless, to which extent market penetration of electric vehicles can be sustained is an important issue worth mentioning. As it is stated in the history of EVs, they were firstly introduced to the public at around 1800s, however they failed to penetrate to automobile market on account of the reasons that were not examined in detail after the failure. Therefore, for a successful penetration of electric vehicles into a market, it is important to understand how adoption process could be affected by influential factors [19].

According to Rogers [40] "diffusion is the process during which an innovation is communicated through certain channels over time among the members of a social system" (p.35). Electrical vehicle penetration is included in the field of diffusion of innovation. Diffusion of innovation models about EVs are developed with the aim of gaining insights about how electric vehicles can initiate growth period in an automobile market [41]. However, the problem here is the diffusion of electric vehicles is hard to analyze due to uncertainties that this new technology brings about. These uncertainties, which diffusion normally includes in different degrees [40], can be technological, or behavioral that affect innovation diffusion firmly. Furthermore, there are uncertain interactions among factors [42]. Uncertainties about electric vehicle may be directly related to the electric vehicle itself, such as future value of cost, performance, and range; indirectly related to EVs, such as the future cost of gasoline, subsidies, and consumer preferences. Additionally, there exists positive and negative feedbacks including various aspects such as social exposure, infrastructure, development, technological progress in the dynamics of alternative fuel vehicle diffusion [43].

If influential variables on EV penetration and their interactions with each other are examined in detail considering all uncertainties, this analysis may likely help to understand possible diffusion patterns and extents of the EV diffusion deeply. In addition, examining EV diffusion process may help to understand how variables and interactions among them are effective on dynamic behavior of diffusion. This assessment may help to discover ineffective factors or the factors that may inhibit or enhance the diffusion of EVs. After specifying these factors, inhibitor ones may be eliminated, or their affects can be diminished with appropriate policies to support EV diffusion. Conversely, beneficial factors may be strengthened to accelerate the diffusion process.

Diffusion of electric vehicles in a country is a comprehensive and big project that includes the government, public and private sector, universities, and drivers. These projects are elementarily about infrastructure, investment planning, R&D, and marketing projects. Analyzing and understanding the influential factors on the dynamic behavior of diffusion of EVs help to develop robust and efficient policies for diffusion.

It is important to point out that the dynamic patterns of EV diffusion process vary from region to region particularly because of the drastic changes in population, transportation needs, and customer preferences. Feasibility studies, infrastructure planning, investment planning projects are usually developed regarding a pilot city. Therefore, choosing an appropriate pilot city is significant to provide a better analysis of adoption. To illustrate, in Turkey, Istanbul is the most outstanding city among options for adoption due to two main reasons. Firstly, Istanbul is the most crowded city in Turkey. Number of private and public car is greater than other cities. This means that transportation in Istanbul causes more greenhouse gas emission compared to other cities. Secondly, Istanbul is the central city of automobile market in Turkey due to broad customer profile, being close to manufacturing plant, and high customer number. Thus, it is more reasonable to start planning projects on Istanbul since the decline in gas emission by replacing ICE vehicles with EVs is hand in hand with the number of potential customers that Istanbul could provide this newly emerging sector.

One of the main objectives of this study is to answer the broad question of what are the plausible diffusion patterns of electric vehicles for Istanbul under different scenarios developed considering both local and global socio-economic, governmental, technological factors and their interaction with each other? (Research question 1 (RQ1)).

In order to understand this broad question, it should be divided into three directly related sub-questions. Firstly, this study focuses on the question of which socio-economic, governmental, technological variables and interactions are influential on the electrical vehicle diffusion? (RQ 1.1) Answering this sub-question helps us to discover both the variables that have considerable influence on electrical vehicle diffusion and the variables that show low effectiveness on EV diffusion. Secondly, the study tries to answer the sub-question that to what extent and in which direction do socio-economic, governmental, technological variables and feedback loops affect the electric car diffusion? (RQ 1.2) This sub-question aims to provide a deeper insight about in which direction effective variables influence EV diffusion. In other words, answering this question assists us to comprehend which variables and interactions among them produce what kind of dynamic behavior patterns. In addition, impact level of these variables can be evaluated. Understanding the variable - dynamic behavior pattern relationship makes it possible to determine variables that induce undesirable dynamics, which can be either eliminated or reduced accordingly. In addition, answering the second question provides the understanding that could help strengthening and advancing the variables, which has a positive impact on diffusion.

Addressing RQ 1.1 and RQ 1.2 provides a better insight and understanding about diffusion process of EVs. Thus, this situation would make it possible to answer the third sub question that what is the expected extent of the diffusion rate for Istanbul after 3 decades? (RQ 1.3). This sub-question aims to estimate the approximate diffusion rate under the different scenarios until 2042 considering the answers of RQ 1.1 and R.Q.1.2 and the current transportation system of Istanbul.

Second major objective of the study is to answer the question of what are the possible policies, which may be recommended in order to increase diffusion rate of electric vehicles? (RQ 2). After observing the RQ1, new policies can be suggested to accelerate diffusion process and adoption of EVs. Answering this question may help authorities such as government, or automobile industry to understand how they should behave, or what measures they should put into action with the purpose of quickening adoption process.

It should be noted that, a dynamic simulation model will be used in order to answer the research questions in the model. The modeling approach and the reasons for choosing this method will be explained in detail in the following sections. However, before the methodology part, a number of academic works in the field of AFV diffusion that study with a similar methodological approach will be presented in the literature section. These works are analyzed mainly with the aim of getting a better and deeper insight about the EV penetration topic. After the literature section, we will discuss the methodological choice and introduce the chosen modeling approach. Afterwards, the model will be described to put structure across completely. Subsequent to description, the model will be simulated under different scenarios and policies. Finally, conclusion of the study will be presented.

3. LITERATURE REVIEW

There have been studies in search of understanding and analyzing the possible transitions from the internal combustion engine vehicles (ICEV) to alternative fuel vehicles (AFV). As stated earlier, a dynamic simulation model will be used to analyze EV diffusion and to answer the research questions. For this reason, among all academic works on AFV diffusion, the ones that use particularly simulation modeling approach are presented here to provide better insight about EV penetration and our work. There are two different methodologies that use dynamic simulation models to analyze EV diffusion in the literature. They are system dynamics methodology and agent-based methodology. Firstly, studies that use the system dynamics methodology and after works that use the agent-based methodology will be mentioned. It should be noted that, we will highlight discussions and outcomes that are relevant to this thesis instead of mentioning all results of the studies in the literature section.

Struben and Sterman state that diffusion of AFVs is a dynamic, complex, as well as a difficult process because the scale of automobile industry is too large, this large system involves great amount of feedbacks, and it has uncertainties. For these reasons, Struben and Sterman develop a system dynamic model to analyze possible penetration of AFVs in the USA automobile market. This study emphasizes that especially word of mouth of non-AFVs' drivers are very influential on diffusion of AFVs. Word of mouth can be explained as all activities done by drivers that may help the public to recognize AFVs such as talking about EVs, or driving them on the road. Struben and Sterman also draw attention to importance of sufficient recharging point for drivers as well as rapid repurchasing period to accelerate AFV diffusion. Finally, they indicate that subsidies and marketing programs should exist for a long period for self-sustaining adoption of AFVs [43].

Shepherd, Bonsall, and Harrison extended the dynamic model of Struben and Sterman [43] and modified it to the UK automobile market. According to the results of their study, 160 mile range of BEV or adequate number of recharging points would likely suffice for BEV diffusion to be self-sustaining [39].

Wansart and Schnieder analyze how long-term penetration of AFV can be provided considering its competition with the dominant conventional vehicle technology. This model mainly focuses on effect of driving range, cost, infrastructure, and customer awareness on AFV diffusion. They indicate that driving range capacity may limit the maximum market share. However, this limitation does not stop the adoption process completely. The study also draw attention that even though high battery cost and insufficient infrastructure seem as the major obstacles of AFV penetration, low level of customer awareness is also one of the biggest challenge that influences the long-term adoption of BEVs [19].

According to Tran, rapid diffusion of AFVs is an important strategy in order to decrease oil dependency and to decrease carbon emissions in the UK. For this reason, Tran developed the model that examines both technological and behavioral sides of consumer adoption of AFV technology. The results of the study stress that performance of AFVs should not only catch, but also exceed the performance of ICE in order to provide rapid diffusion of AFVs. Apart from technology, price gap between the AFV and ICE is also considered to be one of the influential factors on diffusion in this work. Finally, importance of supplementary polices for a rapid adoption of AFVs is emphasized [42].

Kwon utilizes a system dynamics model in order to understand market barriers of AFVs. After understanding the barriers, he suggests policy options to eliminate them. The major difference of this study from the previous ones is that Kwon focuses on strategic niche management (SNM), which is a policy option to enhance market share of new technologies such as AFVs [17]. SNM includes creating niche considering user practices, consumers, and regulatory structures in particular areas. If niches are developed appropriately, it offers better insights to authorities about broader application of related sustainable technology [44]. According to the results of this study, strategic niche management (SNM) alone may not be adequate to increase market share of AFVs. However, it may be helpful as a reinforcing policy for financial incentives [17].

Hereinbefore, apart from system dynamics methodology, there have been studies that use agent based methodology (ABM) to comprehend and analyze diffusion process of AFVs. ABM considers interactions between agents since one agent can affect other agent’s decision. Multi-agent models are constructed for evaluating interactions among defined agents that can be exemplified as consumers, automobile manufacturers, and policy makers in the field of EV diffusion [45].

T. Zhang, Gensler and Garcia examined the factors that can accelerate the diffusion rate of AFVs by using agent based methodology. This study mainly focuses on technology, word-of mouth and governmental regulation. It is indicated that technological developments of AFVs, particularly progresses about charging capacity, would likely cause AFV diffusion to speed up. The study also supports the common observation of [43] and [19] that is customer awareness is a strong tool to provide AFV penetration. Finally, a high car price stands out as one of the major reasons of EV's small sales volume. Therefore, some financial incentives are suggested to the government [45].

Shafiei, Thorkelsson, Asgeirsson, Davidsdottir and Raberto also developed an agent-based model in order to examine consumer behaviors and market share development of passenger EVs. The study is carried out in Iceland and it covers ICEs and EVs. They imply that if operating costs of PHEVs or BEVs decline, or operating costs of CVs increase, this situation is sufficient to exceed the threshold point of diffusion process. The results of the study continue with the argument that even though subsidy incentives may not be adequate alone to increase diffusion rate, they can be used as supplementary policies. They also claim that if tax on EVs is lowered, EV prices are reduced, and consumers concerns about EVs are eliminated, penetration of EVs considerably increases. In addition to this conditions, if gasoline prices go up, this may cause total penetration of EVs to the market. On the other hand, reverse of these conditions come true, EV penetration becomes notably slower. Finally, recharging infrastructure stands out as supplementary factor that may accelerate EV diffusion [15].

Eppstein, Grover, Marshall and Rizzo also constructed an agent-based model to study market diffusion of particularly plug-in hybrid vehicles. According to their results, purchase price appears as a substantial factor for many consumers due to the financial concerns. Another point that they want to draw attention is that even subsidy programs have a positive influence on market penetration of PHEVs, its positive effect would not be long lasting unless consumers are comfortable with PHEV technology [46].

In the light of these studies, certain variables that should be involved in the model for a better analysis of the EV diffusion are roughly specified. According to the studies, technological properties, particularly battery capacity, prices of vehicles, refueling infrastructures of the vehicles, customer awareness as well as financial incentives are the main aspects that the model should contain.

It is important to point out that, although at first glance, academic articles, which are mentioned above, may seem similar to the each other as well as to our study, they differ in many ways. Firstly, what the areas/cities where models are constructed rely on differs in every study. In addition, structure of the model and the model boundary of every study are different from one another. In these academic studies, most of the parameters, assumptions, relations between variables, and formulations used in the models are not appropriate for the automobile market in Istanbul. Moreover, Turkish customer profile, income level, expectations, and priorities of customers, available alternative fuel vehicles types, and regulations of the government in Turkey are substantially different from the USA and other European countries where the earlier studies about the topic can be found. Furthermore, examined AFV types vary in every study. Our study emphasizes particularly on the electric vehicles while some other studies may stress on AFVs including fuel cell vehicle or different type of EVs like plug-in hybrid vehicles. As a result, although our study and these works have common ground; our study differs in most of ways than others.

4. METHODOLOGY

System dynamics is employed in this work. The reasons can be explained that the diffusion of electric vehicles is a dynamic, non-linear, large scale and complex problem. Variables, which characterize the diffusion of electric vehicles, change over time. Variables interact with each other, and dynamics of electric vehicles include positive and negative feedback loops. In this regard, system dynamics appears as an appropriate tool for the aim of understanding diffusion dynamics of EVs through the simulation in this study.

According to Sterman [47] “system dynamics is a perspective and set of conceptual tools that enable us to understand the structure and dynamics of complex systems” (p.vii). In this respect, system dynamics is an effective approach in understanding and analyzing behaviors of complex and dynamic systems. Variables, which constitute the system, are reciprocally related. Structure of a system can be defined as the total of relationship that exists between the variables. Causal relations between the variables creates positive as well as negative feedback loops. These relations and loops can be visualized by causal loop diagrams. To illustrate causal loop diagrams, a ‘+’ sign on the head of an arrow means that there is a positive causal relationship between the variable on the tail and the variable on the head of the arrow. Positive causal relationship means that an increase (decrease) in cause lead effect to either increase (decrease) or decrease (increase) less than what it would otherwise have been. Conversely, a ‘-’ sign on the head of an arrow means that there is a negative causal relationship between the variable on the tail and the variable on the head of the arrow. Negative causal relationship means that an increase (decrease) in cause leads effect to decrease (increase) or increase (decrease) less than what it would otherwise have been [48]. Besides, the algebraic product of all signs around the loop determines sign or polarity of the loop. If result of the algebraic product is +, then the loop is reinforcing (R) feedback loop. If the result is –, then the loop is balancing (B) feedback loop. An example for causal loop diagram is given in Figure 4.1.

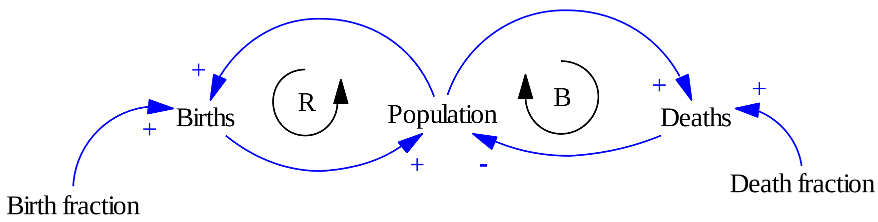

Figure 4.1. Causal loop diagram of population model.

Figure 4.1 shows that when *Births* goes up, *Population* either increases more or decreases less than what it would have otherwise been. Besides, when *Deaths* goes up, *Population* either decreases more or increases less than what it would have otherwise been.

Dynamics of the variables are closely related with the operation of the internal structure. System dynamics particularly deal with the dynamics caused by internal feedback structure of the system. Modeling, which is a scientific tool, is used with the aim of investigating systems, problems, and solutions in system dynamics. A model is defined as a representation of a real system with respect to a clearly stated problem. In system dynamics models, there are two basic variables: stocks and flows. Stocks represent the result of the accumulation over time and flows can be defined as the rate of change in these stocks [48]. Stocks are changed by their inflows and outflows. Some examples of stocks can be given as inventory in a manufacturing company, or number of people employed in a firm. If stock is inventory in a company, for example, inflow and outflow may become the production rate and the shipment rate, respectively. Another example is, if stock is number of people employed in a firm, inflow and outflow of the stock may be hiring rate and rate of quits, respectively [47]. In addition to stocks and flows, the third type of variable is also used in system dynamics. It is called as auxiliary variable, or converter. Auxiliary variables or converters help to define parameters or variables explicitly. Hence, they can be either constant or the function of stock or the flows. An example stock-flow diagram of a simple population model is given in Figure 4.2 [49].

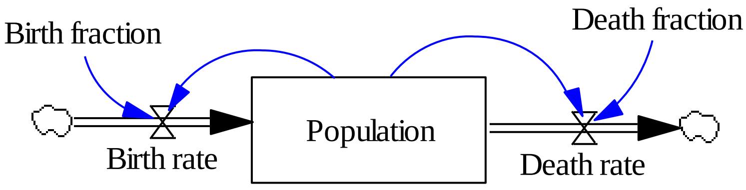

Figure 4.2. Stock-flow diagram of population model.

In the model in Figure 4.2., *Population* is a stock variable. Birth_ rate is the inflow of the model. In addition, it is drained by *Death rate* that is the outflow of the model. *Birth fraction* and *Death fraction* are auxiliary variables.

$$\text{Population}(t) = \text{Population}(t - dt) + (\text{Birth rate} - \text{Death rate}) \times dt \qquad (4.1)$$

$$\text{Birth rate} = \text{Population} \times \text{Birth fraction} \qquad (4.2)$$

$$\text{Death rate} = \text{Population} \times \text{Death fraction} \qquad (4.3)$$

5. DESCRIPTION OF THE MODEL

The dynamic simulation model is constructed to gain a better insight about EV penetration as well as to analyze the diffusion process comprehensively. The model is constructed regarding three types of vehicles, which are conventional vehicle (CV), battery electric vehicle (BEV), and hybrid electric vehicle (HEV). In addition to HEVs, and BEVs, the third kind of EV, plug-in hybrid vehicles (PHEVs), are popular in the world automobile market. Nevertheless, they have not been sold in the Turkish automobile market actively yet. Automobile firms in Turkey do not seem to incorporate PHEV into their product mix in the near future. Both automobile companies and Turkish government tend to give more importance to BEVs and HEVs compared to PHEVs. Apart from that, including PHEVs in the model would less likely enrich the model since technical properties of PHEVs are in between BEVs and HEVs. As a result, PHEVs are not included in the model. Apart from EVs, gasoline-powered vehicles and diesel-powered vehicles may be categorized as different kinds of conventional vehicles in terms of the fuel type, purchase price, and operating cost in real life. In the model, the term of conventional vehicles (CV) is devoted both to gasoline-powered vehicles and to diesel-powered vehicles. The parameters of CV are composite average values that are provided from the actual data of both gasoline vehicles and diesel vehicles. Thus, the parameters of CV represent the both type of vehicles.

The model boundary includes only middle-size passenger vehicle market in Istanbul (lightweight trucks, compact cars, land vehicles, buses, minibuses are excluded). So, the parameters of vehicles, which are the driving range, refueling time, purchase price cost, tax, operating cost, emission rates, are specified considering this particular market. It is possible to determine various market segments and customer profiles relying on their income level, gender, or interests in the middle-size passenger vehicle market. However, the model is designed considering two major customer types. They are people/families with middle income and fleet leasing companies. People/families with middle income buy a car with the private usage aim and fleet leasing companies buy a car with the aim of renting car to the other companies, or organization. There are three reasons to choose these two market segments. Firstly, adding all customer profiles to the model would make the model too complex that would less likely give robust results. Secondly, these two customer profiles cover the majority of the market. Thirdly, available electric vehicle types in Istanbul automobile market mostly fit these customer profiles. It is important to say that, values of the related parameters are estimated regarding these customers.

The whole model is divided into six sectors that are vehicles fleet, vehicle market, customer perception, customer awareness, infrastructure, and environmental impact in order to describe the model eloquently. Relationships between sectors are roughly illustrated in Figure 5.1.

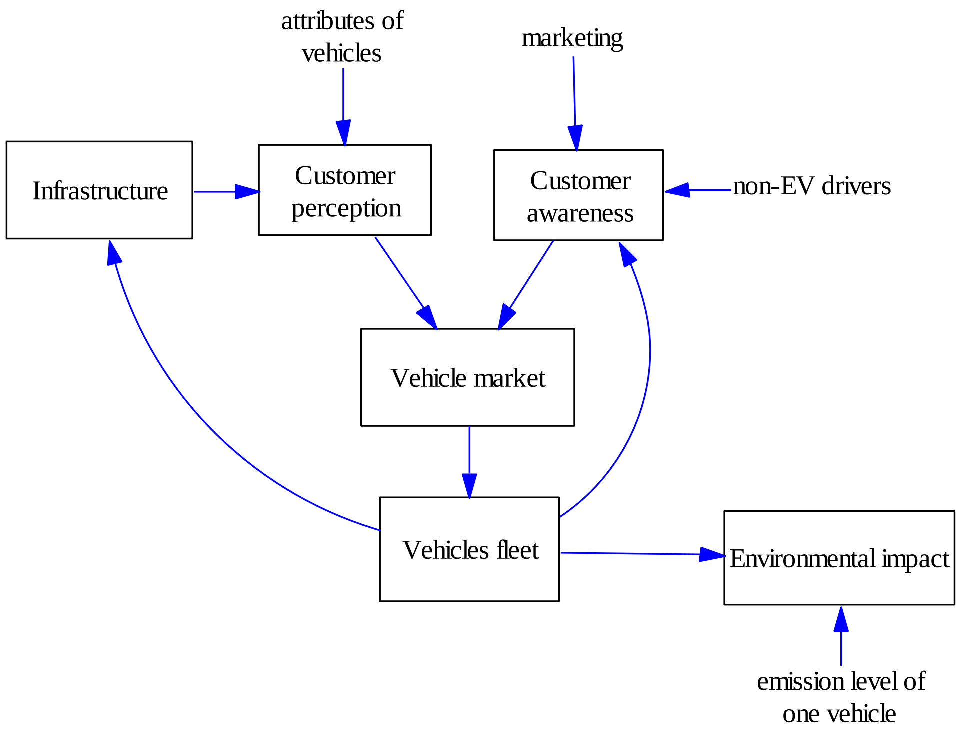

Figure 5.1. Relations between sectors.

These sectors will be explained in detail in this chapter. However, before description, the model will be overviewed to understand causal relations and feedback loops between variables. The simplified causal loop diagram of the model is given in Figure 5.2.

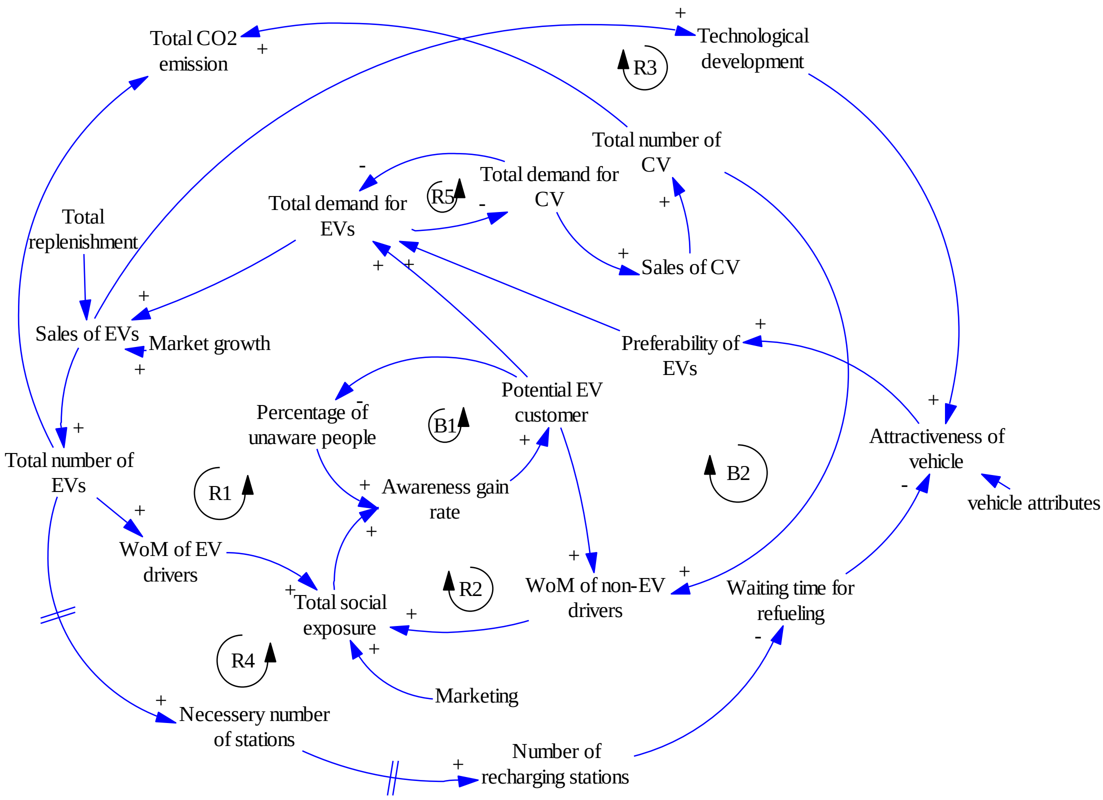

Figure 5.2. Simplified causal loop diagram.

As is seen in the Figure 5.2, the simplified causal loop diagram has five reinforcing feedback loops (R) and two balancing loops (B). It should be noted that although BEV and HEV are separately included in the model; they are represented as EV in the simplified causal loop diagram to provide clear visualization that leads to a better understanding. The model will be examined in detail throughout the next chapter, but, briefly, general overviews of the main feedback loops are as follows;

R1 feedback loop represents the effect of word-of-mouth (WoM) of EV drivers on the total number of EV in Istanbul. Word of mouth can shortly be defined as all actions that may likely help the public to recognize EVs. For example, driving EVs on the road and talking about EVs are involved in the word of mouth effect. Increase in the total number of EV naturally means that increase in the number of EV drivers. That causes the public to be exposed to increased amount of word of mouth than what it would otherwise be. Hence, unaware people gain information about EVs and take EVs into their choice set. Therefore, potential EV customers and demand for EV increase, and that results in an increase in sales. Finally, the total number of EV in Istanbul is positively affected by sales (vice versa).

R2 feedback loop represents word-of-mouth (WoM) effect of non-EV drivers on potential EV customers. WoM level of non-EV drivers increases parallel with the increase in potential EV customers. Since, as stated before, the more potential customers cause the more people to learn about EVs even they do not drive EVs. Further, non-EV drivers spread their information about EVs that contribute to the total social exposure. Finally, this social exposure influences potential EV customers positively (vica versa).

R3 feedback loop represents technological developments' effect on sales of EV. Technological developments mean both research and development (R&D) as well as learning by doing in the causal loop diagram. Raise of EV sales causes the researchers to do more research and developments (R&D) due to two reasons. Firstly, demand in the market may motivate the manufacturers to gain higher market share. Secondly, more money may be allocated for R&D due to revenues coming with sales. When it comes to learning by doing, the manufacturers find opportunity to do more practicing on production of EVs due to higher production level. This situation leads the purchase price of EVs to decrease. Both technological improvements and decreased purchase price cause attractiveness of vehicles to increase and ultimately result in increase of EV sales (vice versa).

R4 *feedback loop* represents the effect of recharging station number on the total EV number in Istanbul. When the total number of EV in Istanbul increases, current recharging stations may less likely meet the electricity recharging demands. Therefore, new charging stations need to be constructed. New constructions causes the waiting time in a queue for refueling to reduce that increase attractiveness of vehicle. Vehicle begin more preferable due to rise of the attractiveness level. As a result, firstly demand for vehicle and than the total number of EV increase (vice versa).

R5 feedback loop represents the effect of EV demand on CV demand. If demand for CV increases, this induces CV demand to decrease. That situation leads EV demands to increase (vice versa).

B1 feedback loop represents the effect of potential EV customers on awareness gain rate. Awareness gain rate means the total number of people who recognize EVs per year. As stated before, when potential EV customers increase, percentage of people who remains unaware about EVs decreases. When number of unaware people decreases, awareness gain rate normally decreases that cause potential EV customers to increase less than what it would have otherwise been (vice versa).

B2 feedback loop represents the effect of total number of CV on EV demand via social exposure. When total number of CV increases, WoM of non-EV drivers increases. As stated earlier, increase of WoM level of non-EV users causes the more social exposure to people that result in the more potential EV customers. In this situation, EV demand goes up that result in CV demand to decline and this ultimately causes total number of CV to decrease or increase less than what it would have otherwise been (vice versa).

Each sector will be explained in detail in the following section. Firstly, relevant background information about sector will be given. Then, description of the related model structure respectively will be discussed. Finally, parameter estimation and assumptions will be presented. It is worth mentioning that only important variables, parameters, and formulations will be given in this chapter, however all formulation and parameters can be found in Appendix A and Appendix B.

5.1. Vehicles Fleet Sector

Vehicles fleet sector covers the variables that are sales, total number of vehicles, and discard rates in Istanbul for all vehicle types as well as relationships of these three variables. Vehicle fleet sector provides extensive explanation of links and formulations between sales, total number of vehicles, and discards for each vehicle type.

5.1.1. Background Information

Number of the each vehicles type in a region firmly relies on two factors that are sales volume and discard rate. Firstly, sales volume is shaped by customer choices about which vehicle type they would purchase. In this model, it is assumed that consumers make a choice when they purchase a car for the first time in their life, or when they replace their current car with another one. On the other hand, discard rate, other major influential factor on vehicle fleet, covers both vehicles that are retired, and vehicles that are sold out of the city. In summary, formulation of the number of vehicles for each type in Istanbul is built up on the grounds that it is filled by sales and drained by vehicles being discarded.

5.1.2. Description of the Structure

Main stock-flow structure of the vehicle fleet sector is given in Figure 5.3. This relation is determined for each type of vehicle separately in the model.

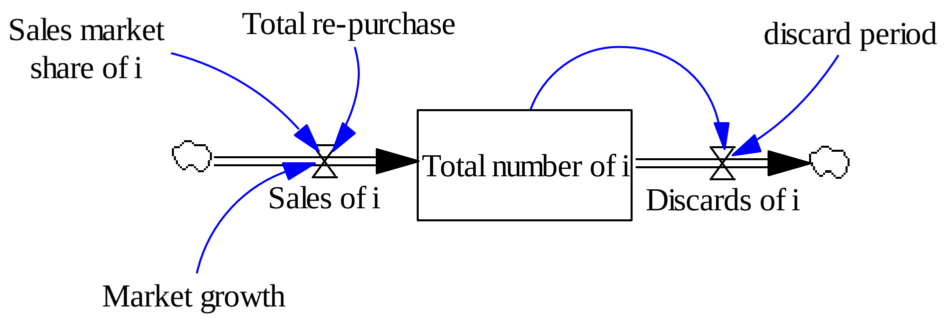

Figure 5.3. Simplified stock-flow diagram of vehicle fleet sector.

i denotes the vehicle type. *i* = 1, 2, 3 mean conventional vehicles (CV), battery electric vehicles (BEV), and hybrid electric vehicles (HEV), respectively.

Formulation of total number of i is given below (Equation 5.1)

$$\text{Total number of i (t)} = \text{Total number of i (t - dt)} + (\text{Sales of i} - \text{Discards of i}) \times \text{dt} \quad (5.1)$$

Total number of i represents total number of *i*-type passenger vehicles within the boundaries of Istanbul. The total number of each vehicle type in Istanbul is a dynamic variable. Its inflow is sales and outflow is discarded vehicles. Formulations of Sales of i and Discards of i are shown by Equation 5.2 and 5.5, respectively.

$$\text{Sales of i} = \text{Sales market share of i} \times (\text{Market growth} + \text{Total re-purchases}) \quad (5.2)$$

Sales of i, which is the inflow of Total number of i, is formulated based on two aspects that are sales market share of vehicles, and total new vehicle purchases. Sales market share of i means percentage of total sales volume captured by *i*-type vehicles. This variable will be explained in detail in Section 5.2. The second variable, total new vehicle purchases is equal to sum of market growth and total re-purchases. Market growth is an annual increase in the demand for a vehicle type. In other words, if person buy a car in Istanbul for the first time in her/his life, then she/he contributes to the market growth. Formulation of the market growth is given in Equation 5.3. Lastly, Total re-purchases, is estimated with the sum of each vehicle type's discards. Vehicles are discarded when they are broken or when they become useless due to completing their useful lifetime. Besides, vehicles that are sold out of the city are counted as discarded vehicles in the study. Once vehicle is discarded, customer begins to need repurchasing. Thus, discard rates of vehicles would likely have the direct contribution to the repurchases and it is assumed that sum of discarded vehicles produces total repurchases. As a result, sales of each type of vehicles are estimated by multiplication of total new vehicle purchase with its own sales market share.

$$\text{Market growth} = (\text{Total vehicle demand} - \text{Total number of vehicle})/(\text{estimation time}) \quad (5.3)$$

As mentioned above, Market growth is defined as an annual increase in the demand for a vehicle. It is estimated by comparing the current demand for a vehicle in Istanbul and the number of vehicles in Istanbul observed in the preceding year.

$$\text{Total vehicle demand} = \text{Motorization rate} \times \text{Population in Istanbul} \quad (5.4)$$

Total vehicle demand is calculated by using both *Population in Istanbul* and Motorization rate of the population. Motorization rate refers to a number of passenger cars per inhabitant. Thus, the total vehicle demand is formulated based upon the assumption that multiplication of population and motorization rate produces total vehicle demand.

$$\text{Discards of i} = \text{Total number of i} / \text{discard period} \quad (5.5)$$

Discards of i, which is the outflow of Total number of i, captures number of *i*-type vehicles that are thrown away due to being broken down, or completing useful time, and a number of *i*-type vehicles, which are sent out of the city. The number of discards coming from each vehicle type is obtained by using total number of *i*-type vehicle and average discard period.

5.1.3. Parameter Estimation and Assumptions

Total number of i is a stock variable that is initialized based on the actual data taken from Turkish Statistical Institute [50]. Motorization rate is assumed as a constant value and it is calculated according to the current ratio of number of passenger vehicles and inhabitant in Istanbul. In this regard, it is obtained as 0.145 vehicle /person. Population in Istanbul changes over time and its three decades future is estimated based on population projection of Turkish Statistical Institute [51]. It is given in Figure 5.4.

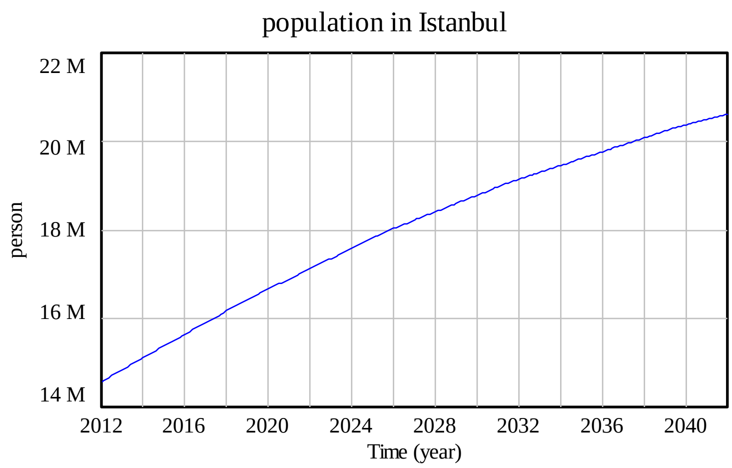

Figure 5.4. Population projection of Istanbul.

5.2. Vehicle Market Sector

Vehicle market sector consists of the sales market share of each vehicle type. This sector provides information and formulations for each vehicle type share in the annual sales.

5.2.1. Background Information

A consumer makes a decision on a car that she/he would want to purchase among all automobile alternatives. Her/his decision may likely be influenced both by attributes of vehicles such as purchase price, operating cost, or size of vehicle and by personal interests. Besides, customer should be aware of any type of vehicle to take it into her/his choice set. Because of this, the customer's awareness along with the customer decisions shape the market share of each vehicle types.

5.2.2. Description of the Structure

Customers are assumed to make a multi-criteria decision during purchasing process. These decisions shape the market share of vehicles. As stated earlier, two costumer groups in the model are people/families with middle income and fleet leasing companies. Based on customer groups, two different market segments are determined. First market segment is called as *segment A* that includes vehicles that are bought by middle-income people/families in Turkey. In addition, the second market segment is called as *segment B* that includes vehicles that are bought by fleet leasing companies. Priorities and importance level of vehicle attributes differ from one market segment to another because customer profiles of each segment are different. To illustrate, a fleet leasing company may have more budget per car compared to budget of the middle-income people. Thus, purchase price of a vehicle may have less importance for fleet leasing companies compared to the middle-income people. Within this context, firstly, market shares of vehicles in every segment and then overall market share of each vehicle types in Istanbul are formulated. The sales market share of vehicle in each segment is estimated by using logit decision model given in the work of McFadden [52]. This logit decision model is one of the discrete choice models that are based on probabilistic consumer theory. This model is particularly chosen because it is regarded as the most suitable one for vehicle market. Certain of academic works in the field of vehicle market utilize from this formula [15,43].

j denotes group types (j = 1, 2 mean segment A, segment B respectively).

$$\delta_i = \sum_j \delta_{ij} \times \text{Percentege of group j} \tag{5.6}$$

δ_i captures the sales market share of i-type vehicle among all customers. δ_i is determined by using sales market share of i-type vehicle in each segment and size of associated market segment (size means the number of vehicle belongs to associated market segment). Percentage of group j refers to the share of related market segment in the whole middle-size passenger car market. Formula of δ_i is:

$\delta_{i,j}$ captures the sales market share of i-type vehicle in market segment j. Its formula is:

$$\delta_{ij} = \frac{e^{-u_{ij}}}{\sum e^{-u_{ij}}} \times \text{Percentage of potential customers for i} \tag{5.7}$$

In Equation 5.7, $u_{i,j}$ refers to the total perceived utility of i-type vehicle by users in group j. $u_{i,j}$ is estimated based on four utility components that are time utility, purchase price utility, operating cost utility, and emission utility. Percentage of potential customers for i captures the customers who are aware of i and who have i in their choice set. Although both utility and percentage of potential customers are briefly defined in here, they will be further described in depth in Section 5.3. and 5.4, respectively.

5.2.3. Parameter Estimation and Assumptions

Percentage of the market segment A and the market segment B are estimated to be 88%, and 12% respectively based on the real data [53].

5.3. Customer Perception Sector

Customer perception sector provides comprehensive description about relation between vehicle attributes and their value perceived by customer. So, this sector consists of attributes of vehicles and their utilities perceived by drivers.

5.3.1. Background Information

While making purchasing decision about a vehicle, consumers consider all attributes of the possible car alternatives. They compare certain attributes of vehicles with other cars and make decision about which one they would purchase based on the total benefit vehicles offer. Perceived utility of a vehicle represents the total benefit that vehicle offers from the viewpoint of customers. Utility of a vehicle is firmly related to the vehicle attributes such as driving range, refueling time, and infrastructure [15,19,36]. Moreover, purchase price of a vehicle is one of the crucial criteria that customers care while buying a car [43,45]. In addition, emission rate and operating costs are also effective factors on consumer's preference [54]. Apart from that, two aspects are particularly determinative on customers about accepting or rejecting new technology. They are perceived usefulness and perceived ease of use. According to Davis [55], perceived usefulness is 'the degree to which a person believes that using a particular system would enhance his or her job performance'(p.320). In addition, Davis [55] says that perceived ease of use refers to 'the degree to which a person believes that using a particular system would be free of effort'(p.320). For example, driving range, refueling time, maintenance cost can be listed under the perceived usefulness aspect. In addition, recharging infrastructure may be included in the perceived ease of use aspect. In this context, it is assumed that consumers regard six criterions during vehicle purchases: purchase price, operating cost, driving range, refueling time, infrastructure availability, and emission rate. In addition to these criterions, people may consider other attributes like the color, brand, acceleration, or luxuriousness of the vehicle when making decisions. However, subjective aspects are ignored.

Importance level of each feature may likely vary in relation to the viewpoint of customers. For example, purchase price criteria may have more priority than emission level criteria for most people. For this reason, when calculating utilities, evaluating each attributes at the same importance level may result in inaccurate results. Therefore, different importance level, which is defined as weights, is assigned to the each attribute in the model. Apart from that, importance weights fluctuate depending on customer types since the significance as well as the priority of attributes differ among people. For instance, operating cost has more priority for the group of people with middle income compared to the fleet leasing companies. Because the middle-income people pay for fuel from their own budget while fuel cost is paid by customers of fleet leasing companies. Correspondingly, same attribute have different weight in each market segment in the study. In the real world, importance level may differentiate for every individual. However, constructing a model considering each individual's priority is almost impossible because of the following reasons. Firstly, it is unattainable to detect desire of every individual. Secondly, even it is possible to figuring out every person's interest, putting every variable in the model makes the model extremely hard, in fact impossible, to analyze. Finally, even the model includes too many importance levels that can be analyzed; result of such kind of study may less likely be robust. Accordingly, we specified representative customer profile for each market segment. They capture mainly population behavior in the related segment and we set the importance levels of attributes regarding these representative profiles.

5.3.2. Description of the Structure

Important parts of customer perception sector and relations between these parts are given in Figure 5.5. This relation is determined for each type of vehicle separately in the model.

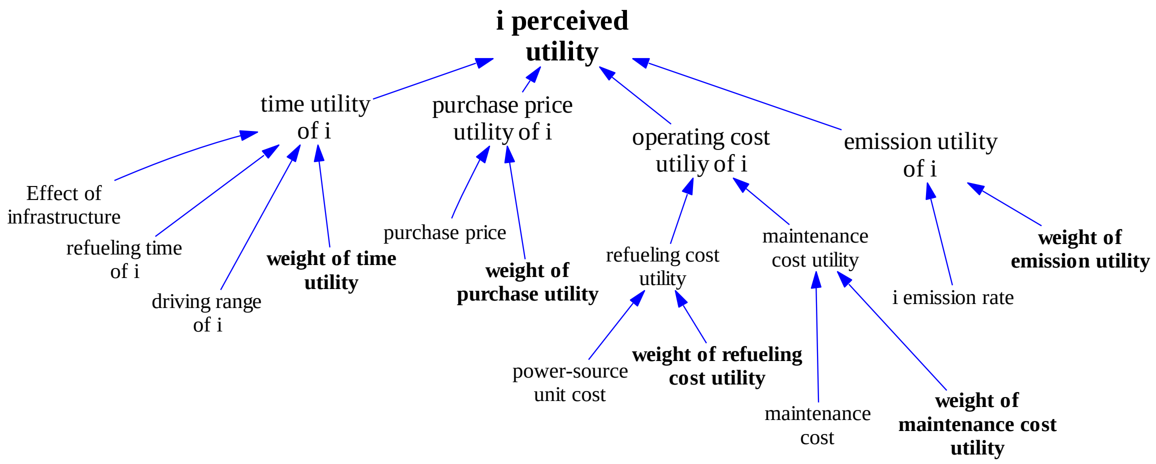

Figure 5.5. Simplified diagram of perceived utility sector.

Consumers choose a vehicle by comparing the utilities they perceive about each vehicle types. Four major utilities are included in the model. They can be listed as time utility, purchase price utility, operation cost utility, and lastly emission utility. In all utility types, two major factors, which are vehicle attributes and weight of these attributes, help to estimate the utility. It is important to point out that the larger absolute value of a weight means a higher importance level. Weights used in the study are estimated considering the revealed-preference multinomial logit model of alternative fuel vehicle preferences estimated by Brownstone, Bunch, and Train [56].

w_{ikj} refer to weight of utility k for i-type of vehicle for users in market segment j (k = 1,2,3,4,5 time utility, purchase price utility, refueling cost utility, and maintenance cost utility, emission utility respectively) Values of all weights are given in Appendix B.

<u>5.3.2.1. Time Utility:</u> Time utility is related to driving range and refueling time features of vehicle, as well as availability of refueling stations on account of being forceful factors on consumer decision. For instance, having less driving range leads to run out of fuel quickly. In this situation, drivers have to find refueling stations, and refuel their vehicle frequently that can be seen as a waste of time from the view of drivers, particularly for busy ones. Besides, if finding refueling stations is not easy, drivers would have to wait for roadside assistance or tow their vehicle to refueling stations. Even if drivers easily find refueling stations, there may be a queue due to lack of adequate recharging points. Moreover, long refueling time causes time loss. The less duration of refueling causes less waste of time. In summary, less driving range, inadequate infrastructure, or long refueling time may be costly in terms of time. Therefore, consumers regard driving range, refueling time, and refueling infrastructure while purchasing a car. In this respect, time utility formula is developed considering average time loss stemming from driving range, refueling time, and refueling infrastructure in a certain distance.

Time utility formula:

$$tu_{ij} = \frac{\text{Maximum range}}{\text{Driving range of vehicle i}} \times \text{Refueling time of vehicle } i \times \text{effect of recharging infrastructure} \times w_{i1j} \tag{5.8}$$

tu_{ij} refers to the time utility of i type of vehicle for users in market segment j

w_{i1j} refers to weight of time utility for i-type of vehicle for users in market segment j. w_{i1j} helps to determine quantitatively importance level of time.

Maximum range refers to maximum range that customers desire to drive without a need of recharging process. It is a function of daily driving habits. Driving range of vehicle is defined as the average range of km before vehicle needs a refuel. This corresponds to how much a conventional car and a hybrid car can drive with one tank gasoline (50 lt-tank), and the total range of km, which a BEV can drive with one full battery. Refueling time of vehicle is the duration of refueling of gasoline tank/battery fully. Driving range and refueling time are not constant and these two parameters change due to learning curve effects for BEV. Learning curve effects provide a mean to count improvements about battery technology in the model since improvements about battery technology would likely continue gradually due to cumulative research and development studies. Formulation of learning curve effect is given in Equation 5.9.

$$\alpha(t) = \alpha(0) \times (E(t) / E(0))^{\alpha} \tag{5.9}$$

$\alpha\ (\boldsymbol{t})$ denotes value of the attribute at time t

$E(\boldsymbol{t})$ denotes value of cumulative experience at time t

$\propto$ denotes learning factor

Learning curve effects for battery technology show accumulation of suppliers experience on vehicle potentially turning into improvement in terms of research and developments [57]. In the study, learning curve effect is regarded for only battery technology. In other words, HEV technology or CV technology is not improved by learning curve effects in the study.

Effect of infrastructure on i refueling time shows impact of refueling infrastructure on time utility. It will be analyzed in detail in Section 5.5.

<u>5.3.2.2. Purchase Price Utility:</u> As stated earlier, purchase price is a substantially influential factor in the course of choosing a car. Because of this, purchase price criterion is included in the model and its weight is relatively high. In addition to price, costumer budget is also included in the purchase price utility formula because natural logarithm of the budget is used to normalize purchase price of vehicles. In this context, budget is determined as annual income level of household for middle-income people and total money earned from one car for fleet leasing companies. In addition to budget, normalization factor (*nf*) is also used to normalize purchase price. Purchase price utility formula is given as;

$$pu_{i1} = \frac{\text{Purchase price of vehicle i} / nf}{\ln(\text{annual income level of household})} \times w_{i21} \tag{5.10}$$

$$pu_{i2} = \frac{\text{Purchase price of vehicle i} / nf}{\ln(\text{money earned from one car})} \times w_{i22} \tag{5.11}$$

pu_{ij} refers to purchase price utility of *i*-type of vehicle for users in market segment *j*

w_{i21} refers to weight of purchase price utility for i-type of vehicle for users in market segment *A*.

w_{i22} refers to weight of purchase price utility for i-type of vehicle for users in market segment *B*.

w_{i2j} helps to determine importance level of purchase price for market segment *j* quantitatively.

$$\text{Purchase price of vehicle } i = i \text{ price before taxes} \times (1 + i \text{ PCT}) \times (1 + \text{VAT}) \tag{5.12}$$

Purchase price of vehicle consists of price before taxes, private consumption taxes, and value added taxes. Private consumption taxes (PCT) and value added taxes (VAT), which are determined by the government, are added to the price before taxes. That produces purchase price of a vehicle. Another important point here is that even purchase prices of vehicles may be relatively high currently; prices would decline gradually due to learning curve effect that comes from learning-by-doing of manufacturers. Learning by doing helps manufacturers to gain experience about production of vehicle. Experiences ultimately would yield a decrease in production cost that induces decline in purchase price costs. Therefore, it is assumed that purchase prices of BEV, HEV, and CV will decrease gradually over time.

5.3.2.3. Operating Cost Utility: Operating cost is constituted of fuel cost and maintenance cost in the model. Thus, operating cost utility is equal to sum of refueling cost utility and maintenance cost utility.

$$ou_{ij} = ru_{ij} + mu_{ij} \tag{5.13}$$

ou_{ij} refers to operating cost utility of *i*-type of vehicle for users in market segment *j*

ru_{ij} refers to refueling cost utility of *i*-type of vehicle for users in market segment *j*

mu_{ij} refers to maintenance cost utility of *i* type of vehicle for users in market segment *j*

$$ru_{ij} = \text{refueling cost}_{\text{i}} \times w_{i3j} \tag{5.14}$$

w_{i3j} refers to weight of refueling cost utility for i-type of vehicle for users in market segment *j*. w_{i3j} helps to quantitatively determine importance level of refueling cost for j market segment.

Refueling cost is defined as the cost of fuel that vehicle uses in order to travel one km distance. Fuel types, which are supplied from refueling stations, are gasoline for conventional and hybrid cars, and electricity for battery electric vehicle.

$$mu_{ij} = \text{maintenance cost}_{\text{i}} \times w_{i4j} \tag{5.15}$$

w_{i4j} refers to weight of maintenance utility for i-type of for users in market segment j. w_{i4j} helps to quantitatively determine importance level of maintenance cost for users in market segment j.

Maintenance cost is defined as normalized version of monthly maintenance cost of vehicle. Monthly maintenance cost consists of normalized versions of both battery renting cost (if portable battery is available) and routine monthly maintenance cost. BEVs need portable battery, which can be purchased or rented to operate. However, purchase price of a battery is extremely high, thus drivers mostly prefer to rent the battery. Therefore, it is assumed that battery is rented monthly. Routine monthly maintenance cost refers to cost of maintenance that every vehicle should have in every month. In the maintenance cost calculation, BEV maintenance cost is taken as a base value for normalization. Maintenance cost of both CV and HEV are normalized based on BEV maintenance cost.

5.3.2.4. Emission Utility: Emission is defined as total CO_2 released from conventional and hybrid vehicles during their trip. However, there is no tailpipe emission coming from battery electric vehicles. Therefore, emission of BEV is specified as CO_2 that is released to the atmosphere from electricity plant during electricity generation. Moreover, emission level is total CO_2 level released for a km drive of CV, HEV, and BEV.

Formulation of emission utility is given in Equation 5.16.

$$eu_{ij} = \text{emissionrate}_{\text{i}} \times w_{i5j} \tag{5.16}$$

eu_{ij} refers to emission utility of *i* type of vehicle which belongs to group *j*

w_{i5j} refers to weight of emission utility for i-type of vehicle which belongs to group j. w_{i5j} helps to determine importance level of emission for j market segment quantitatively.

Emission utility of vehicle is equal to multiplication of vehicle-normalized version of emission rate and weight of emission utility. For normalization, emission rate of conventional vehicle is chosen as a base value. Accordingly, normalized version of emission level of HEV and BEV are estimated.

5.3.3. Parameter Estimation and Assumptions

Choosing appropriate attribute values for each car type in the model appears as a challenge due to the broad profile of the middle-size passenger vehicles. In order to overcome this challenge, representative vehicle profiles that mainly capture market segment of the middle-income people and fleeting companies are determined for CV, HEV, and BEV. After that, value of each attribute is estimated by taking the average value of vehicles that are fit to that profile.

Available battery technology currently provides 165 km range [58] and 1-hour refueling time [59] for BEVs. Maximum range is determined heuristically considering the area of Istanbul and it is assumed as 300 km. However, sensitivity tests are applied to the maximum range.

There are fundamentally three types of recharging stations based on their power and refueling time in the EV market. Those are home-type, normal, and quick charging stations. Their charging time is about 6 hours (usable at night at home, or parking area), 3-6 hours (usable in parking area of shopping malls), 0.5-2 hours (recharging stations) respectively [59]. Long charging is commonly used when vehicle is idle whereas quick charging is mostly used during trips if vehicle runs out of the fuel. In the model, time utility of a vehicle that is during operation is estimated. Thus, only quick recharging stations are considered in the model. Refueling time for BEV is assumed to be an hour on average. It is assumed that recharging points are distributed evenly across Istanbul.

Moreover, recharging infrastructure affects time utility via effect function. Effect function of infrastructure is given in Figure 5.6.

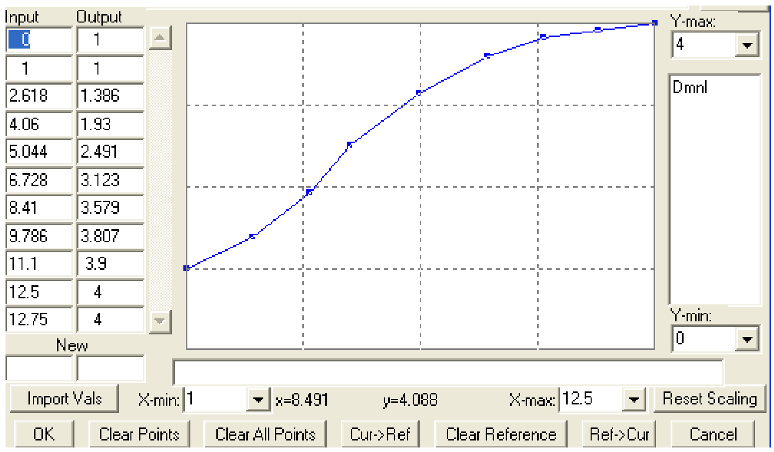

Figure 5.6. Effect function of infrastructure on BEV time utility.

$$\text{effect of recharging infra. on } tu_{2j} = f\left(\frac{\text{BEV number per station}}{\text{reference BEV number per station}}\right) \quad (5.17)$$

Effect functions can help to show non-linear relations between variables. In this context, effect function, which is seen in Figure 5.6, is used to show non-linear relation between time utility and recharging infrastructure. Reference BEV number per stations is called as normal value. If BEV number per station exceeds normal value, then time utility begins to be affected negatively from this situation. For example, f(1) represent the situation that BEV number per station is equal to normal value. Figure 5.6 shows that if BEV number per station becomes 12.5 times more than reference BEV number, then time utility of BEV becomes one fourth of f(1).

Annual income level of a household is determined regarding middle-income families. For this reason, household income is determined as 5000 TL per month that equals annually 60000 TL. Besides, money earned from one car for fleet leasing companies is determined as 80000 TL. It should be noted that these two values are used for normalization of the purchase price. Natural logarithms of these values are included in purchase price utility formula.

The government has offered a new regulatory law about private consumption tax (PCT) for BEVs for incentive. PCT for vehicles that have only electric motor is determined as 3%, 7%, and 15% depending on motor power in accordance with the new law. It is chosen as 3% due to the motor power of representative BEV. However, this value is 37% for both CVs and HEVs. Value added tax is 18% for all vehicles types [60].

Refueling cost is estimated regarding current prices of gasoline and electricity. According to [61] gasoline vehicles consume about 8 lt/100 km. Current price of gasoline is about 4.8 TL/lt in Turkey. Thus, cost per km is estimated to be 0.384 TL. This value is 25% less for hybrid cars due to efficiency of HEV. Besides, BEV uses 0.2 kWh per km on average [61,62]. Electricity cost for households is 0.0563 TL/ 0.2 kWh (0.0563 TL/ km) on average. However, the model includes only commercial refueling and in this sense, electricity cost is determined considering a profit margin.

Tailpipe CO_2 emissions of conventional vehicle is about 188 g/km [64]. Emission rate of a hybrid car is about 25% less than a conventional car [12]. As it is stated earlier, although BEVs release zero tailpipe emission, certain amount of CO_2 is created during the electricity generation process. Amount of CO_2 depends on energy sources. Emission level stemming from BEV varies among countries because of the using different energy sources. For example, in Turkey, around 362.8 tons CO_2 is released to the atmosphere for one GWh electrical energy production [65]. As it is said before, BEV uses 0.2 kWh per km on average [61,62]. Therefore, emission arisen from electricity generation process for one BEV to drive one km is estimated to be 72.56 g/km in Turkey based on actual data taken from Turkish Electricity Transmission Company [65].

5.4. Customers Awareness Sector

Customer awareness sector includes social exposure coming from marketing and drivers as well as impact of social exposure on customer familiarity with a vehicle. This sector provides explanation for relation between social exposure and customer awareness.

5.4.1. Background Information

Any vehicle type can enter choice set of consumer, if and only if consumer is aware of that vehicle type. Therefore, awareness of people about vehicles is a substantial factor for purchasing decisions [19,43]. As a result, customer awareness is analyzed in depth in this work.

Everybody in Istanbul is aware of conventional vehicles. On the other hand, EVs are new technology and Turkish customers are not completely familiar with the EV concept. If customers gain awareness of the EVs, they become potential EV customers and take EVs their choice set during purchasing a car. However, being potential EV customer requires sufficient social exposure because drivers need cognitive and emotional process to consider EVs during purchasing vehicle. Social exposure also accelerates this emotional process. It is assumed that social exposure, which helps people to become potential EV customers, is provided by marketing activities and word-of-mouth (WoM) of people about EVs in this work. Marketing activities cover all marketing channels such as TV advertisements, newspapers, journals, magazines, and internet. Moreover, word-of-mouth includes all ways that drivers can spread information about EVs on their own such as conversation, driving EV on the road, internet, or social media.

5.4.2. Description of the Structure

Important parts of customer awareness sector and relations between these parts are given in Figure 5.7.

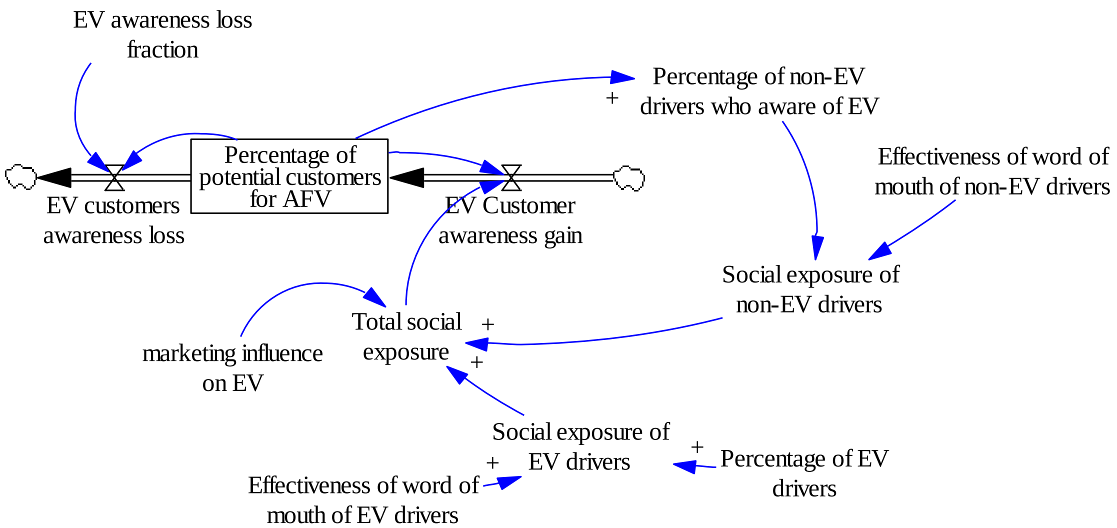

Figure 5.7. Simplified stock-flow diagram of customer awareness sector.

New types of products, particularly innovative ones, necessitate consumer-learning process for adoption. EVs are also innovative products that need process to be accepted by customers. Percentage of potential EV customers is a term that is used to represent portion of customers who accept EV technology emotionally and cognitively in the model. Percentage of potential EV customers refers to a percentage of customers who are willing to take EVs into their consideration set during purchasing. It is assumed that customers are equally familiar with HEV and BEV, potential EV customers have all information and understanding about EVs. If customers gain awareness about EVs, they become potential EV customers.

$$\begin{aligned}\text{Percentage of potential EV customers(t)} = {} & \text{Percentage of potential EV customers (t - dt)} \\ & + (\text{Customer awareness gain} \\ & - \text{Customer awareness loss}) \times \text{dt}\end{aligned} \tag{5.18}$$

Percentage of potential EV customers is formulated using familiarity model of Struben and Sterman [43]. Potential EV customers is filled by awareness gain and drained by awareness loss.

$$\begin{aligned}\text{Customer awareness gain} = {} & \text{Total social exposure} \\ & \times (1 - \text{Percentage of potential EV customers})\end{aligned} \tag{5.19}$$

Customer awareness gain is shaped by multiplication of total social exposure and percentage of customer, who are not aware of EVs. In other words, unfamiliar people with EVs learn about EVs through social exposure.

$$\begin{aligned}\text{Total social exposure} = {} & \text{Marketing influence} + \text{Social exposure of EV drivers} \\ & + \text{Social exposure of non - EV drivers}\end{aligned} \tag{5.20}$$

Total social exposure refers to all social influences that help people to recognize EVs, and learn information about EVs. Total social exposure is equal to the sum of marketing, social exposure of EV drivers, and social exposure coming from non-EV drivers. Marketing is an important strategy in launching process of new products. It helps peoples to recognize product or it shows profitable sides of product. Apart from marketing, both social exposure of adopters and non-adopters of the technology spread via word of mouth (WoM) of drivers. Word-of-mouth includes all activities that drivers can spread information about EVs such as conversation, driving EV on the road, internet, or social media. These activities make people gain information about electrical vehicles and take EVs into their consideration set. Formulations of social exposure of EV drivers and non-EV drivers are given in Equation 5.21 and 5.22, respectively.

Marketing influence is the effect of marketing on percentage of potential EV customers.

$$\text{Social exposure of EV drivers} = (\text{Effectiveness of WoM of EV drivers}) \times \frac{V_{EV}}{V_t} \quad (5.21)$$

V_{EV} denotes the total number of EV (sum of BEV and HEV) in Istanbul.

V_t denotes the total number of vehicle in Istanbul.

Social exposure of EV drivers is equal to multiplication of fraction of total EVs driven in Istanbul and effectiveness of WoM of EV drivers. Number of adopters is substantially important factor for adoption because when people talk to vehicle owners or see them on the road, they recognize the availability of EVs and learn about them. Thus, the more adopter would likely cause more aware people. Effectiveness of WoM of EV drivers represents quantitative estimation of potential effectiveness of EV-drivers on consumer awareness level.

$$\begin{aligned} \text{Social exposure of non - EV drivers} = {} & (\text{Effectiveness of WoM of non - EV drivers}) \\ & \times \text{Percentage of potential EV customers} \qquad (5.22) \\ & \times (1 - \frac{\mathrm{V_{EV}}}{\mathrm{V_t}}) \end{aligned}$$

Social exposure of non-EV drivers stems from drivers who are aware of EVs but not owing one. It is shaped both by fraction of the non-EV number whose drivers are aware of EV driven in Istanbul and by effectiveness of WoM of non-EV drivers. Effectiveness of

WoM of non-EV drivers represents quantitative estimation of effectiveness of non-EV-drivers consumer awareness level.

$$\text{Customer awareness loss} = \text{Percentage of potential EV customers} \times \text{EV awareness loss fraction} \tag{5.23}$$

Customer awareness loss is equal to multiplication of percentage of potential customers for EVs and EV awareness loss fraction. Awareness loss is included to the model because even people learn about EVs; some of them may take EVs out of their consideration set after a while unless their perception is reinforced by continuing social exposure. This situation causes potential EV customers to decrease. EV awareness loss fraction represents percentage of potential consumers that forget about EVs.

5.4.3. Parameter Estimation and Assumptions

It is assumed that every driver in Istanbul is aware of CVs and CV is included in all drivers' choice set. Therefore, percentage of potential CV customers is stable variable and it is set to 100% throughout simulation.

Effectiveness of WoM of EV drivers and Effectiveness of WoM of non-EV drivers is determined to be 0.25 and 0.15, respectively. EV drivers are more influential compared to non-EV drivers because they directly experience EV technology. This situation makes them more persuasive. In real life, marketing influence is a dynamic variable and it depends on budget coming from sales. However, in the model, marketing influence is assumed to be a constant value. It is important mentioning that these values are estimated considering the study of Struben and Sterman [43]. Sensitivity tests are also applied to these values.

EV awareness loss fraction is equal to 1% per year. In other words, every year, 1% of potential EV customers forgets about EVs and takes EV out of their consideration set. Sensitivity tests are also applied to the EV awareness loss fraction.

5.5. Infrastructure Sector

Infrastructure sector provides explanation about refueling infrastructure of vehicles. This sector covers all infrastructural process of vehicles.

5.5.1. Background Information

Refueling infrastructure sufficiency means that number of refueling stations adequately meets the refueling demand of all vehicles. Refueling infrastructure sufficiency is a serious factor for driver comfort because inadequate infrastructure may cause drivers to wait for roadside assistance or tow their vehicle to refueling stations in the case of running out of the fuel. Besides, there may be a queue on the recharging points due to the lack of adequate recharging stations. These circumstances would likely result in time lost during trip, which may be very important for a driver. As a result, infrastructure sufficiency is an important criterion for customers [15,19] and this factor is incorporated to the model.

BEVs differ from CVs and HEVs in terms of refueling points. CVs are gasoline-powered vehicles that use gasoline stations for refueling. BEVs are electricity-powered vehicles that use electricity-recharging points. When it comes to HEV, it uses gasoline stations because it does not supply electricity from external source. The point is that gasoline stations are currently adequate for CV and HEV in Istanbul. Thus, refueling is not a problem for both CV and HEV drivers. However, inadequate infrastructure is one of the substantial concerns about BEVs [54]. There is potential and growing demand for BEVs and current number of recharging stations would not meet this potential demand. Construction of recharging point for BEV continues and total station number is a dynamic variable. Hence, it is examined in detail whereas number of gasoline stations for CV and HEV is assumed as stable and sufficient for vehicles.

Recharging stations can be built under two different strategies; proactive or reactive. In proactive strategy, stations are constructed before diffusion of BEVs in order to prepare infrastructure of the city to BEV usage. Thus, it is expected that there would be no obstacle arisen from infrastructure in the proactive strategy. On the other hand, stations are constructed right after the penetration of BEVs in the reactive strategy. Current number of BEVs in the city would be estimated and necessary station number would be determined. Recharging points would be built considering this estimation under reactive strategies. Station construction policy taken by Turkey is exactly same neither proactive nor reactive ones. However, in the base model, reactive strategy is regarded because it seems that recharging points construction would begin to speed afterwards increase of BEVs sales in Turkey. Therefore, current infrastructure policy, which is applied in Turkey, resembles closer to reactive strategy.

5.5.2. Description of the Structure

Important parts of infrastructure sector and relations between these parts are given in Figure 5.8.

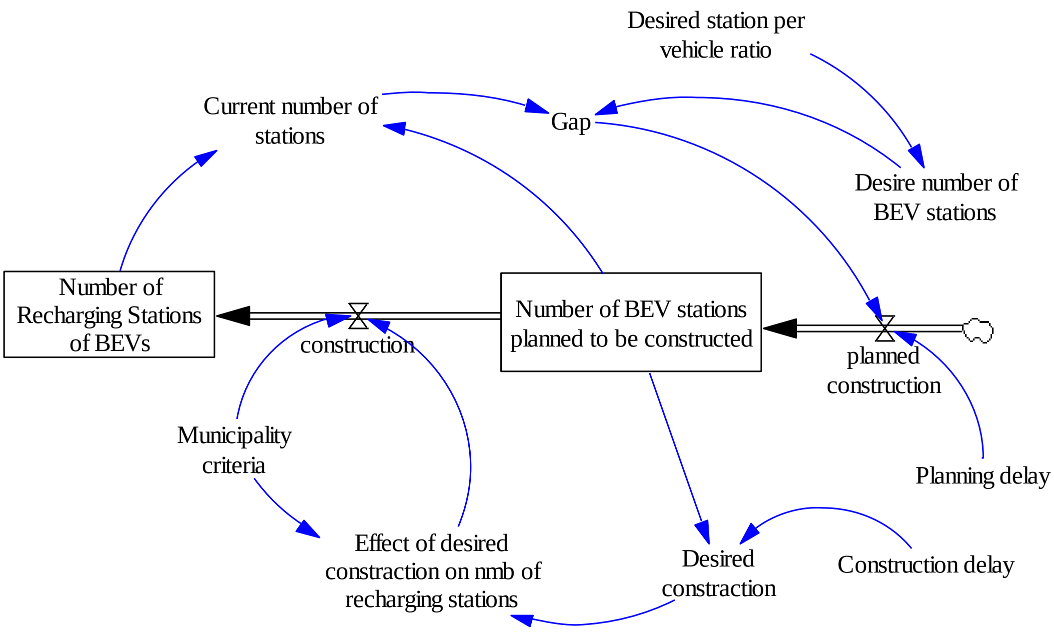

Figure 5.8. Simplified stock-flow diagram of infrastructure sector.

As stated before, gasoline stations are currently adequate for CVs and HEVs Istanbul. Thus, refueling infrastructure is not a problem for CV and HEV drivers. On the other hand, there are currently thirteen charging points in Istanbul and this number appears to be notably inadequate value when potential BEV demand is considered. However, new constructions would be implemented in parallel with beginning of EV penetration. In this context, number of recharging stations is formulated and it is given in Equation 5.24.

$$\begin{aligned} \text{Number of recharging stations of BEVs (t)} &= \text{Number of recharging stations of BEVs(t - dt)} \\ &+ \text{construction} \times \text{dt} \end{aligned} \tag{5.24}$$

Number of recharging stations is a stock variable and it is changed by construction.

Construction is defined as a number of recharging points being completed per year. New charging points are built in the case of current ones begin insufficient to cover the total demand. The recharging point number that shows sufficient value to supply electricity to all BEV market is defined with the term of desired number of BEV stations. Formulation of this term is shown in Equation 5.25.

$$\begin{aligned} \text{Desired number of BEV stations} &= \text{Perceived number of BEV in Istanbul} \\ &\times \text{Desired station per vehicle ratio} \end{aligned} \tag{5.25}$$

Desired number of BEV station refers to a necessary station number in Istanbul for drivers to find recharging points easily and not to wait in a queue for a long time. It is equal to multiplication of perceived number of BEVs in Istanbul and desired station per vehicle ratio. Perceived number of BEV in Istanbul is a smoothed version of the total number of BEVs in Istanbul. Besides, Desired station per vehicle ratio is a ratio that is formulated regarding how many station points per vehicle should be available in Istanbul to sustain adequate infrastructure. In other words, after total number of BEVs is estimated with a delay, its multiplication with desired station per vehicle ratio produces desired number of station in Istanbul.

Lastly, the gap between desired number of stations and current ones may such a huge that it may be hard to cover due to limited budget or feasibility studies. Therefore, it is assumed that there is an upper municipality criterion, which restricts construction of stations.

5.5.3. Parameter Estimation and Assumptions

Number of Recharging Stations of BEVs is initiated with thirteen stations that is the current number of recharging points in Istanbul. Desired station per vehicle ratio is determined to be 0.05 station/vehicle regarding refueling time, and accessibility of stations.

In real life, the municipality, or private companies may implement construction of recharging stations. However, there has been no clarified information about who would be responsible for recharging points' construction, or what would be regulations. Thus, in the base model, it is assumed that both municipality and private companies may construct recharging points but there is an upper limit for number of annual construction for recharging stations due to budget, and proper area constraints. It is assumed that maximum 1000 station per year can be constructed (municipality criterion). Besides, sensitivity analyzes are applied to the desired number of stations per vehicle ratio and the municipality criterion.

5.6. Environmental Impact Sector

Environmental impact sector includes CO_2 reduction coming from EV penetration. This sector provides understanding for possible CO_2 reduction associated with fleet.

5.6.1. Background Information

There are various kinds of emission gases arisen from transportation industry such as hydrocarbons, CO, NO_x, and CO_2. In the study, when environmental impacts of EVs are estimated, only CO_2 is regarded on account of the two reasons. Firstly, scientific studies show that CO_2 plays the most significant role in the transportation related climate changes. Secondly, CO_2 amount stemming from vehicles is substantially higher compared to the other emission gases [66]. As mentioned earlier, most of researches claim that EVs may likely be an effective solution for CO_2 emissions. However, this substantially depends on both number of EVs that replace CVs, and means of electricity generation. For these reasons, once diffusion rate of EV is observed, its effect on CO_2 will be analyzed in order to estimate ultimate environmental impact of EVs.

5.6.2. Description of the Structure

Impact of the EV diffusion on the environment is traced comparing two different cases. In the first case, CO_2 emission rate is estimated assuming that all vehicles in Istanbul are CV and thus, CO_2 can only arise from CV. In other words, it is estimated regarding that how much CO_2 would be emitted if there were not any penetration of EVs. In the second case, CO_2 stemming from associated fleet sizes of CV, BEV, and HEV are estimated. Finally, these two cases are compared and impact of EV diffusion on CO_2 emission is estimated. Formulation of CO_2 reduction in every year is given in Equation 5.26. In addition, formulation for cumulative CO_2 reduction is given in Equation 5.27.

$$\text{Reduction of CO}_2 = \frac{\text{Total emission level when all cars are CV - Total emission level}}{\text{Total emission level when all cars are CV}} \tag{5.26}$$

$$\begin{aligned}\text{Cumulative CO}_2\,\text{reduction (t)} = {} & \text{Cumulative CO}_2\text{ reduction(t - dt)} \\ & + \text{CO}_2\text{ emission difference} \times \text{dt}\end{aligned} \tag{5.27}$$

$$\begin{aligned}\text{CO}_2\text{ emission difference} = {} & \text{Total emission level when all cars are CV} \\ & - \text{Total emission level}\end{aligned} \tag{5.28}$$

$$\begin{aligned}\text{Total emission level when all cars are CV} = {} & \text{Annual range of CV} \times \text{Emission level of CV} \\ & \times \text{Total vehicle in Istanbul}\end{aligned} \tag{5.29}$$

Total emission level when all cars are CV represents amount of CO_2 if all cars on the road are conventional vehicles. Annual range of CV means total range that a CV is driven in a year. Emission level of CV is equal to the sum of emission levels arisen from each CV.

$$\text{Total emission level} = \sum_{\forall i} \text{Emission level of total } i \tag{5.30}$$

Total emission level represents the total amount of CO_2 coming from BEVs, HEVs, and CVs in Istanbul. To observe total emission level, firstly, emissions arisen from each vehicle groups are separately calculated and then estimated values are summed.

$$\begin{aligned}\text{Emission level of total } i = \text{Annual range of } i \times \text{Emission level of one } i \\ \times \text{Total number of } i \text{ in Istanbul}\end{aligned} \tag{5.31}$$

Emission level of total i represents total annual amount of CO_2 released from all i -type vehicles. Emission level of one i equals to amount of CO_2 released by one i-type vehicle for a km-drive. Multiplication of emission level of one i with annual drive produces annual CO_2 level released from one car. Then, total emission level of i is estimated for total i-type cars. Annual range of i means total range that a vehicle is driven in a year.

5.6.3. Parameter Estimation and Assumptions

Annual range of vehicles is determined as 18000 with assuming daily travel range of a vehicle as 50 km.

6. VALIDATION AND ANALYSIS OF THE MODEL

Vensim software is used for running the simulation model. It is continues time model and integration type is Euler. In this context, for all the simulation runs, time step is selected as 0.125. This value is neither too large to give inaccurate results nor too small to cause computer calculation errors.

The time unit of the model is taken as a year. The time horizon of the simulation is set to three decades, from 2012 to 2042 in order to be long enough to capture direct, indirect, and delayed effects of the variables and feedbacks.

In this chapter, firstly, validation of the model will be discussed in Section 6.1. Right after validation, base behavior of the model will be presented in Section 6.2.

6.1. Model Validation

Model validation is an important step of system dynamics methodology that checks if the model is an acceptable and adequate representation of the system with respect to dynamic problem of interest. Model validity is tested both in structural and behavioral aspects [48]. For testing the model validity, two major test groups, structural and behavioral, are applied to the model. These major groups and their related sub-groups will be extensively explained in the following sections.

6.1.1. Structural Validity

Structural validity tests analyze if the structure of the model can reflect the actual relations that exist in the real problem of interest meaningfully and satisfactorily. These tests should be established before behavior validity tests because if the structure of the model is invalid, then its behavior becomes unreliable. Structure validity involves two distinct tests that are direct structure tests and structure oriented behavior tests [67].

Significant portion of structural validation has been done during the model construction process. For example, variables of the model have real life counterparts. Moreover, the structure of the model is a meaningful description of the real relations that exist in the problem. Besides, direct structure tests and structure oriented behavior tests are applied after construction. Some of direct and structure oriented behavior tests will be given below.

<u>6.1.1.1. Direct Structure Tests:</u> Direct structure tests analyze the model structure validity by direct comparison with knowledge about real system structure. Structure and parameter confirmation tests, dimensional consistency tests, and direct extreme conditions tests are covered by the direct structure tests group [48]. For example, all variables and parameters in the model have real life counterparts. To illustrate, all parameters about attributes of the vehicle types, current vehicle number, and station numbers that are involved in the model are estimated from empirical data. Furthermore, each equation and relationship is compatible with available knowledge about the real system. In addition, there is dimensional consistency in the model (Units can be found in the Appendix B). Finally, the model equations are evaluated to be valid under extreme conditions.

<u>6.1.1.2. Structure Oriented Behavior Tests:</u> Structure oriented behavior tests analyze the validity of the structure indirectly. In this regard, extreme condition tests and sensitivity analysis, which are the two basic test groups under structure oriented behavior tests, are performed. Firstly extreme condition tests and following that sensitivity analysis will be clarified.

Extreme condition tests (ect): Extreme condition tests help to understand if the model is robust under extreme conditions or not. Robustness under extreme situations means that the model should behave in a realistic way independent from how extreme policies are applied to the model [47]. In this context, three different extreme condition tests are applied to the model. They are given below.

Extreme condition test 1 (ect 1): In the first extreme condition test, BEV attributes are modified. Its refueling time is set to 20 hours, and its driving range is set to 5 km. In addition, purchase price of vehicle is shifted from 50000 TL to 100000 TL. In these conditions, it would be expected that there would be no BEV sales due to insufficient attributes of BEV. Sales market share of EV is given in Figure 6.1.

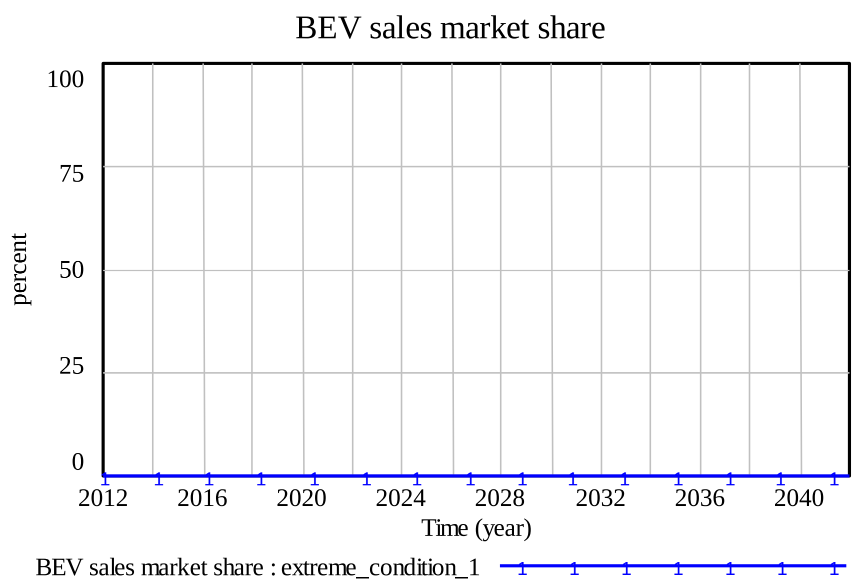

Figure 6.1. BEV sales market share under the 1st ect.

As can be seen from the Figure 6.1, nobody buys BEV. The results that were reached are matching with the expected outcomes because in first extreme situation, battery electric vehicle attributes become not satisfactory for consumers due to both extremely low value of time utility and high value of purchase price. Thus, it is logical that nobody prefers BEV and market share becomes zero. As a result, the model is valid under extreme condition test 1.

Extreme condition test 2 (ect 2): In the second extreme condition test, marketing influence on customer awareness is modified. As mentioned earlier, inflow of percentage of potential EV customers is directly affected by sum of marketing influence, social exposures of EV drivers and non-EV drivers. Normally, marketing influence is equal to 0.01 in the base model. However, it is set to 0.99, which means that marketing exposure on people becomes quite intense. It is expected in this test that percentage of potential customers reaches 100% fast and cannot be greater than 100% naturally no matter marketing influence is notably high. Behavior result of percentage of potential EV customers is given in Figure 6.2.

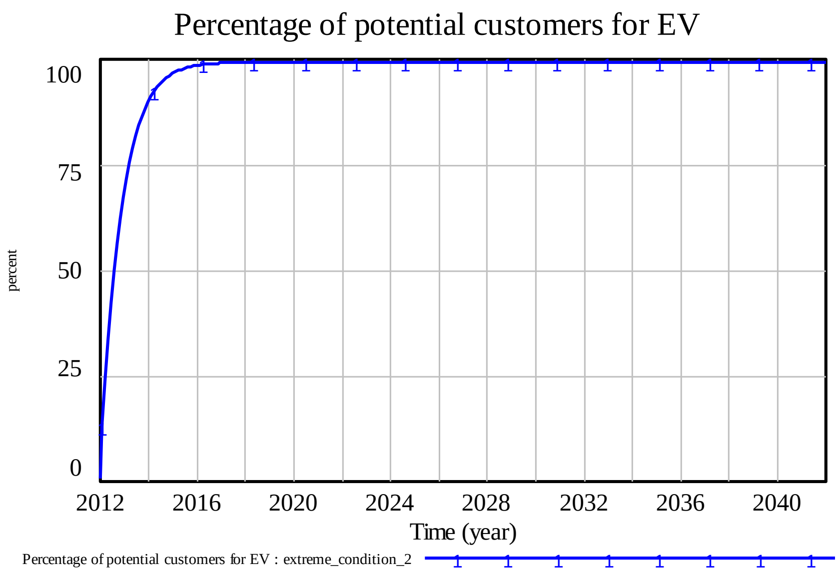

Figure 6.2. Percentage of potential EV customers under 2th ect.

Figure 6.2 shows that when marketing influence is set to 0.99, percentage of potential EV customers converges to one but it does not exceed it. The result is similar to what is expected because independent from the variables, percentage of potential EV customers cannot be greater than 100% in the nature of things. As a result, the model is valid under extreme condition test 2.

Extreme condition test 3 (ect 1): In the third extreme condition test, attributes of the BEV and HEV are improved equally and extremely. In other words, their driving ranges are set to the 1000 km, refueling time, maintenance costs, operating costs and purchase price are decreased excessively. Both emission rates are set to zero. Conversely, attributes of the CV are deteriorated as much. Purchase price, operating cost, maintenance cost, and refueling time are increased immensely. After this modification, behaviors of customers who are aware of all type of vehicles are analyzed. In this test, it is mainly expected that 50% of customers who are familiar with EVs would choose BEV whereas other 50% would choose HEV. In addition, it is expected that no one would prefer CV due to insufficient attributes of CV. Figure 6.3, Figure 6.4, Figure 6.5 show shares in annual sales of BEV, HEV, and CV among potential EV customers respectively.

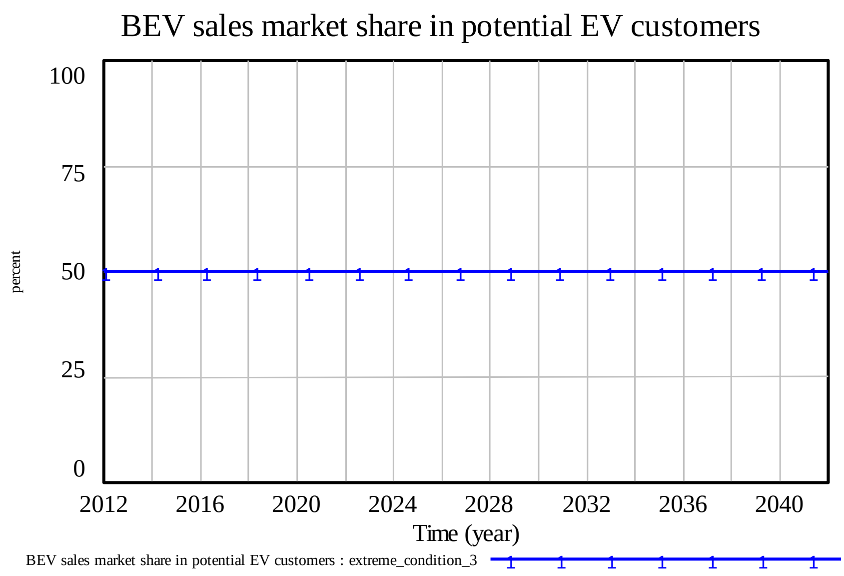

Figure 6.3. BEV share among potential EV customers under 3rd ect.

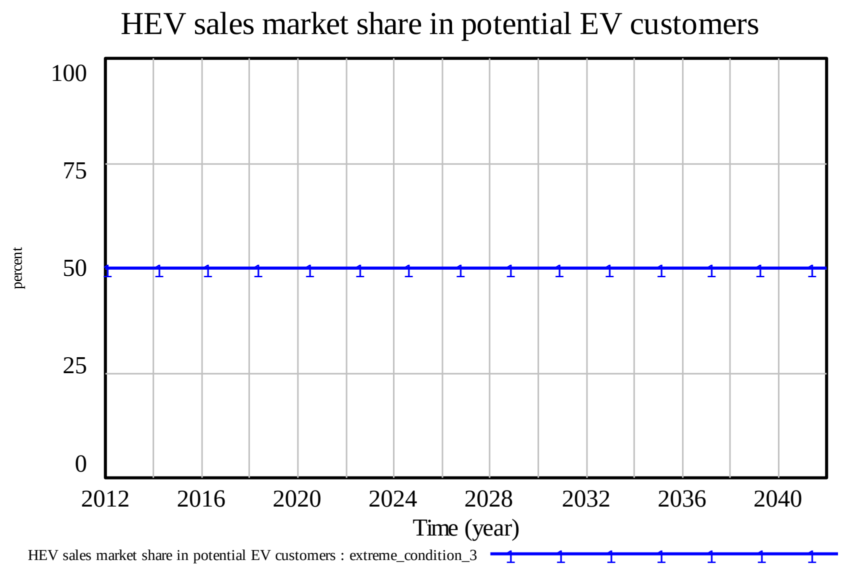

Figure 6.4. HEV share among potential EV customers under 3rd ect.

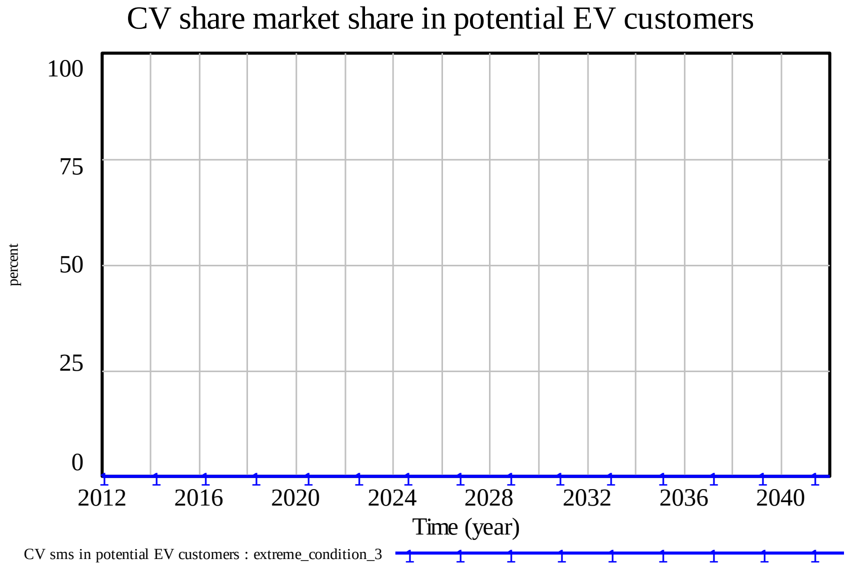

Figure 6.5. CV share among potential EV customers under 3rd ect.

Results show that 50% of people who are familiar with EVs prefer BEVs and other 50% of people who are familiar with EVs prefer HEVs. In addition, no one prefers CVs among potential EV customers. The results behave in expected direction because if attributes of CVs becomes much worse than HEVs' or BEVs', nobody wants to buy CVs. Moreover, if BEVs and HEVs exactly have same attributes, utilities coming from them become at same level that cause their market shares to be equal. These results indicate that the model is valid under 3rd extreme condition test.

In conclusion, the model is valid under these three extreme condition tests.

Sensitivity analysis: Sensitivity analysis is another sub-group of structure oriented behavior tests. According to Barlas [67], 'Behavior sensitivity tests consist of determining those parameters to which the model is highly sensitive, and asking if the real system would exhibit similar high sensitivity to the corresponding parameters'(p.4). In the study, most of the parameters are tested to understand whether there are parameters, to which the model is highly sensitive or not. In this regard, sensitivity tests are applied to all parameters that do not have exact values taken from their real counterparts. Results of all analysis can be found in Appendix C. However, an example set, which contains effectiveness of WoM of EV drivers, motorization rate, and weight of emission utility, will be analyzed in detail below. Another important point is that the range of sensitivity is arranged between plus 20% and minus 20% of the base value in all tests. In other words, the minimum value of range is determined as 20% less than the base value of parameter and maximum value of range is specified as 20% higher than the base value of same parameter in sensitivity tests.

Effectiveness of word of mouth of EV drivers: In the model, quantitative estimation of effectiveness of WoM of EV drivers is assumed as 0.25 (dimensionless). In the sensitivity analyses, this value is tested between the range of 0.2 and 0.3. The impact of this modification on the BEV fleet market share is given in the Figure 6.6.

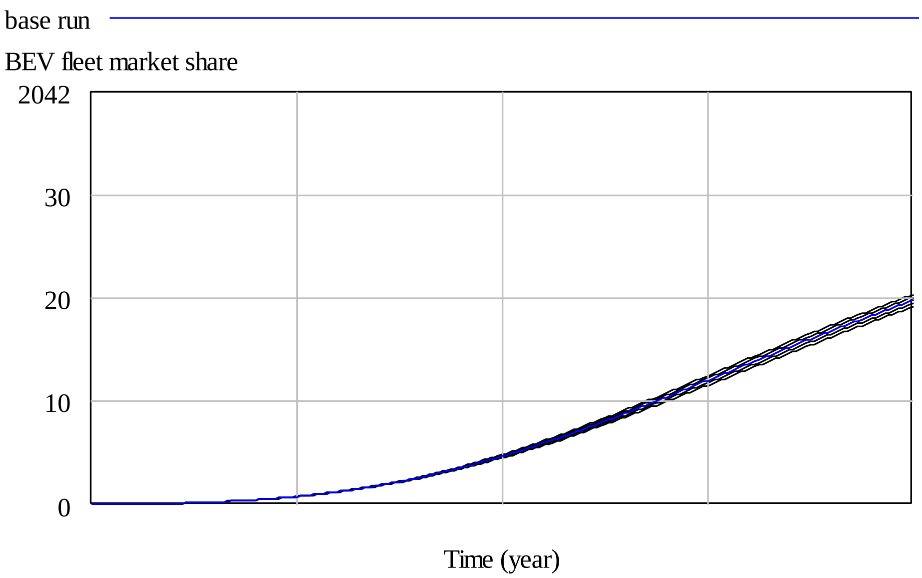

Figure 6.6. Sensitivity result for effectiveness of WoM of EV-drivers.

The Figure 6.6 shows that BEV fleet market share is not strongly sensitive to effectiveness of WoM of EV-drivers.

Motorization rate: Motorization rate is assumed as 0.145 vehicle/person in the model. Although this value is observed from current habitat motorization rate, sensitivity tests are applied to this parameter, too. This value is changed between the range of 0.115 and 0.175 (vehicle/person). The impact of this adjustment on the BEV fleet market share is given in Figure 6.7.

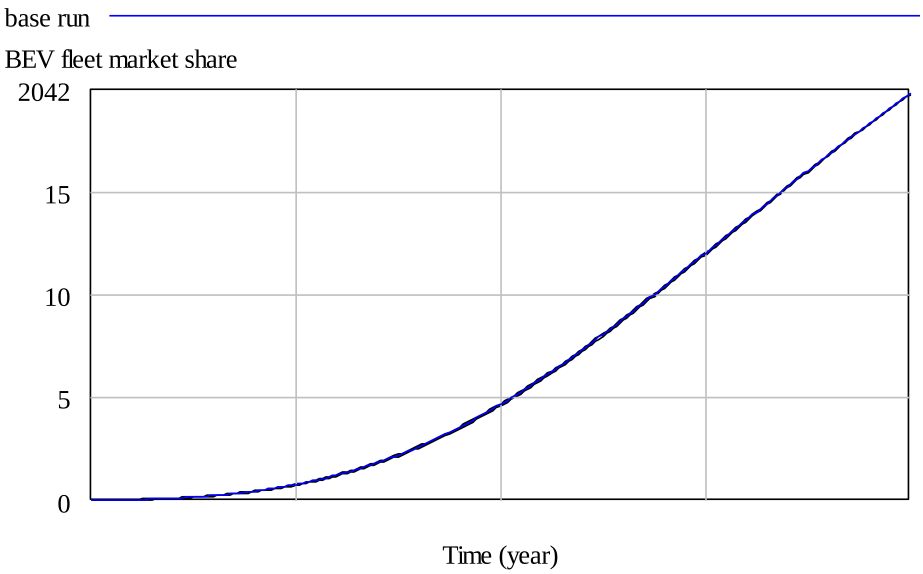

Figure 6.7. Sensitivity result for motorization rate.

Figure 6.7 shows that BEV fleet share seems relatively insensitive to motorization rate.

Weight of emission utility: Weight of emission utility is assumed to be -0.07 (dimensionless) for market segment A, and -0.09 (dimensionless) for market segment B. These values are adjusted based upon the revealed-preference multinomial logit model estimated by Brownstone, Bunch, and Train [56]. Nonetheless, sensitivity tests are applied to the weights to assess their influence on the model sensitivity. In this test, weight of emission utility for A is changed between the range of (-0.085) and (-0.056). In addition to A, for B, the range is arranged between (-0.011) and (-0. 7). Impact of this modification on the BEV fleet share is given in Figure 6.8.

In conclusion, all results (the results given here and results in the Appendix) indicate that the model is valid in terms of parameters that are max range, effectiveness of WoM of EV drivers, effectiveness of WoM of non-EV drivers, motorization rate, every estimation time, annual range of vehicles, weight of every utility. It must be noted that there may be sensitivity in numerical results. However, the model has low sensitivity in terms of pattern dynamics. This means that long-term behavior of the model strongly depend on structure of the model rather than some uncertain variables.

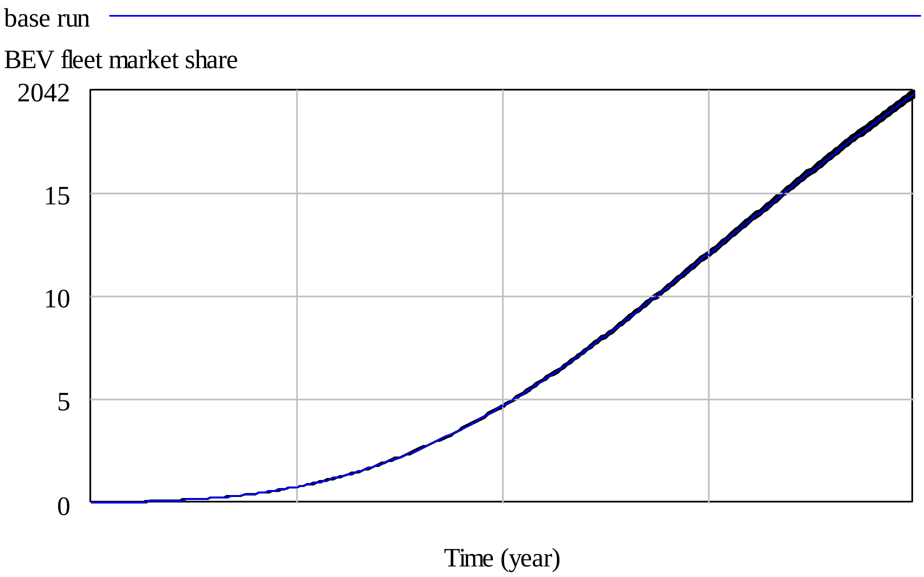

Figure 6.8. Sensitivity result for weight of emission utility.

Figure 6.8 shows that in given range, impact of weight of emission utility do not substantially varies.

6.1.2. Behavior Validation

Once model succeeds structural tests, behavior validity tests are applied to control if the dynamic patterns, which the model produces, are close enough to the real patterns of concern. Behavior validation tests assess the pattern prediction, not point prediction. This type of validation involves some statistical and quantitative tests like regression and trend comparison, periods and amplitude comparison, or BTS software [48]. However, EVs, particularly BEVs, have been a topical issue in Turkish automobile market for less than 2 years. Thus, Istanbul or Turkey has no historical data about battery electric vehicles or hybrid vehicles to compare with behavior patterns of the simulation result of the model. However, the model generates patterns that resemble the ones perceived in other mobility systems. Behavior patterns show similar trajectories the ones in observed in the literature. BEV and HEV fleet share results of this study and an example result from the study in the literature are respectively given in Figure 6.9 and Figure 6.10 to show pattern similarity. An example result is taken from the work of Wansart and Schnieder [19].

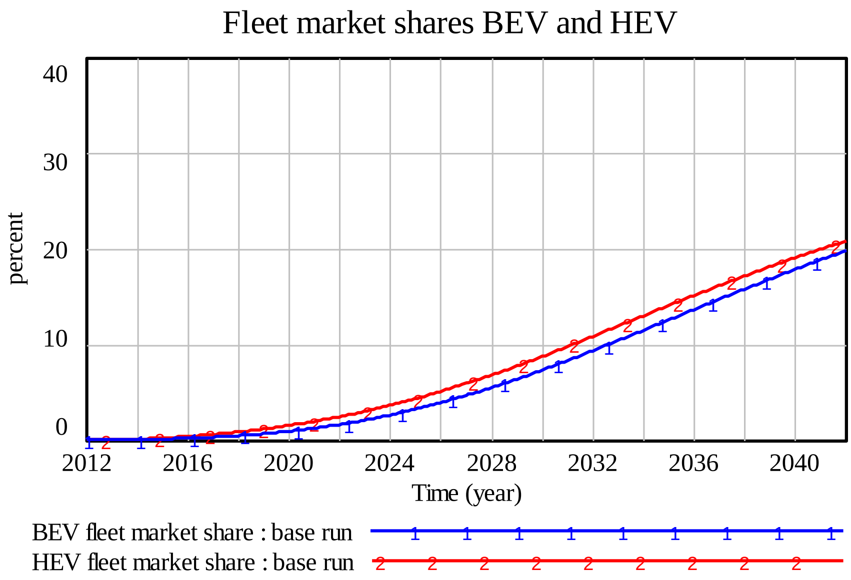

Figure 6.9. Fleet share patterns of this study.

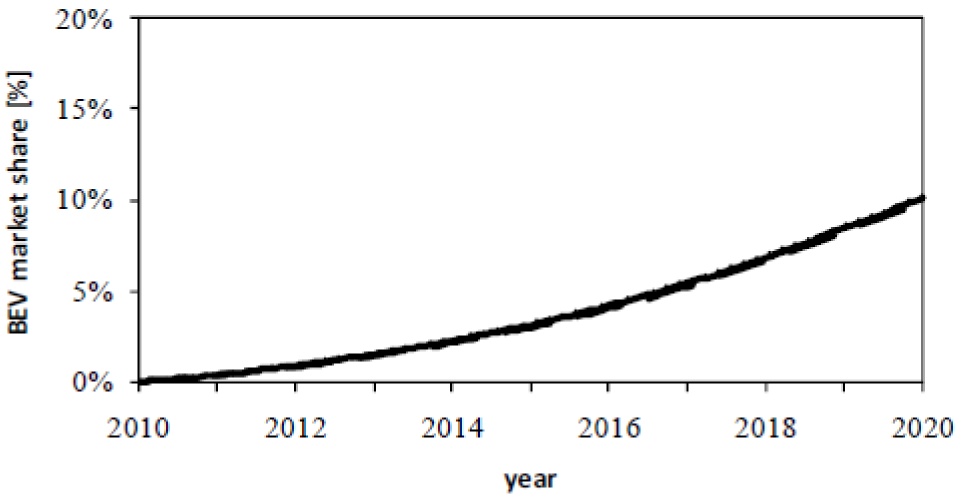

Figure 6.10. Fleet share pattern of the work of Wansart and Schnieder.

6.2. Analyses of the Base Behavior

The base model is a case that forms a reference for comparison and assessment of the scenarios and policies in the analysis. In the base case, it is assumed that the recent trends would likely continue with no major changes. In other words, all technological improvements, prices, costs, and regulations given in the beginning of the analysis would be progressed gradually according to broadly accepted trajectories. Driving range, refueling time, and maintenance cost of BEV improve gradually over time. Purchase price of BEV, HEV and CV decrease gradually over time. It is assumed that both electricity and gasoline prices would show similar trend to their historical data. Finally, emission rates are assumed to be constant for all vehicle types.

The base model includes three types of vehicles that are conventional vehicle (CV), battery electric vehicle (BEV), and hybrid electric vehicle (HEV). Customers buy a vehicle among three types with comparing attributes of each vehicle. Preferences of customers shape market share of each vehicle type. It must be noted that two different market shares are defined in the study. They are sales market share and fleet market share. Sales market share represents percentage of total sales volume captured by each vehicle in the market. It is a share in the annual flow. On the other hand, Fleet market share represents the ratio of number of each vehicle type to the total number of vehicle available on the road of Istanbul. It is a share in the active stock. Sales, which fill amount of each vehicle type, are shaped by sales market share. Ratio of number of each vehicle type to the total vehicle number produces fleet market share of related vehicle type.

The behavior pattern of sales market share of vehicles is illustrated in Figure 6.11.

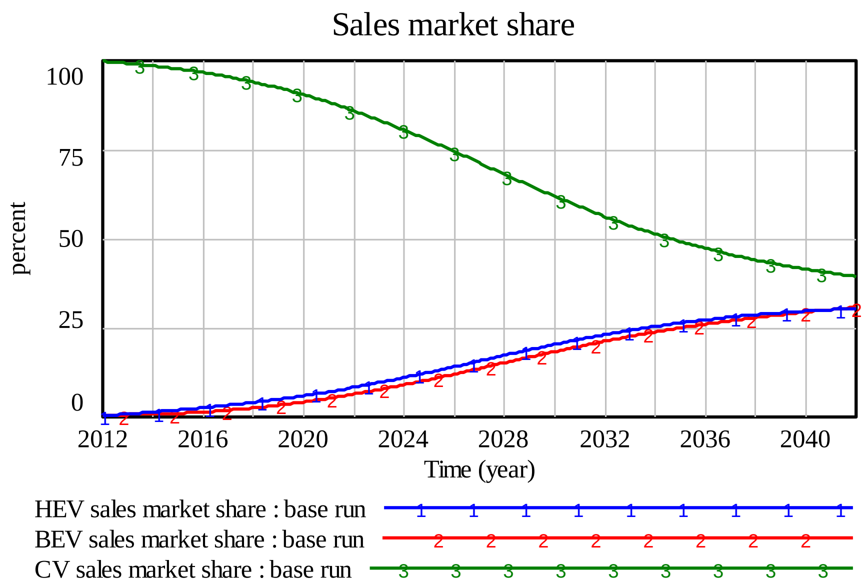

Figure 6.11. Sales market share of vehicles under the base run.

As stated earlier, Sales market share represents percentage of total sales volume captured by each vehicle in the market. As is seen from the Figure 7.1, after three decades, sales market share of each of BEV and HEV reaches 30.64% and 30.21% respectively. There are two main reasons why sales EV market share is still lower than CVs' even after 3 decades. Firstly, although percentage of potential customers goes up gradually, there are still people who do not recognize EVs yet. These unaware customers directly buy CV due to the perception of the unavailability of other choices. Secondly, although attributes of BEV and HEV may have preferable sides compared to CV, they remain still less efficient than the attributes of CV. For instance, driving range of BEVs is lower, refueling time of BEVs is longer, or maintenance cost of BEV is higher compared to CVs' throughout simulation period. In addition, purchase price of HEV is higher than both BEV and CV. Apart from these, sales market share of HEV is slightly higher than BEV's sales market share in the first 25 years of the simulation. After this point, BEV sales begin to catch and exceed HEV sales. This means that some attributes (maintenance cost utility and time utility) of HEV are more preferable from the view of customers until the last years of the simulation. However, improvements about battery technology provide BEVs to be more advantageous.

Sales of new vehicles add to the total number of each vehicle type in Istanbul, which is given in Figure 6.12.

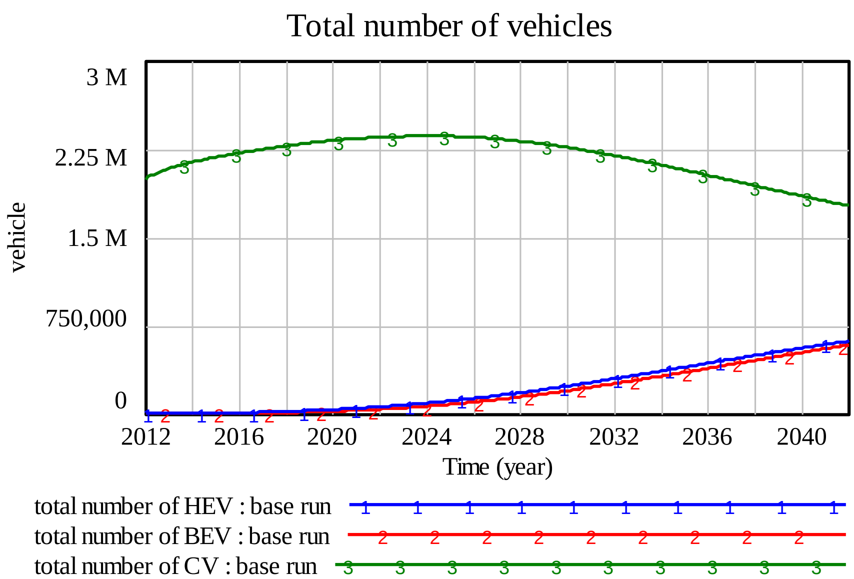

Figure 6.12. Total number of each vehicle under the base run.

According to the simulation results, total number of every type of vehicles increases in the first 10 years. The reason of why total number of CV increases while sales market share of CV decreases is the growth of automobile market in Istanbul. After the first decade, while number of BEV and HEV continue to increase, CV starts to decline due to the high market share captured by BEV and HEV.

Total number of each vehicle forms the fleet market share of vehicles. Fleet market share represents the ratio of number of each vehicle type to the total number of vehicle available on the roads of Istanbul. Fleet market share of each vehicle type is presented in Figure 6.13.

As it could be seen from the Figure 6.13, even the sum of BEV and HEV cannot achieve to capture 1% market share in the first years of diffusion. After 2016, penetration gains speed and increases gradually. BEV and HEV diffusion ultimately reaches respectively around 19.76%, and 20.7% of the total fleet in Istanbul by 2042. The reasons of the increase in the fleet share can be explained as rise of familiarity with EV, improved BEV technology, fall in price of BEV and HEV as well as developed BEV recharging infrastructure. All these circumstances lead EVs to become more attractive for customers that result in EV market share to increase over time.

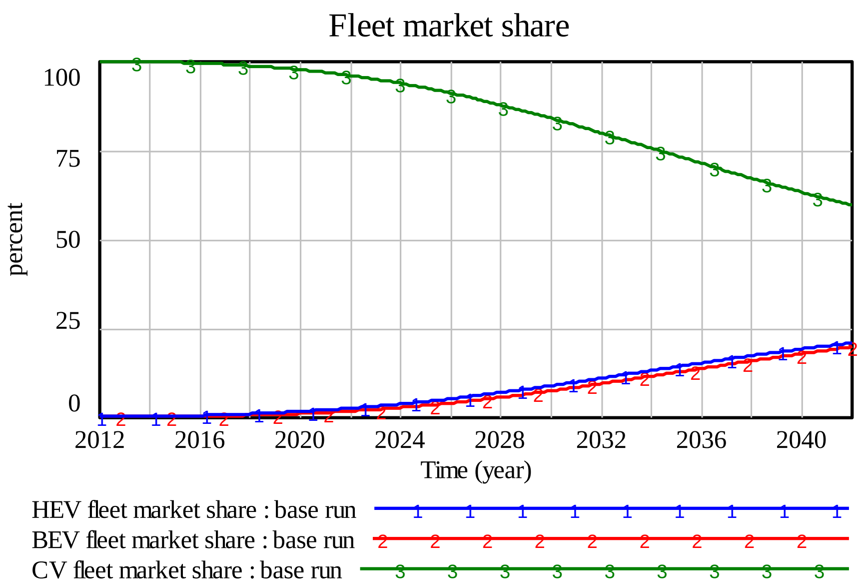

Figure 6.13. Fleet market share of vehicles under the base run.

As stated in the previous part, sales firmly depend on awareness about vehicle. Percentage of potential customers for CV is equal to 100% due to the assumption of 100% familiarity of costumers to the conventional vehicles. However, percentage of potential customers for EV is not 100% and it is increased by marketing activities, and word of mouth of adopters and non-adopters. In this sense, observed simulation result of potential customers for EV is given in Figure 6.14.

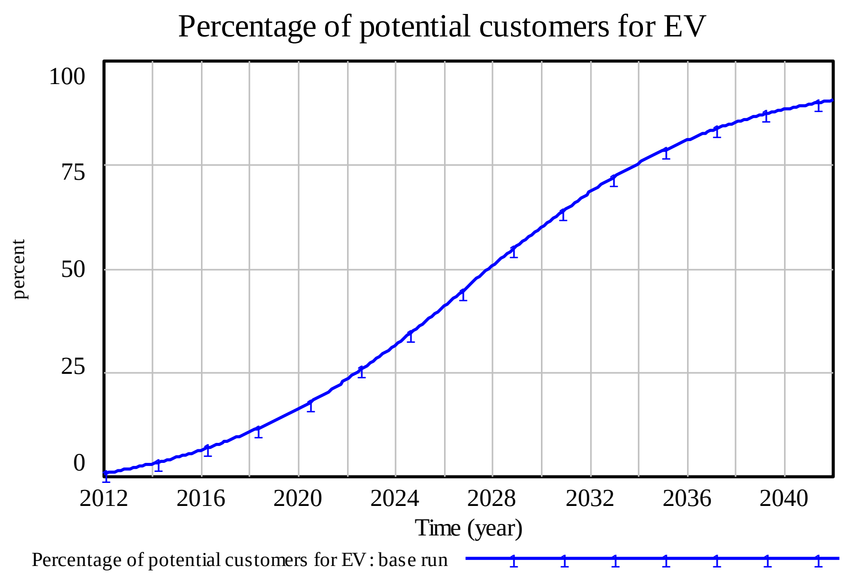

Figure 6.14. Percentage of potential EV customers under the base run.

Figure 6.14 illustrates that the percentage of potential EV customers has an S-shaped behavior pattern since it grows slowly in the beginning due to the lower number of adopters and higher number of non-adopters. In addition, major population among non-adopters does not have knowledge about EVs. After a while, it grows faster because both non-adopters who are familiar with EVs and adopters increase.

One of the main reasons of why EVs are suggested to replace CVs is the potential reduction in greenhouse gas emissions. In this work, ultimate impact of EV diffusion on CO_2 reduction is estimated. Reduction percentage is observed based on EV penetration data coming from the simulation results. It should be noted that reduction of CO_2 does not mean cumulative reduction. It means reduction in the associated year. Figure 6.15 shows CO_2 reduction under base run.

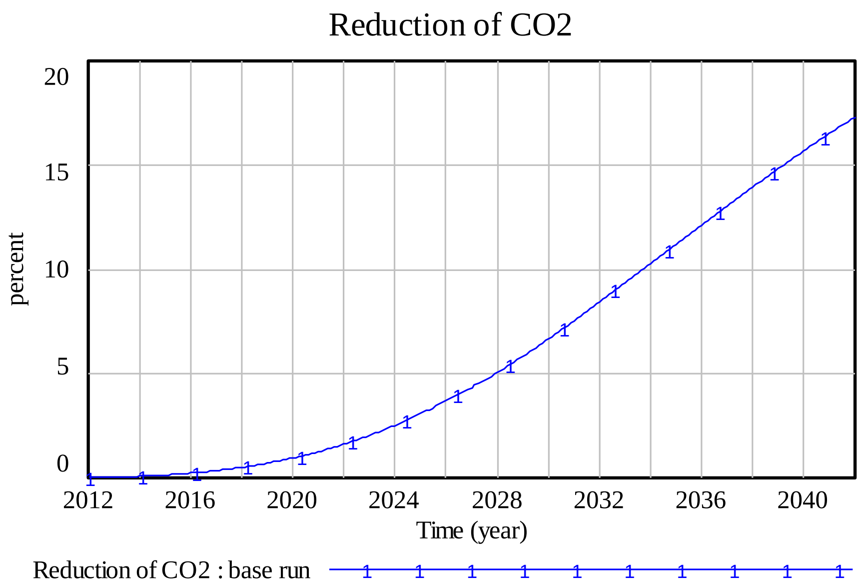

Figure 6.15. Reduction of CO_2 under the base run.

The Figure 6.15 shows that CO_2 reduction related to EV penetration would be around 5% at 2028. In addition, even with both 19.76% fleet market share of BEV and 20.77% fleet market share of HEV, reduction of CO_2 emission would only reach around 17% in 2042. In addition, cumulative CO_2 reduction would be around 17.07×10^6 tons by 2042.

As it seems in the base run figures, S-shaped pattern is observed for the sales market share of both BEV and HEV. This is mainly due to the fact that domination of CV in the beginning of penetration process causes low level of familiarity of consumers about EV. Thus, market diffusion of EVs shows slow growth in the early periods despite competitiveness of EVs in terms of operating costs, purchase price, and emission rate. Even after familiarity level increases, market share of neither BEV nor HEV reach the market share of CV due to the two reasons. Firstly, even if awareness level increases, there are people who do not recognize EVs throughout simulation. Secondly, certain preferable properties of conventional vehicles, which are lower purchase price and maintenance cost compared to both BEV and HEV, and higher time utility compared to BEV induce higher CV market share.

7. SCENARIO AND POLICY ANALYSIS

In this section, eleven different scenarios, ten policies, and four scenario-policy combinations are evaluated to explore how they would influence diffusion pattern and market share of EVs in Istanbul. Each scenario, policy, and combination will be explained in detail below.

7.1. Scenario Analysis

In scenario analysis section, eleven different scenarios are examined to capture plausible changes in the context. Topics of these scenarios are basically future costs of electricity and gasoline, BEV technology, refueling infrastructure, launching only BEV in to the market, customer awareness, and repurchasing rate. The results of these scenarios will mostly be presented comparing them with the base run to provide better understanding for analysis.

7.1.1. Electricity and Gasoline Costs Related Scenarios (Scenario 1)

Battery electric vehicles are electricity-powered vehicles whereas their conventional and hybrid counterparts use gasoline as a power source. Because of this reason, costs of electricity and gasoline may likely be effective factors on customer decisions about vehicle types. However, future prices of electricity and gasoline are uncertain. Thus, it would be better to specify possible trends about electricity and gasoline and then to analyze impact of these trends on EV penetration.

Resources used in electrical energy generation and their usage rates differ among countries. Despite the fact that renewable resources (such as wind power) can be used in electricity generation, natural gas, brown coal, imported coal, hydraulic resources are basic resources that have considerably high shares in electricity generation in Turkey. In addition, some of these resources (such as high percentage of natural gas or some portion of coal) are imported, which can be limited amount or have high tax or price. Electricity price is highly related to the shares of different resources in the generation mix. Cost of the energy resources is also influenced by exogenous factors like economical or political development [68]. In brief, there are many factors on electricity price that cause uncertainty of the future electricity price in Turkey.

Future prices of gasoline is also an uncertain factor for vehicle diffusion because gasoline prices may be dramatically affected by global fuel prices, exchange rates, and political and economical developments [68]. These reasons make it hard to predict future trends of gasoline prices.

In the base case, it is assumed that both electricity and gasoline prices would show similar trend to their historical data. Historical electricity prices data shows fluctuation. Therefore, it is hard to determine a constant annual raise percentage for electricity price. However, in the base case, annual increase rate of electricity price is assumed as 9% on average. This value is an estimation based on historical trend of electricity prices. In addition, historical data about gasoline prices show that increase rates of gasoline prices highly fluctuate and thus, it is hard to determine annual raise percentage due to great variance. However, in the base case, annual raise percentage is determined as constant value that is forecasted as 7.5% on average based on historical trends.

Four scenarios about the future situation of energy prices are constructed to analyze their effect on EV penetration. In the first scenario, it is assumed that there would be no further changes in the value of the gasoline and electricity prices throughout simulation period. It is assumed that electricity cost is slightly affected by BEV demands in the second scenario whereas electricity cost is firmly affected by BEV demands in the third scenario. Lastly, rapid increase in gasoline prices is assessed in the final scenario. These four scenarios will be analyzed in detail in the following part. It should be noted that the term of cost does not exactly represent power prices. Gasoline cost and electricity cost are estimated based on the fuel usage rate of vehicle per km and prices of resource that they use. In other words, cost refers to operating cost of a vehicle for a km drive. However, cost directly reflects increase or decrease of the gasoline and electricity prices.

7.1.1.1. Constant Electricity and Gasoline Costs (Scenario 1_1): In this scenario, it is assumed that there will be no factor that can influence gasoline or electricity prices directly. Therefore, gasoline and electricity costs will not change throughout simulation. The result of Scenario 1_1 on BEV and HEV fleet shares are illustrated in Figure 7.1 and Figure 7.2, respectively.

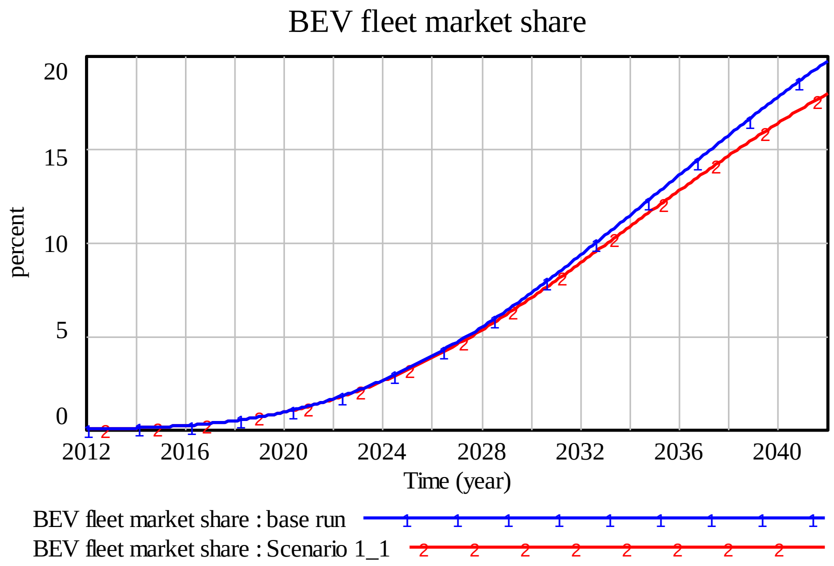

Figure 7.1. BEV fleet market share under the Scenario 1_1.

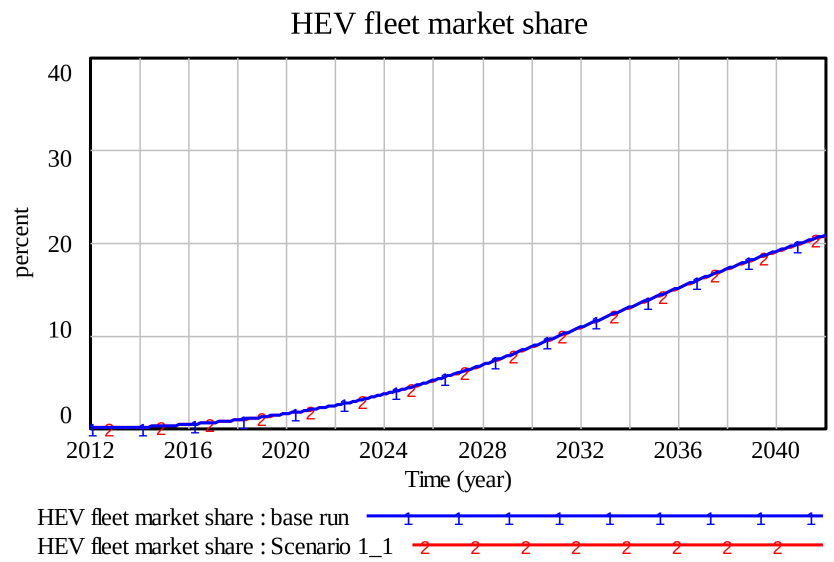

Figure 7.2. HEV fleet market share under the Scenario 1_1.

As can be seen from the graphs, if gasoline and electricity costs do not change, diffusion of BEVs would be lower compared to the base run because in the base run, gasoline and electricity costs keep rising and the gap between them gradually widens. This situation influence BEV diffusion positively. However, in this scenario, cost gap remains the same.

7.1.1.2. Low Level of Sensitivity to Electricity Demand (Scenario 1_2): There has been a debate about whether increase of electricity demand due to BEVs affects electricity prices or not. In this scenario, annual increase percentage of gasoline is assumed as constant and 7.5%. However, annual rise percentage of electricity price is not constant in this case. It positively depends on total electricity supply. In other words, the more electric vehicle causes more electricity consumption. This situation may lead to rise of electric prices. In this scenario, it is assumed that when BEV share in fleet reaches 5%, electricity prices begin to be affected by electricity demand slightly. In other words, sensitivity of electricity prices to electricity demand is at low level in this scenario. Pattern of electricity and gasoline prices and their impact on BEV fleet market share are respectively given in Figure 7.3. and Figure 7.4.

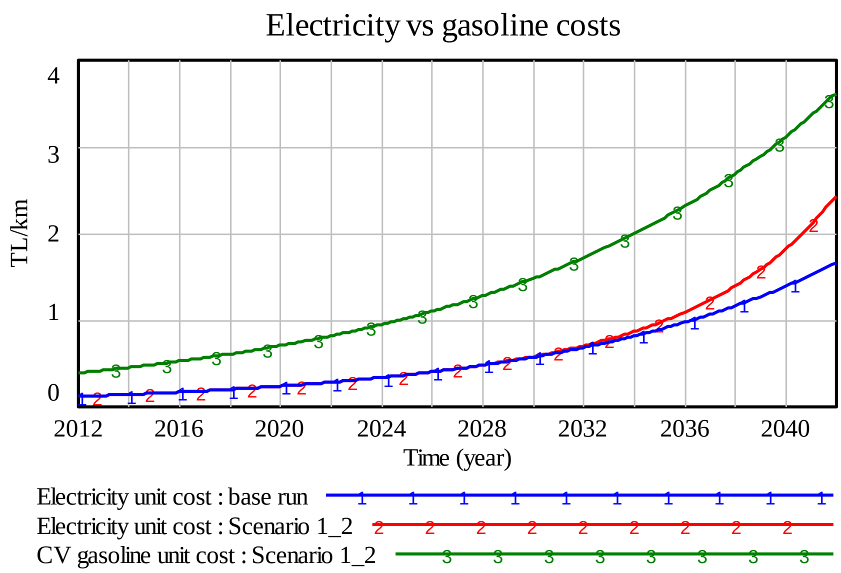

Figure 7.3. Electricity and gasoline costs under the Scenario 1_2.

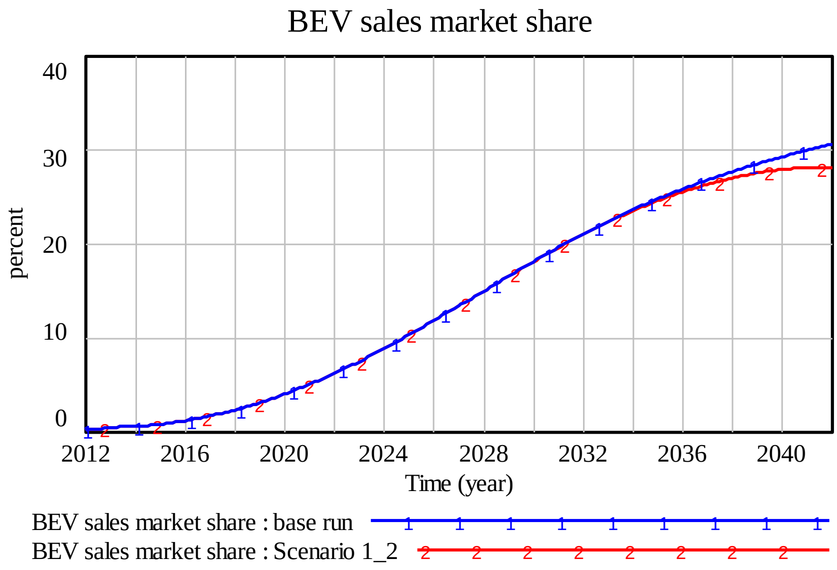

Figure 7.4. BEV fleet market share under the Scenario 1_2.

In this scenario, electricity cost increases to its maximum, 2.42 TL/km, by 2042. As seen from the figures, if electricity cost is slightly affected by electricity usage rate, this situation does not create considerable change on BEV sales in the first 25 years of the diffusion. However, after 25 years, it begins to influence sales strongly because after 25 years high-level electricity demand causes a balancing mechanism against diffusion.

7.1.1.3. High Level of Sensitivity to Electricity Demand (Scenario 1_3): As stated in Scenario 1_2, electricity prices can be influenced by electricity demand. On the other hand, unlike previous one, in this scenario, it is assumed that the electricity prices are highly affected by electricity demand coming from BEV drivers. After a while, electricity cost exceeds gasoline cost due to price-demand relation. It is assumed that when BEV share in fleet reaches 5%, electricity prices begin to be affected by electricity demand. After this point, electricity prices continue to increase parallel in with increase of BEV share. Moreover, it is assumed that annual rise of gasoline price would follow its historical trend, which is 7.5% per year. Although the end of the simulation is determined to be 2042 at whole analysis, the model is simulated until 2050 to provide visual clarity only for this scenario.

The simulation results show that the gap between gasoline and electricity costs begins to narrow at around 2040. In addition, electricity cost exceeds gasoline cost at 2045. After 2040, BEV sales begin to decrease while HEV continue to go up. After breakeven point is exceeded, BEV sales begin to decline increasingly.

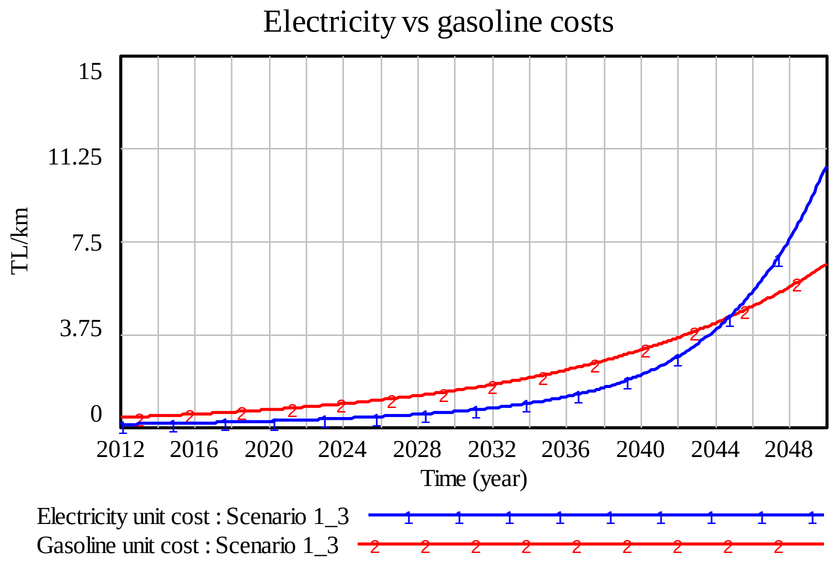

Figure 7.5. Electricity vs gasoline prices under the Scenario 1_3.

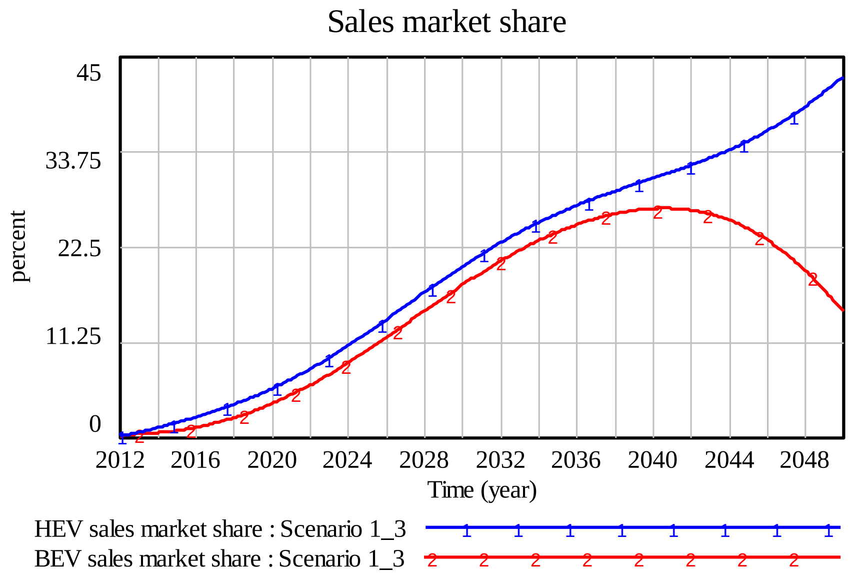

Figure 7.6. Sales market share of BEV and HEV under the Scenario 1_3.

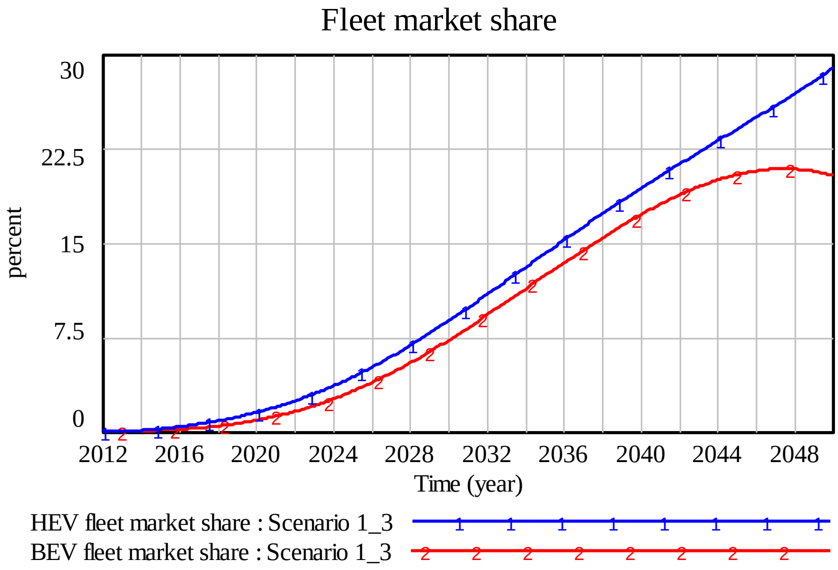

Figure 7.7. Sales market share of BEV and HEV under the Scenario 1_3.

<u>7.1.1.4. High Gasoline Cost vs Normal Electricity Cost (Scenario 1_4):</u> Gasoline prices may rise due to the reasons such as political or economical issues, relationship of countries, supply problem, or new tax regulations. In the last scenario, it is assumed that gasoline cost increases normally (7.5% in every year) until 2020. After 2020, it shows exponential increase. However, electricity cost increases normally (9% per year) throughout simulation. Patterns of sales and fleet market share of vehicles under Scenario 1_4 are respectively given in Figure 7.8 and 7.9.

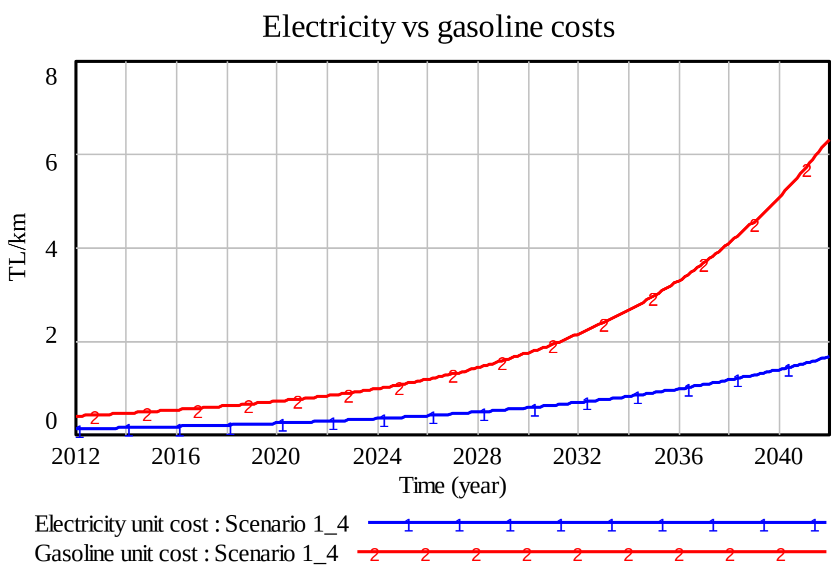

Figure 7.8. Gasoline vs electricity cost under the Scenario 1_4.

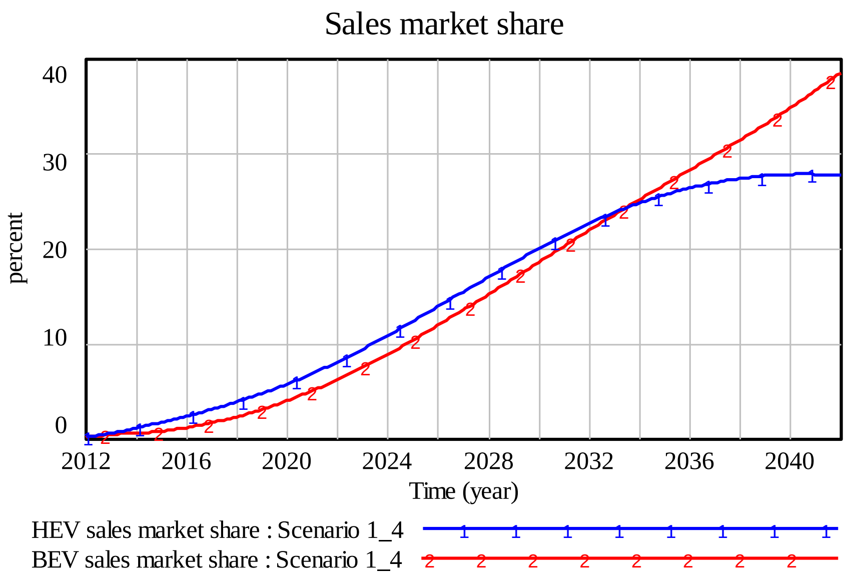

Figure 7.9. Sales market shares of BEV and HEV under the Scenario 1_4.

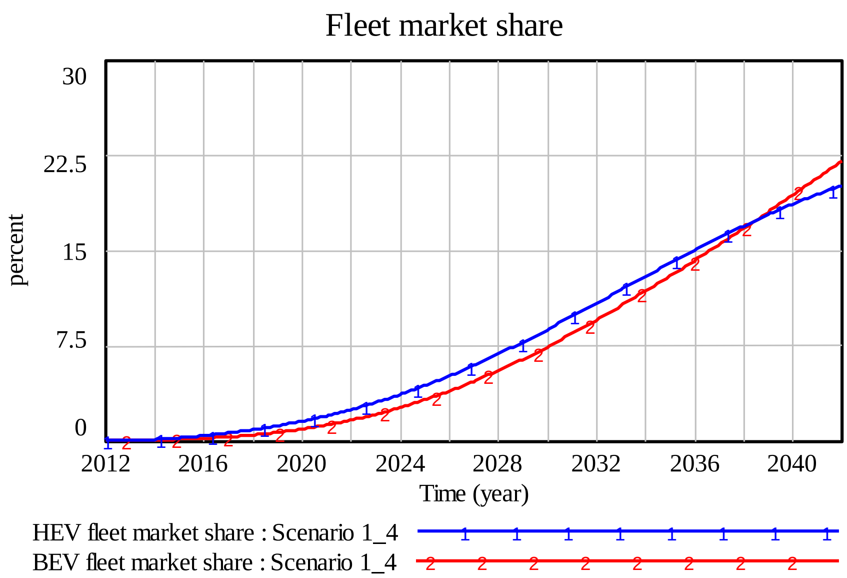

Figure 7.10. Fleet market shares of BEV and HEV under the Scenario 1_4.

Results show that the gap between electricity and gasoline costs widens gradually until around 2030. However, the gap begins to increase rapidly after this year. Thus, after around 2030, BEV sales exceed HEV sales and BEV sales continue to show its existing trend. However, HEV sales firstly begin to increase decreasingly and then begin to decrease. This shows that if gasoline cost increases substantially while electricity cost keeps rising gradually, after a while sales market share of HEV begins to decline.

The summarized results of scenarios related to changes in electricity and gasoline costs are given in Table 7.1.

Table 7.1. The results of electricity and gasoline costs related scenarios.

	Market Share 2012 (%)	Market Share 2042 (%)	Total sales until 2050 (Million)
Base Run			
CV	99.99	59.47	6.990
BEV	0.003	19.76	1.032
HEV	0.007	20.77	1.131
Scenario 1_1	Constant electricity and gasoline costs		
CV	99.99	61.33	7.071
BEV	0.003	17.94	0.954
HEV	0.007	20.73	1.127
Scenario 1_2	Low level sensitivity to electricity demand		
CV	99.99	59.76	6.999
BEV	0.003	19.19	1.014
HEV	0.007	21.05	1.139
Scenario 1_3*	High level sensitivity to electricity demand		
CV	99.99	59.96	6.552
BEV	0.003	18.80	1.113
HEV	0.007	21.24	1.485
Scenario 1_4	Higher gasoline cost vs normal electricity cost		
CV	99.99	55.83	6.923
BEV	0.003	22.07	1.125
HEV	0.007	20.10	1.103

*Scenario 1_3 is simulated until 2050. However, the values on the Table 7.1 are results in 2042. Shares in fleet of CVs, BEVs, and HEVs by 2050 are 50.73%, 20.37%, and 28.90%, respectively.

7.1.2. Technological Development Related Scenarios (Scenario 2)

Vehicle attributes are influential factors on customer preferences about vehicle types. Although BEVs have competitive properties such as lower operating cost or lower emission rate compared to CV and HEV; BEVs may fall behind them due to the insufficient infrastructure and the limited battery properties such as lower driving range, longer refueling hour, or higher maintenance cost.

Research and developments have been continuing all over the world to improve BEV technology because researchers imply that technological improvements about the battery technology may yield penetration of BEV to speed up [27,42,43,45]. Although it is believed that technological improvements about battery are going to occur, possible improvement level and time are highly uncertain. In this sense, three possible scenarios about technological improvement are assessed. It is assumed that progress level of battery technology would gradually grow in the base case. After that, first scenario is developed assuming moderate technological improvement whereas it will be at optimistic level in the second scenario. Finally, the case of no technological improvement is analyzed in the third scenario.

<u>7.1.2.1. Moderate Technological Improvement (Scenario 2_1):</u> In this scenario, improvement about battery technology is assumed to happen at medium level. In other words, driving range, refueling time, and maintenance costs are improved more than the base run, but eventually, they do not become as efficient as conventional vehicles even after three decades. Progresses of these three properties are respectively presented in Figure 7.11, 7.12, and 7.13. In addition, impact of these improvements on fleet shares is given in Figure 7.14.

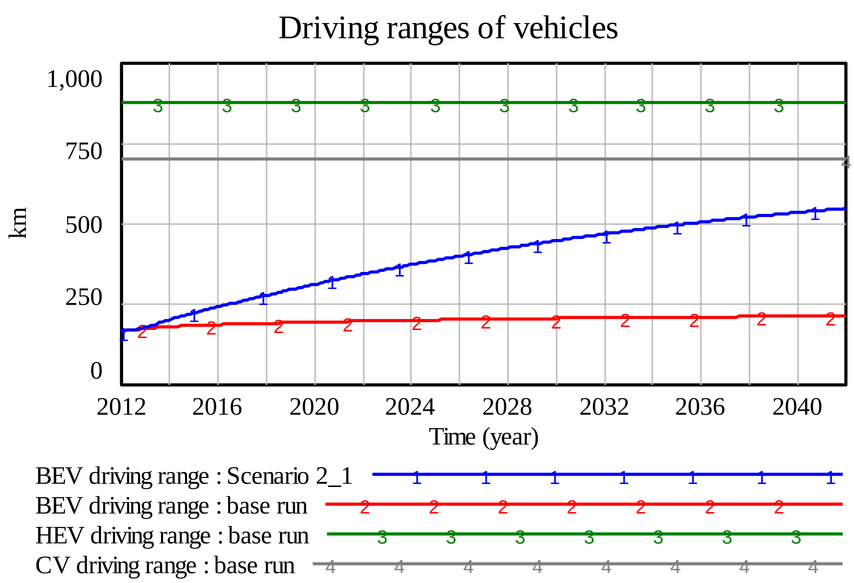

Figure 7.11. BEV driving range under the Scenario 2_1.

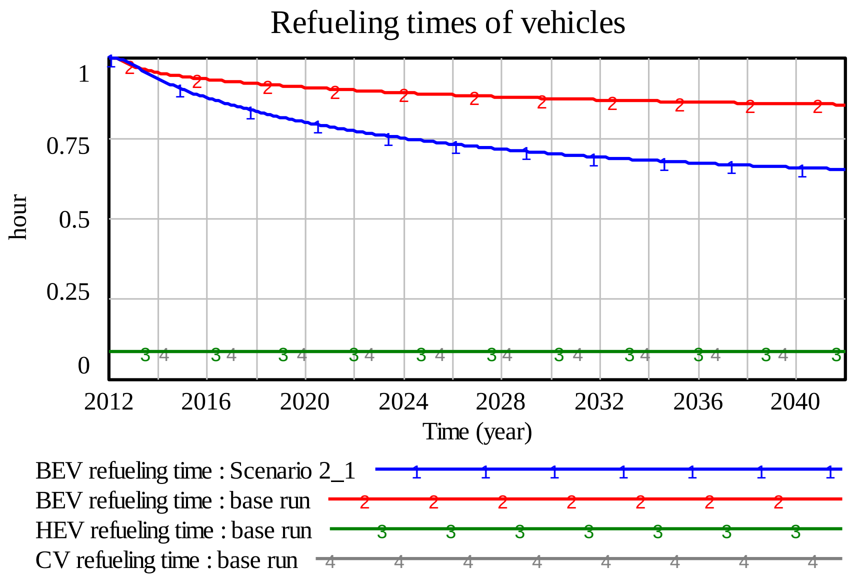

Figure 7.12. BEV refueling time under the Scenario 2_1.

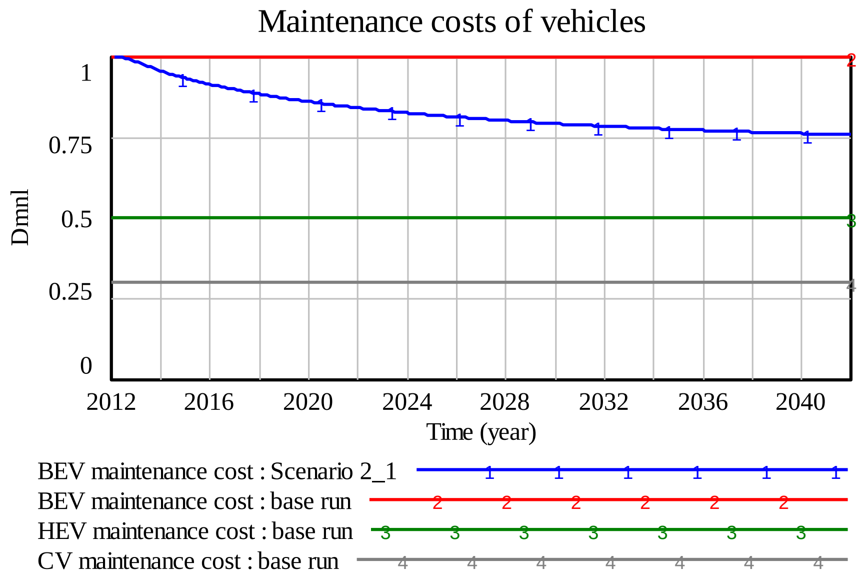

Figure 7.13. BEV maintenance cost under the Scenario 2_1.

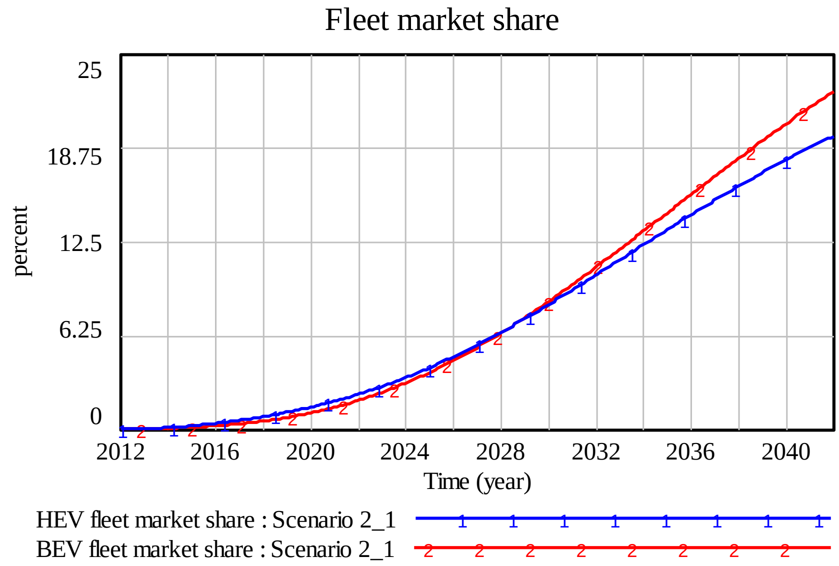

Figure 7.14. Fleet market share of BEV and HEV under the Scenario 2_1

As is seen from the Figure 7.14, HEV has slightly higher market share than BEV in the first years, but after a while, improvements of the battery technology cause BEV to exceed the market share of HEV. Improvements do not create substantial change on the fleet share because despite of the medium-level developments, driving range, refueling time, and maintenance cost are still less preferable than CV and HEV.

7.1.2.2. Optimistic Improvements (Scenario 2_2): In this scenario, it is assumed that BEV technology would immensely be improved and some of attributes of BEV would be better than CV technology over time. Moreover, there would not be any infrastructural obstacles for BEVs throughout the simulation. In other words, the coupled effects of evolving technological features and advanced infrastructure on adoption process are captured in this scenario. It should be noted that developments of battery attributes are parallel with optimistic scenarios given in the literature. Advanced progress of technological features and infrastructure situation is illustrated in Figure 7.15. Moreover, effect of this scenario on BEV fleet share is given in Figure 7.16.

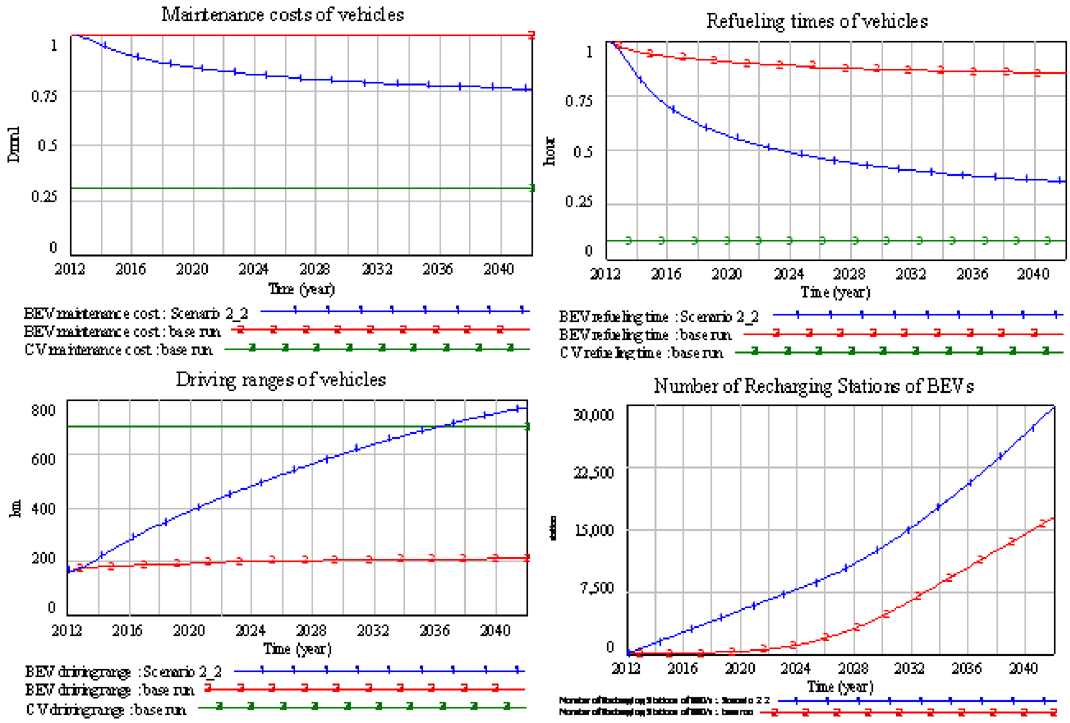

Figure 7.15. Technological and infrastructural improvement under the Scenario 2_2.

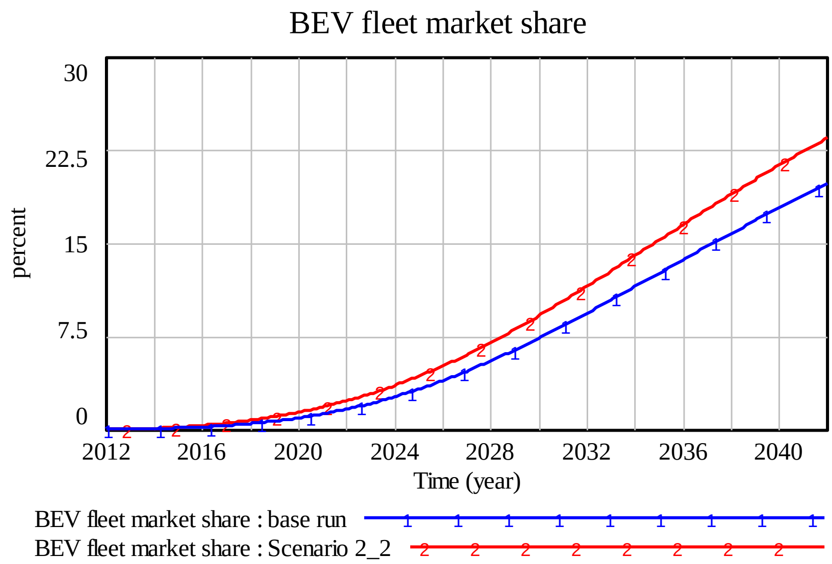

Figure 7.16. BEV fleet market share under the the Scenario 2_2.

The results show that as it is expected, advanced technological improvements and sufficient recharging stations cause BEV diffusion to increase. However, even if all technological and infrastructural conditions are advanced like in the Figure 7.15, fleet market share of BEV would achieve to reach 23.46% of the market by 2042. This is mainly due to the fact that the driving range of BEVs exceeds driving range of CVs after 25 years, refueling time and maintenance cost of BEVs are improved but they still does not keep pace with or exceed CVs' attributes.

7.1.2.3. No Improvement (Scenario 2_3): In the last technological development related scenario, it is assumed that there would be no improvement about technology, or reduction of the purchase price of BEVs. In addition, it is assumed that construction of recharging points to be continued. However they remain insufficient to meet the recharging demand throughout the simulation. This scenario is the worst-case scenario about BEVs. Results of this scenario are given by comparing results with the base run and Scenario 2_2.

The results of the last scenario indicate that even if there were no improvements about technology, purchase price, and infrastructure, BEV may succeed to penetrate 9.52% of the market. Furthermore, Figure 7.18 shows that if BEV technology remains at its current level, more customers will choose HEVs and CVs compared to the base run. This situation causes HEVs and CVs to capture higher market share.

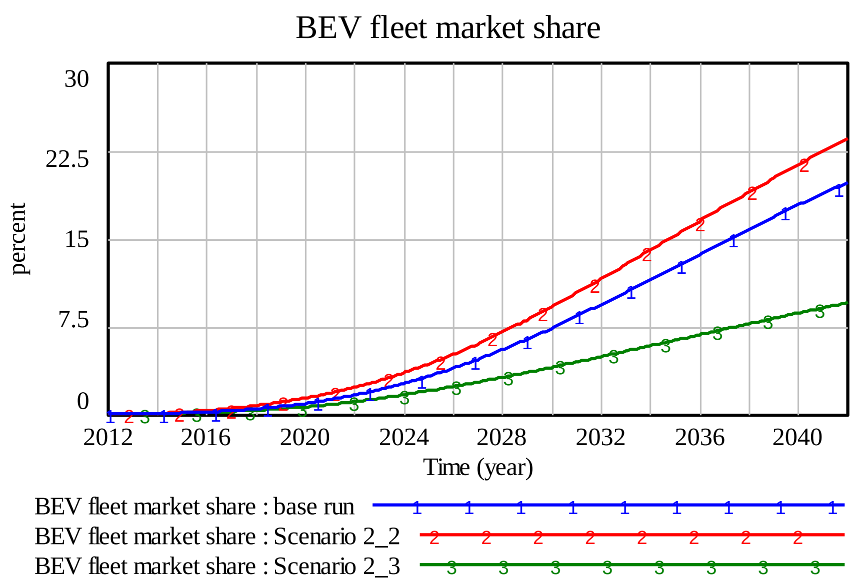

Figure 7.17. BEV fleet market share under the Scenario 2_3.

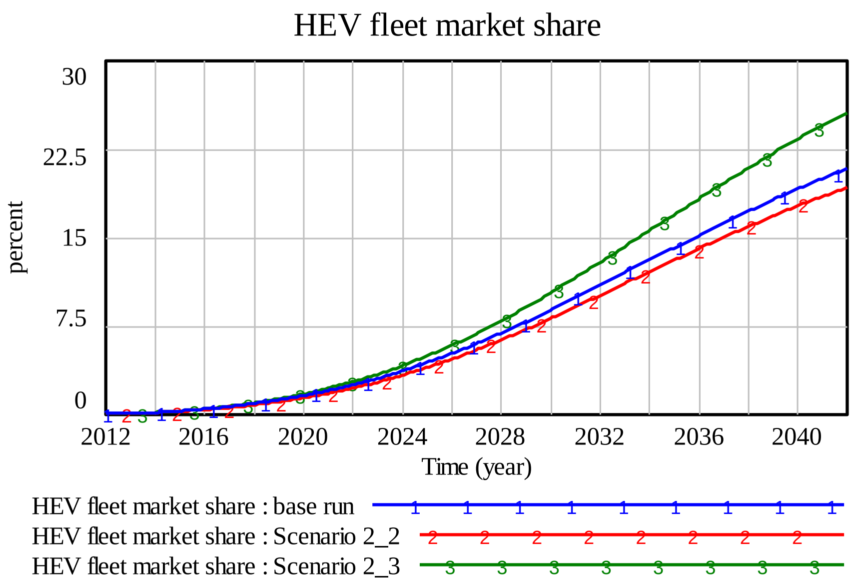

Figure 7.18. HEV fleet market share under the Scenario 2_3.

The summarized results of scenarios related to changes in technology are given in Table 7.2.

Table 7.2. The results of technological development related scenarios.

	Market Share 2012 (%)	Market Share 2042 (%)	Total sales until 2050 (Million)
Base Run			
CV	99.99	59.47	6.987
BEV	0.003	19.76	1.036
HEV	0.007	20.77	1.129
Scenario 2_1	Moderate technological improvements		
CV	99.99	57.98	6.905
BEV	0.003	22.49	1.183
HEV	0.007	19.53	1.063
Scenario 2_2	Optimal technological improvement rate and infrastructure		
CV	99.99	57.37	6.865
BEV	0.003	23.46	1.247
HEV	0.007	19.17	1.040
Scenario 2_3	No technological improvement and bad infrastructure		
CV	99.99	64.94	7.269
BEV	0.003	9.52	0.514
HEV	0.007	25.54	1.369

7.1.3. Recharging Infrastructure Based Scenarios (Scenario 3)

Recharging infrastructure is considered as an important criterion for customers [15,27,28] because insufficient number of refueling point leads drivers to be stranded, or stand in a queue for long hours for recharging. However, future station number and adequacy of these stations are uncertain and these uncertain factors may affect the BEV penetration. Hence, two distinct scenarios are constructed to evaluate impact of infrastructure on BEV diffusion. First one is called as excellent infrastructure while second one is called bad infrastructure. Excellent infrastructure represents a situation that the number of recharging points would be sufficient to cover the charging demand. Thus, there would be no time loss coming from waiting in a queue or being stranded. On the other hand, in the case of bad infrastructure, number of recharging points would not be adequate for BEV drivers and they would have to wait long hours for charging. Comparison of the results of these two scenarios is given in Figure 7.19.

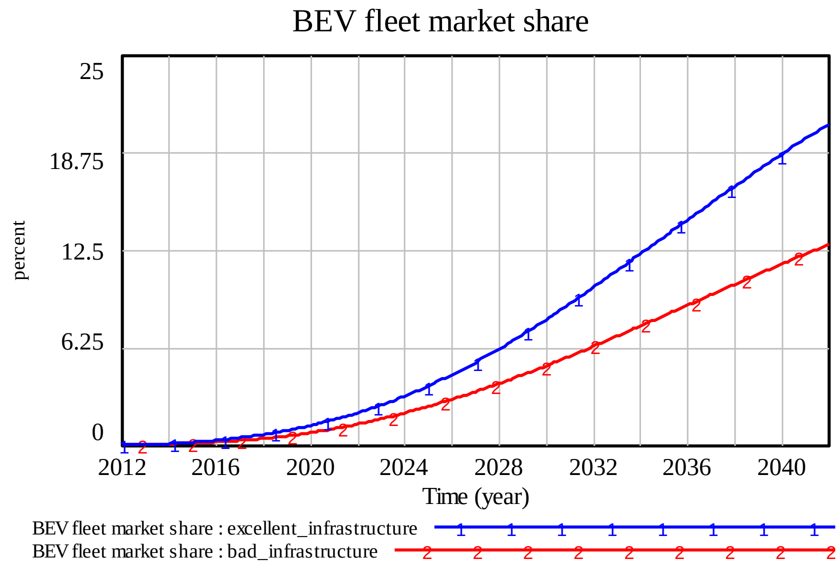

Figure 7.19. BEV market share under different infrastructure conditions.

The results show that recharging infrastructure is a relatively effective factor on BEV penetration. For instance, according to the simulation results, the BEV fleet share would reach 12.5% by 2034 in the excellent infrastructure scenario, whereas it reaches to same penetration rate, 12.5%, by 2042 in the bad infrastructure scenario. Thus, insufficient infrastructure causes the BEV diffusion to be delayed. Apart from that, cumulative CO2 reduction would reach around $17.8x10^6$ tons in the excellent infrastructure scenario, while it reaches around $14x10^6$ tons in the bad infrastructure scenario by 2042.

The summarized results of recharging infrastructure related scenario are given in Table 8.3.

Table 7.3. The results of recharging infrastructure related scenarios.

	Market Share 2012 (%)	Market Share 2042 (%)	Total sales until 2050 (Million)
Base Run			
CV	99.99	59.47	6.987
BEV	0.003	19.76	1.036
HEV	0.007	20.77	1.129
	Excellent infrastructure		
CV	99.99	58.94	6,949
BEV	0.003	20.56	1.110
HEV	0.007	20.50	1.093
	Bad infrastructure		
CV	99.99	63.14	7.176
BEV	0.003	12.85	0.684
HEV	0.007	24.01	1.292

7.1.4. Introducing only BEV to the Market (Scenario 4)

As stated earlier, the model includes three types of vehicles; CV, HEV, and BEV. However, there has been a debate about the possibility of HEV inhibiting BEV diffusion. In addition to this debate, people also argue that How much CO_2 reduction would be if only BEVs were introduced to the market. Therefore, in this scenario, the model is reconstructed considering imaginary world that only CVs and BEVs are available in the market.

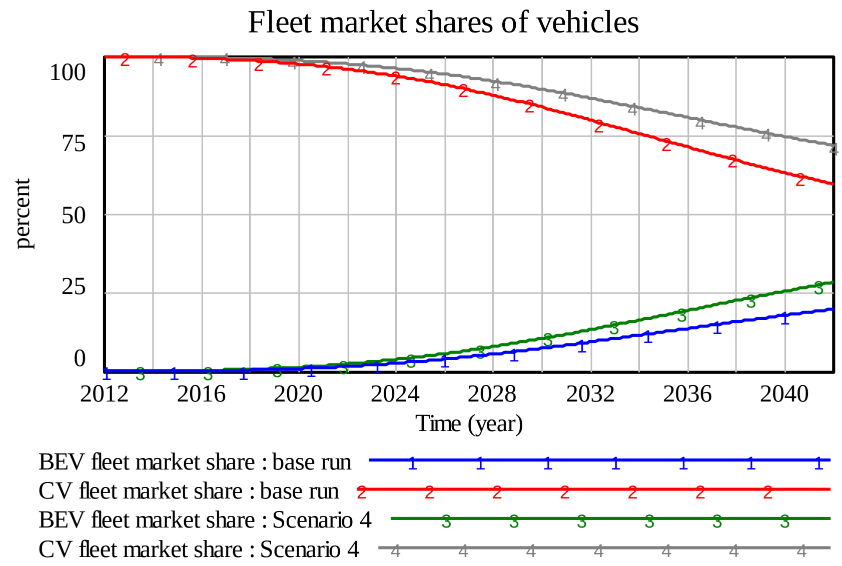

Figure 7.20. Fleet market share under Scenario 4.

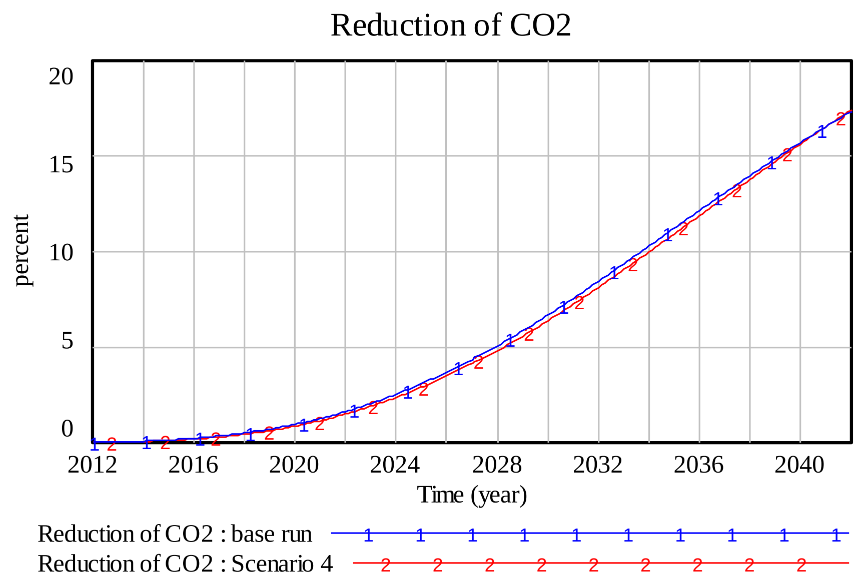

Figure 7.21. Reductions of CO_2 under the base run vs Scenario 4.

As is seen from the graphs, if there were only CVs and BEVs in the market, market share of BEV would become higher than its market share in the base run. However, Figure 7.21 shows that if there were only CVs and BEVs in the market, reduction of CO_2 level would be almost same compared to the base run. This is because of the fact that even fleet market share of BEV increases; most of potential HEV customers prefer CVs over BEVs and the more CV causes the more gas emissions.

The summarized results of this scenario are given in Table 7.4.

Table 7.4. The results of introducing only BEV to the market

	Market Share 2012 (%)	Market Share 2042 (%)	Total sales until 2050 (Million)	Reduction of CO_2 at 2042 (%)
Base Run				
CV	99.99	59.47	6.987	17.32
BEV	0.003	19.76	1.036	
HEV	0.007	20.77	1.129	
Scenario 4	Introducing only BEV to the market			
CV	99.999	71.67	7.670	17.39
BEV	0.001	28.33	1.482	

7.1.5. Word of Mouth Related Scenarios (WoM) (Scenario 5)

A customer intending to buy a vehicle needs to be aware of vehicle types to take them into her/his choice set. The awareness about new type of vehicles is provided via marketing and word of mouth. Marketing influence will be analyzed in the policy section. However, word of mouth related scenarios are analyzed in this section.

As mentioned before, the term, word of mouth (WoM), covers all actions of people that help to spread information about EVs and actions that cause people to recognize EVs in the study. For example, driving EV on the road, talking about EVs, mentioning about them in the social media are included in the word of mouth definition in this study. WoM is regarded as a substantial factor on innovation penetration. There are two WoM related scenarios. In the first scenario (Scenario 5_1), influence of WoM of non-EV drivers, and in the second one influence of non-EV drivers are intensified (Scenario 5_2).

7.1.5.1. Intensive non-EV Drivers' Word of Mouth (Scenario 5_1): In the Scenario 5_1, word of mouth of non-EV drivers is analyzed. It should be noted that non-drivers represent non-EV drivers who are aware of EVs in the study. In this scenario, exposure level coming from non-EV drivers is doubled. In other words, it is assumed that they are twice as effective as in the base run in terms of creating awareness about EVs. Behaviors obtained from Scenario 5_1 is given below.

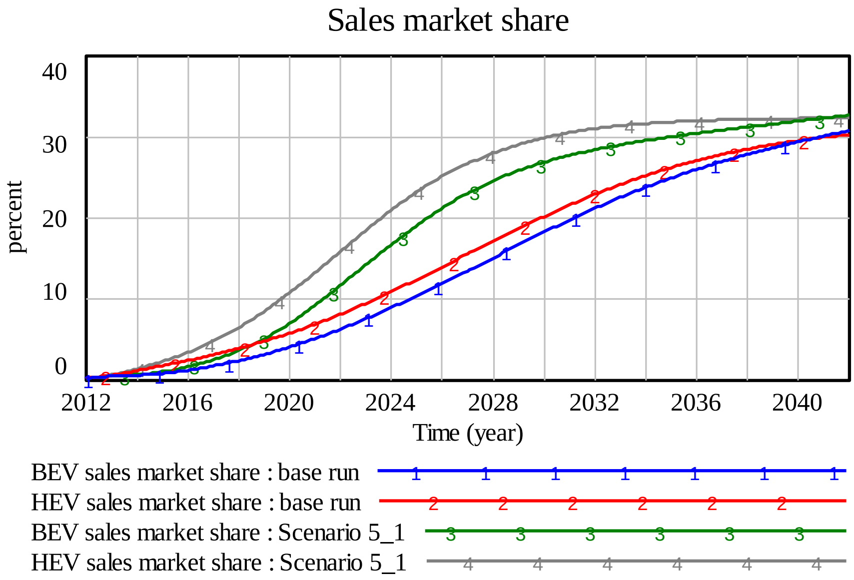

Figure 7.22. Sales market share of BEV and HEV under the Scenario 5_1.

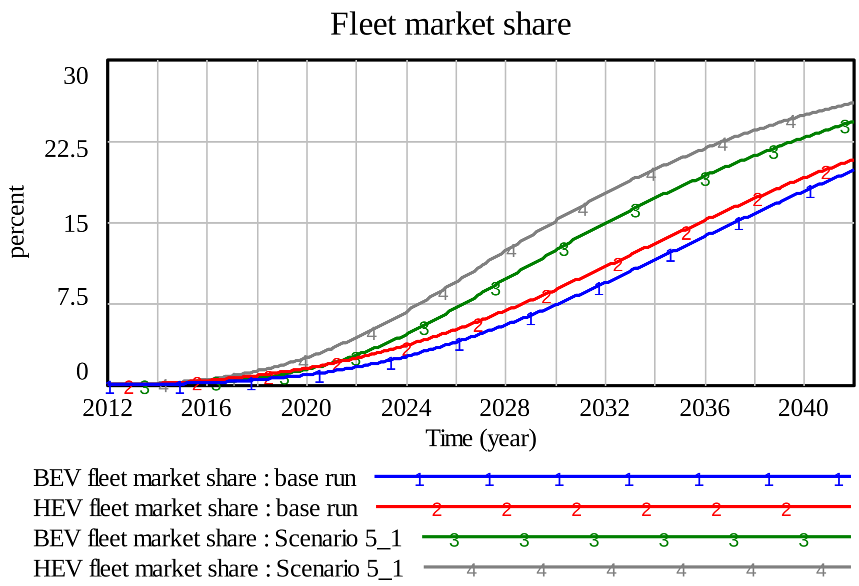

Figure 7.23. Fleet market share of BEV and HEV under the Scenario 5_1.

As seen in the graphs, WoM of non-adopters has a remarkable impact on the diffusion of BEVs and HEVs, particularly between 2016 and 2038. This range is mainly because of the fact that in the first years of diffusion, number of non-EV users, who are aware of EV is very low. Thus, even if their effectiveness is intensified, their impact remains quite small. However, when their number increases, then information about EVs begin to spread rapidly. After 2038, influence of WoM on the EV market share begins to decline because the number of people who are not familiar with EV becomes considerably lower. If unaware people diminish, then WoM naturally does not cause huge number of people to gain awareness about EVs. In addition, cumulative CO_2 reduction would be around 25 x 10^6 tons by 2042.

7.1.5.2. Intensive EV Drivers' Word of Mouth (Scenario 5_2): In the Scenario 5_2, word of mouth of EV drivers is analyzed. In this scenario, exposure level coming from EV drivers is doubled. In other words, they are twice as influential as in the base run in terms of creating awareness. Behaviors obtained from Scenario 5_2 is given below.

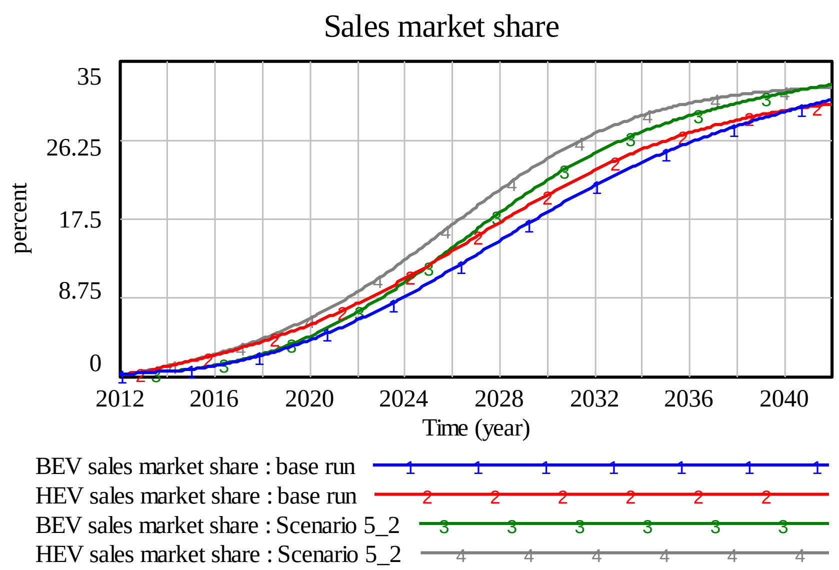

Figure 7.24. Sales market share of BEV and HEV under the Scenario 5_2.

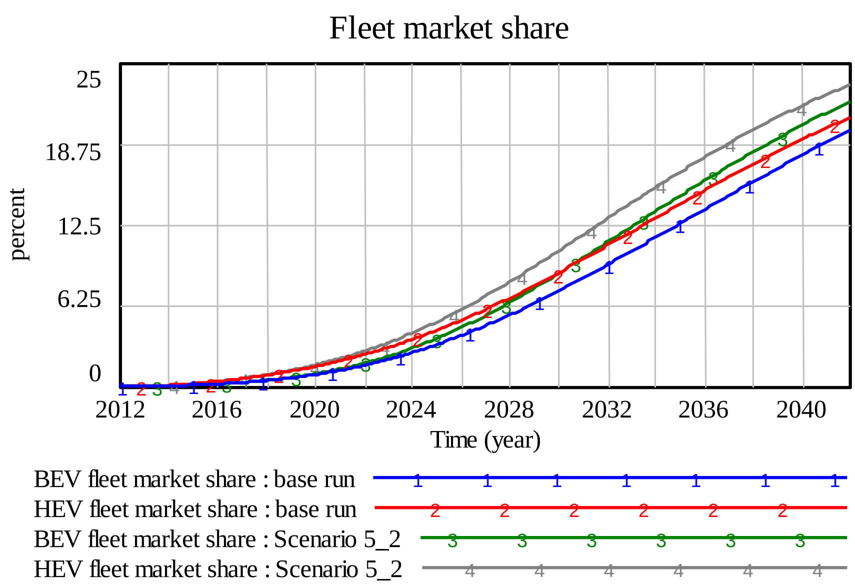

Figure 7.25. Fleet market share of BEV and HEV under the Scenario 5_2.

As can be seen from the graphs, WoM of the EV adopters is also influential on EV diffusion. Its impact on market shares is similar to effect of non-adopters but it seems that effect of adopters is less than effect of non-adopters. This is because of the fact that non-EV drivers outnumber EV drivers. In addition, cumulative CO_2 reduction would be around 19.7 x 10^6 tons by 2042.

The summarized results of WoM scenarios are given in Table 7.5.

Table 7.5. The results of WoM scenarios.

	Market Share 2012 (%)	Market Share 2042 (%)	Total sales until 2050 (Million)
Base Run			
CV	99.99	59.47	6.987
BEV	0.003	19.76	1.036
HEV	0.007	20.77	1.129
Scenario 5_1	Influence of non-EV drivers' word of mouth		
CV	99.99	49.73	6.245
BEV	0.003	24.27	1.371
HEV	0.007	26.00	1.536
Scenario 5_2	Influence of EV drivers' word of mouth		
CV	99.99	54.70	6.696
BEV	0.003	22.00	1.171
HEV	0.007	23.30	1.285

7.1.6. Repurchasing Rate (Scenario 6)

As stated earlier, new cars are sold in the case of repurchasing or market growth. Therefore, sales of any type of vehicles highly depend on how frequently people renew their cars. However, long life of vehicles or desire to use same car for a long time or high car prices may cause very low repurchasing. Regarding this situation, discard period of vehicles is rearranged in the two scenarios to assess influence of repurchasing rate on EV diffusion. Base run value of the average discard period is 8% per year which translates to 12.5 years of average life time. In the first scenario, discard period is set to 6% per year (less repurchasing rate) that is equal to 17 years. In the second scenario, it is set to 10% per year (high repurchasing rate) that is equal to 10 years. Influence of these two modifications on the fleet shares are shown in Figure 7.26 and 7.27.

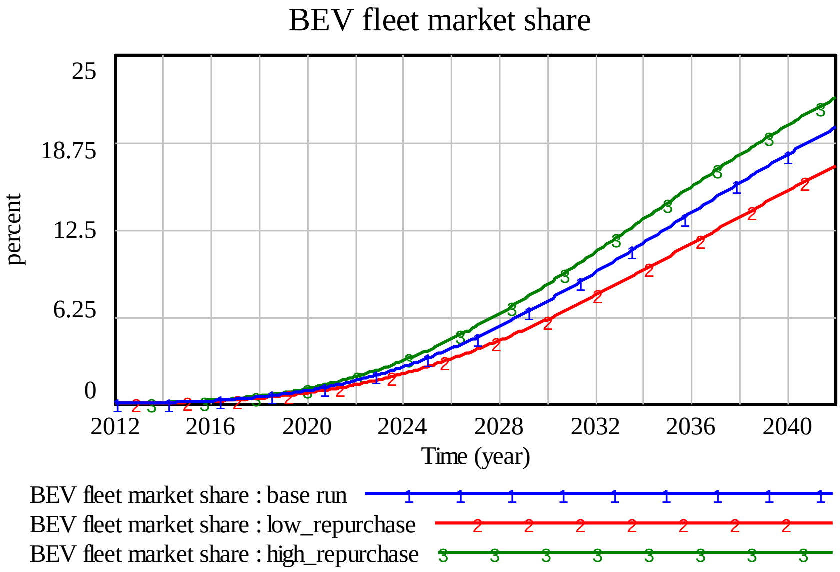

Figure 7.26. BEV fleet market share under the re-purchasing scenario.

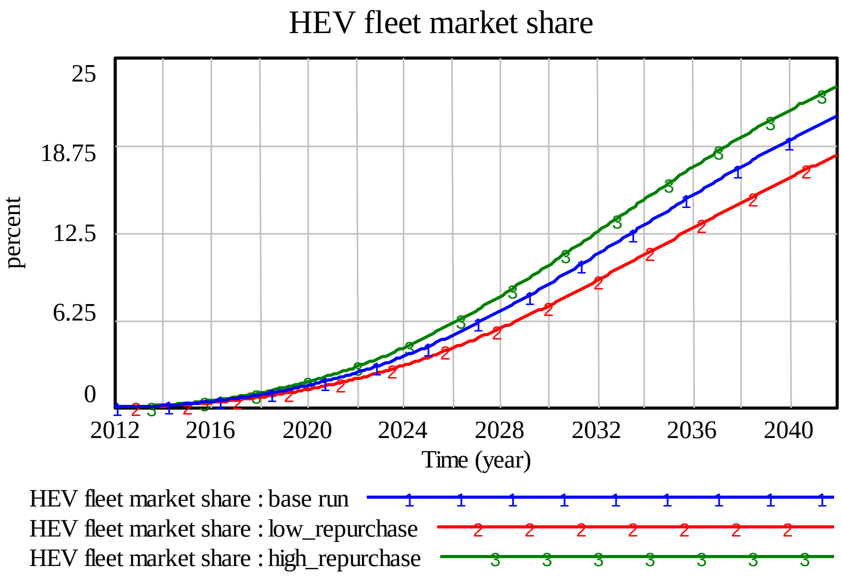

Figure 7.27. HEV fleet market share under the re-purchasing scenario.

The results show that repurchasing rate is notably influential on the EV diffusion. For example, BEV fleet share reaches 12.5% at 2033 in the case of high repurchasing. However, it achieves to reach same penetration level (12.5%) at 2037 in the availability of low repurchasing rate. If repurchasing rate is low in a city, then EV diffusion may be delayed.

The summarized results of repurchasing scenarios are given in Table 7.6.

Table 7.6. The results of repurchasing scenarios.

	Market Share 2012 (%)	Market Share 2042 (%)	Total sales until 2050 (Million)
Base Run			
CV	99.99	59.47	6.987
BEV	0.003	19.76	1.036
HEV	0.007	20.77	1.129
Scenario 5_1	Low repurchasing		
CV	99.99	64.98	5.961
BEV	0.003	17.03	0.788
HEV	0.007	17.99	0.858
Scenario 5_2	High repurchasing		
CV	99.99	55.21	8.003
BEV	0.003	21.88	1.288
HEV	0.007	22.91	1.406

7.2. Policy Analysis

When launching a new technology, various strategies are applied by governments and manufacturers in order to provide faster diffusion of new technology. It is commonly indicated that policies and incentives are needed to sustain broader penetration of new technologies. For this reason, ten policies about EV diffusion are analyzed in this section. Their main contexts are subsidy, tax, and marketing. The results of these policies will be presented mostly by comparing them with the base run to provide a better insight. All policies will be explained in detail in this section.

7.2.1. Subsidy Based Policies (Policy 1)

Most automobile manufacturers and researchers claim that financial incentive is necessary for successful EV adoption. Subsidy for a purchase price is considered as one of the financial incentive options [17,39,43]. Impacts of subsidy strategies are assessed with the help of six subsidy policies. There are two basic different strategies are defined related to subsidy regimes. Firstly, each one is applied to only BEVs, and then for only HEVs. Afterwards, they are applied to both BEVs and HEVs. It should be noted that there is no clear information about subsidy regimes for EVs in Turkey. Therefore, subsidy strategies are determined considering the work of Shepherd, Bonsall, and Harrison, which analyzes EV diffusion in The UK [39]. Besides, there is no subsidy in the base run.

7.2.1.1. 5000 TL Subsidy for BEV (Policy 1_1_1): In this policy, it is assumed that every BEV buyer would take 5000 TL as subsidy and this regulation would last until the end of simulation. It is important to mention that this subsidy regulation is specific for only BEV in the Policy 1_1_1. Impact of this strategy on the BEV fleet share is given in Figure 7.28.

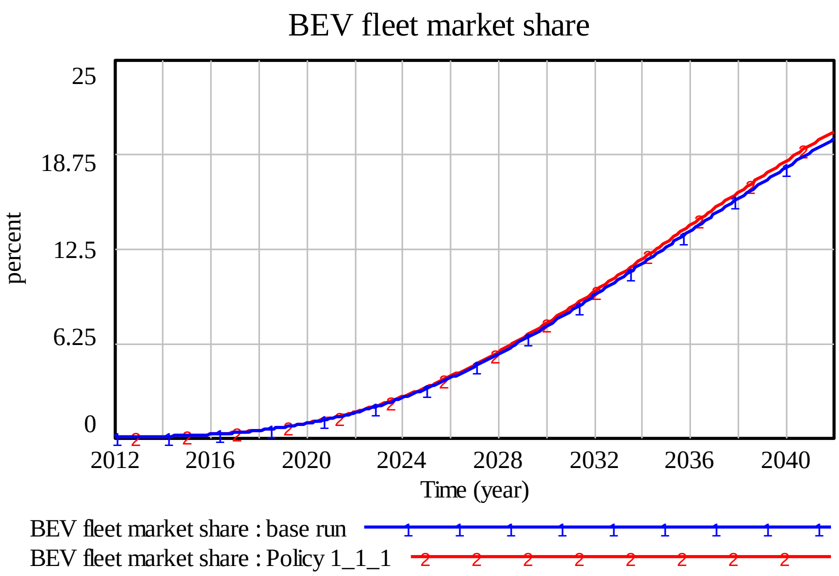

Figure 7.28. Fleet market share of BEV under the Policy 1_1_1.

It can be obviously seen from the Figure 7.28 that ‘5000 TL subsidy for BEV’ regime has little impact on the BEV fleet market share. In addition, total cost coming from this subsidy is estimated as 5315 million TL.

7.2.1.2. 10000TL Subsidy for the First 10 Years for BEV (Policy 1_2_1): In this policy, it is assumed that every BEV buyer would take 10000 TL for subsidy and the time duration of this regulation would be the first ten years of the simulation. After the first ten years, the subsidy would be removed because the government would less likely decide 10000 TL subsidy for every vehicle throughout 30 years due to financial concerns. This subsidy policy is applied to only BEV in the Policy 1_2_1. Impact of this strategy on BEV fleet share is given in the Figure 7.29.

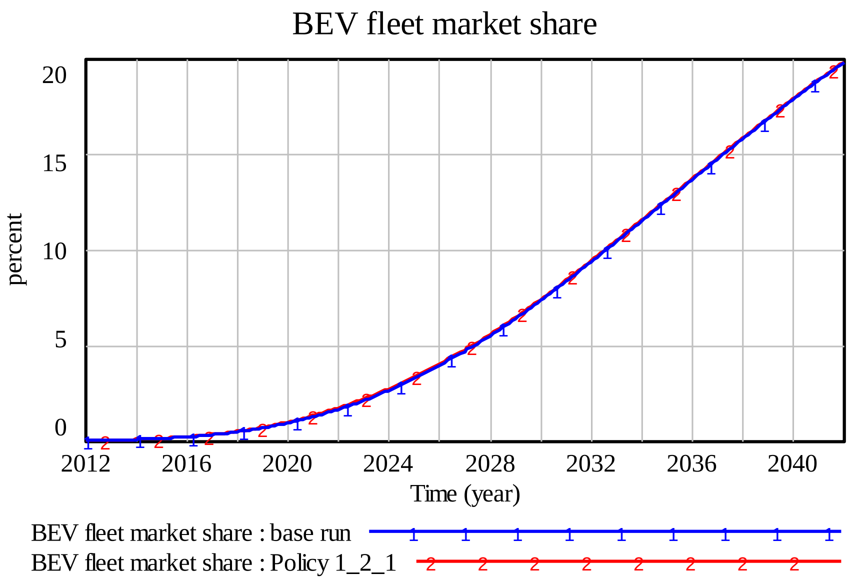

Figure 7.29. Fleet market share of BEV under the Policy 1_2_1.

As is seen from the Figure 7.29, ‘10000 TL subsidy for BEV regime’ has ignorable impact on BEV fleet market share. Moreover, total cost coming from this subsidy is estimated as 518 million TL.

7.2.1.3. 5000 TL Subsidy for HEV (Policy 1_1_2): In the Policy 1_1_2, 5000 TL subsidy, which is assessed in the Policy 1_1_1, is applied to only HEV instead of BEV. In other words, it is assumed that every HEV buyer would take 5000 TL for subsidy and this regulation would last until the end of simulation. This subsidy policy is applied to only HEV in the Policy 1_1_2. Impact of this strategy on the HEV fleet share is given in Figure 7.30.

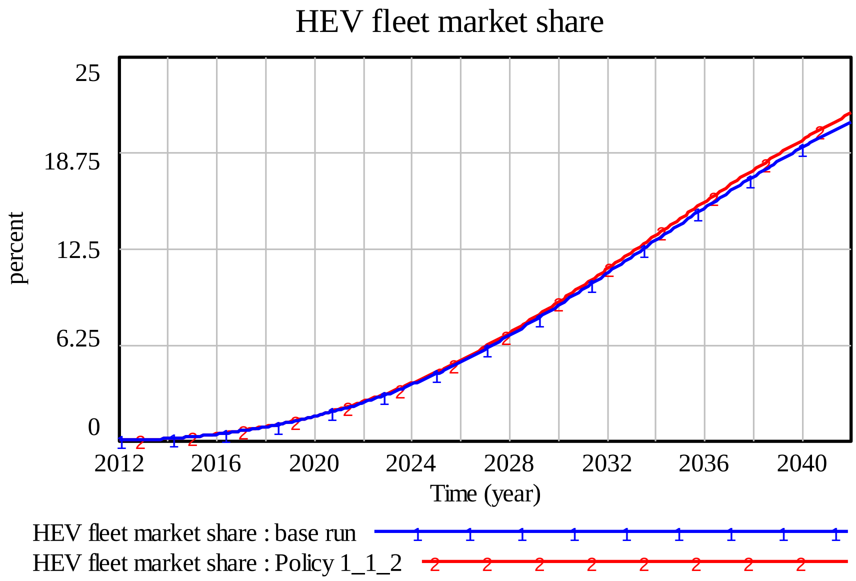

Figure 7.30. Fleet share of HEV under the Policy 1_1_2

As is seen in the Figure 7.30, ‘5000 TL subsidy for HEV regime’ has little impact on HEV sales. Moreover, total cost coming from this subsidy is estimated as 5120 million TL.

<u>7.2.1.4. 10000TL Subsidy for 10 Years for HEV (Policy 1_2_2):</u> In the Policy 1_2_2, 5000 TL subsidy, which is assessed in the Policy 1_1_2, is applied to only HEV instead of the BEV. In this policy, it is assumed that every HEV buyer would take 10000 TL for subsidy and the time duration of this regulation would be the first ten years of the simulation. After the first ten years, the subsidy would be removed. This subsidy policy is applied to only HEV in the Policy 1_2_1. Impact of this strategy on the HEV fleet share is given in Figure 7.31.

Figure 7.31 shows that ‘10000 TL subsidy for HEV regime’ has quite a little impact, almost zero, on HEV penetration. Moreover, total cost coming from this subsidy is estimated as 788.56 million TL.

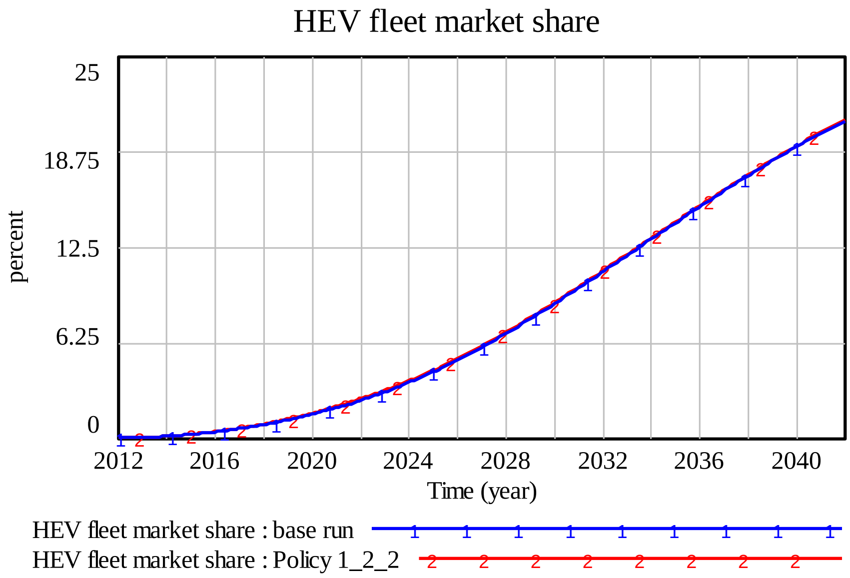

Figure 7.31. Fleet market share of HEV under the Policy 1_2_2.

7.2.1.5. 5000 TL Subsidy for Both BEV and HEV (Policy 1_3): In this policy, 5000 TL subsidy is performed for both BEV and HEV to estimate if implementing 5000 TL subsidy for both types is profitable or not. In this policy, it is assumed that every BEV and HEV buyer would take 5000 TL for subsidy and this regulation would last until the end of simulation. This subsidy policy is applied to both BEV and HEV in the Policy 1_3. Impact of this strategy on the fleet shares is given in Figure 7.32.

As is seen in Figure 7.32, ‘5000 TL subsidy for both BEV and HEV regime’ has quite a little impact, almost zero, on both BEV and HEV penetration. Besides, total cost coming from this subsidy is estimated as 10980 million TL. This is the highest cost among all subsidy scenarios analyzed in the study.

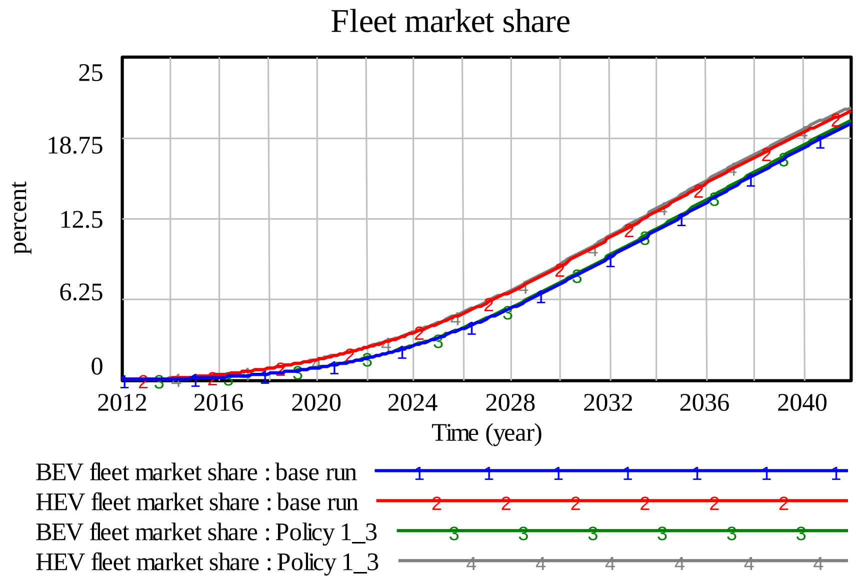

Figure 7.32. Fleet market share of BEV and HEV under the Policy 1_3.

<u>7.2.1.6. 10000TL Subsidy for 10 Years for Both EVs (Policy 1_4):</u> In this policy, 10000 TL subsidy is performed for both BEV and HEV to estimate if implementing 10000 TL subsidy for both types is profitable or not. Similar to the previous 10000 TL subsidy regimes, it is assumed that every EV buyer would take 10000 TL and the duration of this regulation would be the first ten years of the simulation. After the first ten years, the subsidy would be removed. This subsidy policy is applied to both BEV and HEV in the Policy 1_4. Impact of this strategy on the fleet shares is given in the Figure 7.33.

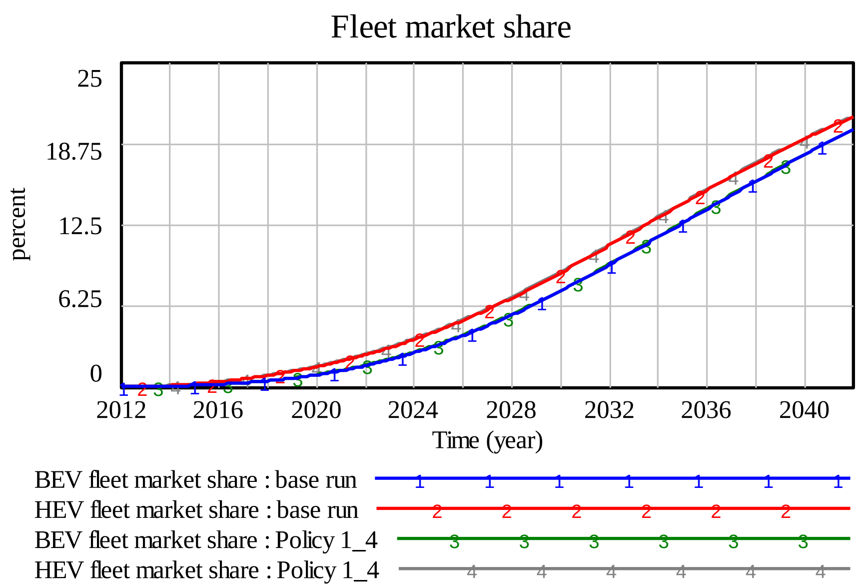

Figure 7.33. Fleet market share of BEV and HEV under the Policy 1_4.

Figure 7.33 shows that '1000 TL subsidy for both BEV and HEV regime' has little, almost ignorable, impact on EV penetration. Moreover, total cost coming from this subsidy is estimated as 1282 million TL.

The summarized results of subsidy-based policies are given in Table 7.7.

Table 7.7. The results of subsidy based policies.

	Market Share 2012 (%)	Market Share 2042 (%)	Total Sales until 2050 (Million)	Total social cost (Million TL)
Base Run				
CV	99.99	59.47	6.987	-
BEV	0.003	19.76	1.036	
HEV	0.007	20.77	1.129	
Policy 1_1_1	5000 TL Subsidy for BEV for 30 years			
CV	99.994	59.2	6.972	5315
BEV	0.001	20.26	1.063	
HEV	0.005	20.54	1.117	
Policy 1_2_1	10000 TL Subsidy for BEV for 10 years			
CV	99.994	59.43	6.984	518
BEV	0.001	19.80	1.040	
HEV	0.005	20.77	1.128	
Policy 1_1_2	5000 TL Subsidy for HEV for 30 years			
CV	99.994	59.16	6.970	5120
BEV	0.001	19.54	1.024	
HEV	0.005	21.30	1.158	
Policy 1_2_2	10000 TL Subsidy for HEV for 10 years			
CV	99.994	59.43	6.982	788.56
BEV	0.001	19.76	1.035	
HEV	0.005	20.81	1.134	
Policy 1_3	5000 TL Subsidy for both BEV and HEV for 30 years			
CV	99.994	58.9	6.956	10980
BEV	0.001	20.03	1.051	
HEV	0.005	21.07	1.145	

Table 7.7. The results of subsidy based policies (cont.)

Policy 1_4	10000 TL Subsidy for both BEV and HEV for 10 years			
CV	99.994	59.39	6.979	1282.12
BEV	0.001	19.80	1.040	
HEV	0.005	20.81	1.133	

7.2.2. Tax Based Policy (Policy 2)

A car is one of the product types that have private consumption tax (PCT) in Turkey. However, amount of this tax varies depending on vehicle properties such as motor type, or capacity. When representative vehicle types used in this work is considered, it is 37% for internal combustion engine based vehicles. Besides, PCT of vehicles that have only electric motor is 3% for incentive for EVs. On the other hand, hybrid vehicles, which are one of the electric vehicles, have 37% private consumption tax since if a car have both internal combustion engine and electric motor, then PCT for that car becomes 37% in accordance with the law. However, there have still been debates in Turkey about that PCT should be the 3% for also HEV to increase the EV penetration. In this respect, private consumption tax of HEV is set to the 3% instead of 37% to analyze its effect on the EV diffusion and to assess the necessity of tax regulations.

Figures show that new tax regulation may be supportive for HEV diffusion, but it does not cause considerable change in the first years of diffusion due to low level of awareness about EV. Figures show that application of new tax regulation after 2023 may be profitable since tax regulation increase its influence due to upward awareness level.

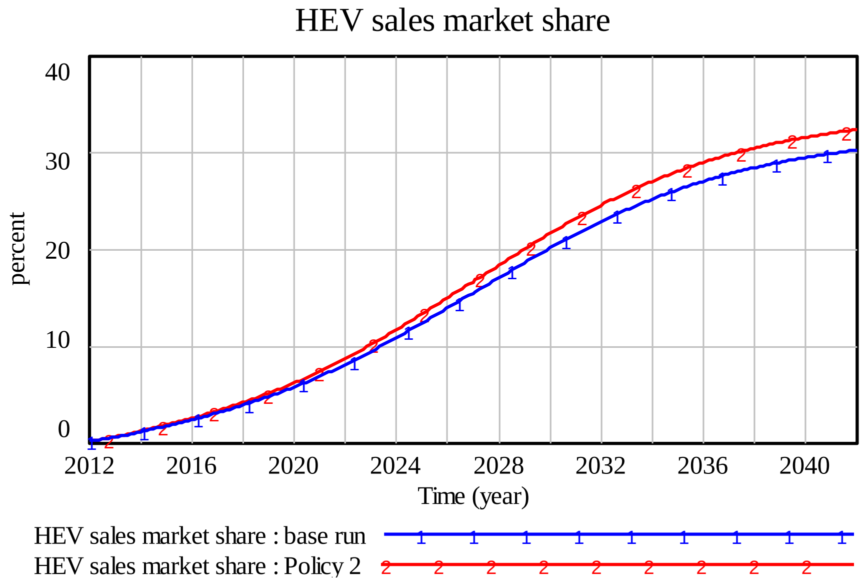

Figure 7.34. Sales market share of HEV under the Policy 2.

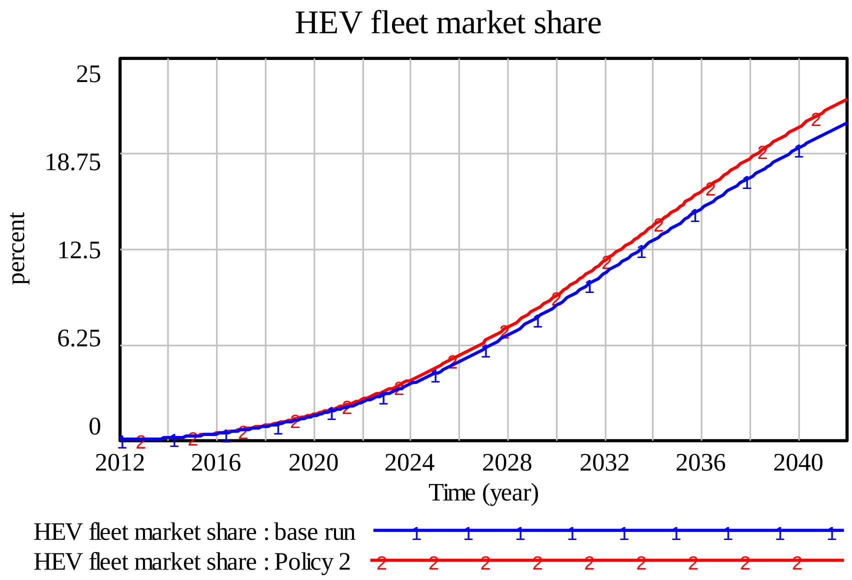

Figure 7.35. Fleet market share of HEV under the Policy 2.

The summarized results of the tax based policy are given in Table 7.8.

Table 7.8. The results of private consumption tax based policy.

	Market Share 2012 (%)	Market Share 2042 (%)	Total sales until 2050 (Million)
Base Run			
CV	99.99	59.47	6.987
BEV	0.003	19.76	1.036
HEV	0.007	20.77	1.129
Policy 2	Tax policy		
CV	99.994	58.61	6.938
BEV	0.001	19.12	1.002
HEV	0.005	22.27	1.211

7.2.3. Marketing Based Policies (Policy 3)

As mentioned before, people need social exposure to take EVs into their consideration set. Two distinct social exposures are defined in the study. First one is word of mouth of people and second one is marketing. Marketing is regarded as one of the most efficient strategies to promote new products, or innovations. People recognize new products and gain information about them thanks to marketing activities. Marketing activities cover every advertisement channel such as TV, radio, newspaper, magazine, or social media for this study. Impacts of marketing strategies on EV penetration are analyzed via three policies. First policy helps to observe behavior if there were no marketing activities about EVs. In the second policy, it is assumed that marketing activities are lessened. In the final policy, it is assumed that marketing activities would continue for limited duration and it would be stopped. In addition, it is important activities are also included in the base run throughout simulation.

7.2.3.1. No Marketing Activities (Policy 3_1): In the Policy 3_1, it is assumed that there would be no marketing activities about EVs. The effects of this case can be seen in Figure 7.36 and 7.37.

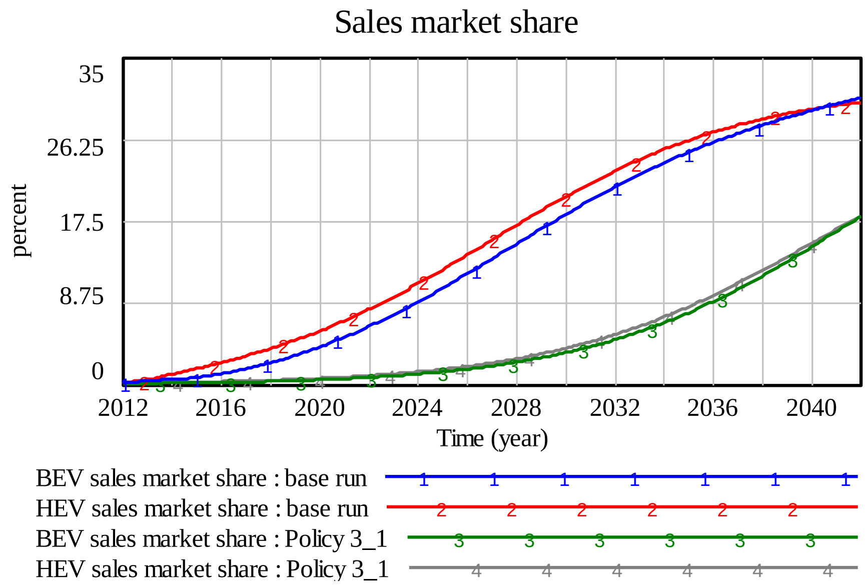

Figure 7.36. Sales market share of BEV and HEV under the Policy 3_1.

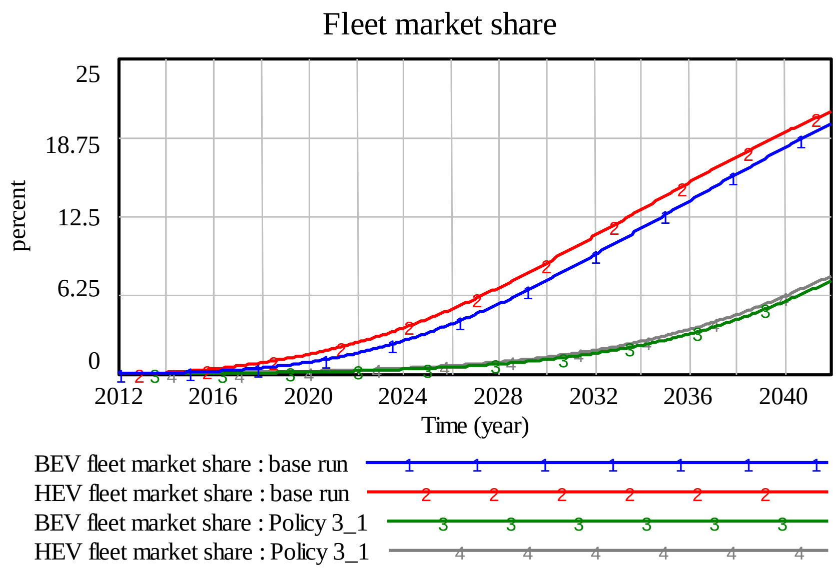

Figure 7.37. Fleet market share of BEV and HEV under the Policy 3_1.

As is seen from the graphs, if there would be no marketing activity for EV, adoption process is heavily affected from this situation since people do not recognize EVs or they do not know any information about them. Hence, they do not naturally take EVs into their choice set, which results in low sales. The results also show that if marketing activities are not implemented, the time to seize the fleet market share of 15% for total EVs is delayed by more than a decade.

7.2.3.2. Less Marketing Activities (Policy 3_2): In this policy, it is assumed that marketing activities are halved. In other words, number of advertisements, interviews, or news on both broadcast and printed media is cut in half. Impacts of this situation on the market shares are given in the Figure 7.38 and Figure 7.39.

The simulation results show that if all marketing activities are halved, EV penetration is affected negatively from this situation. However, it is still sufficient to make people familiar with EVs.

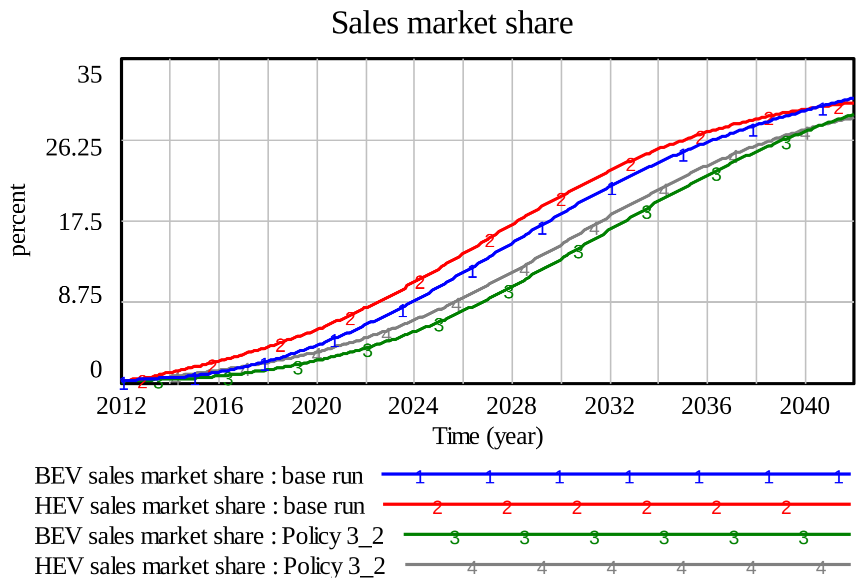

Figure 7.38. Sales market share of BEV and HEV under the Policy 3_2.

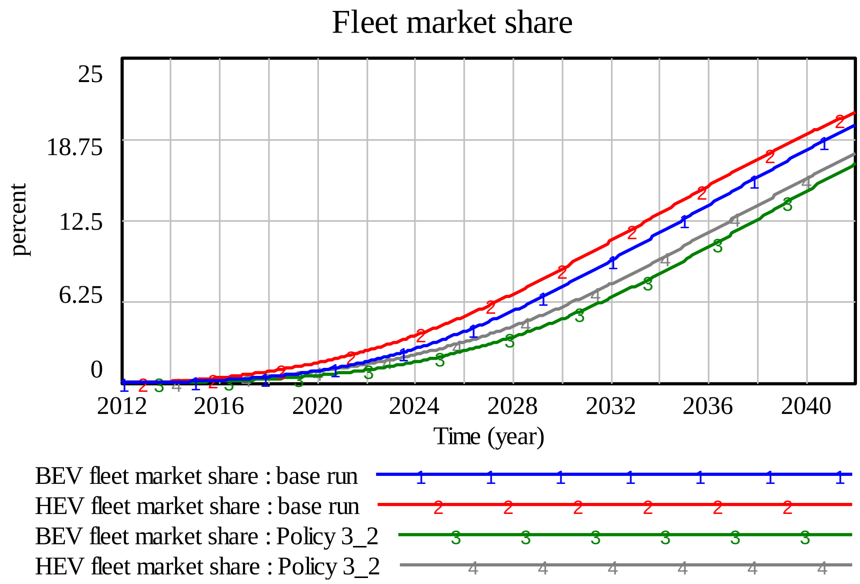

Figure 7.39. Fleet market share of BEV and HEV under the Policy 3_2.

<u>7.2.3.3. Marketing Activities for Limited Duration (Policy 3_3):</u> In this scenario, it is assumed that marketing activities continue for a while and then they are stopped. In this context, influence of different marketing durations on the market shares is analyzed to assess roughly optimum marketing duration. Hence, four different marketing periods are determined that are 15, 10, 5, and 3 years. To illustrate, if the first period is regarded, marketing activities will continue through 15 years from the beginning and then all activities would be stopped at the end of 15th the year. The results of the limited marketing duration are given in Figure 7.40 and Figure 7.41.

According to the simulation results, marketing is particularly important in the first years of the diffusion process. If marketing activities are stopped before the 5th year of the penetration process, certain amount of people would less likely recognize EVs or learn information about them. As a matter of course, this situation causes low level of EV sales. However, after 5 years, the number of people who are familiar with EVs sufficiently increases to sustain adequate social exposure. Thus, marketing duration needs to exceed minimum 5 years for EVs to be adequate for self-sustaining. Additionally, after 10 years, marketing activities begin to lose its effect on the EVs sales since most people are already aware of EVs.

According to the results, marketing for 3 years may result in around 12x10[6] tons cumulative CO_2 reduction, while marketing for 15 years may result in around 17x10[6] tons cumulative CO_2 reduction.

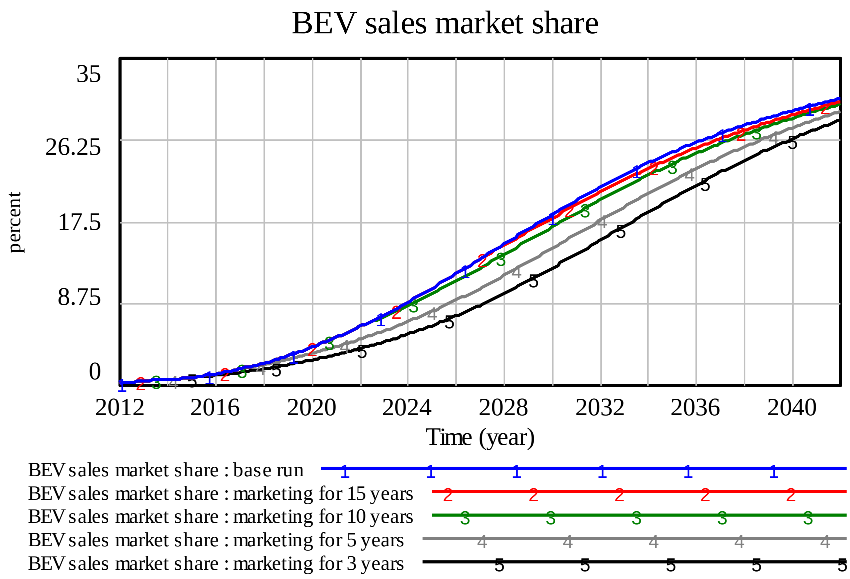

Figure 7.40. Sales market share of BEV under different marketing strategies.

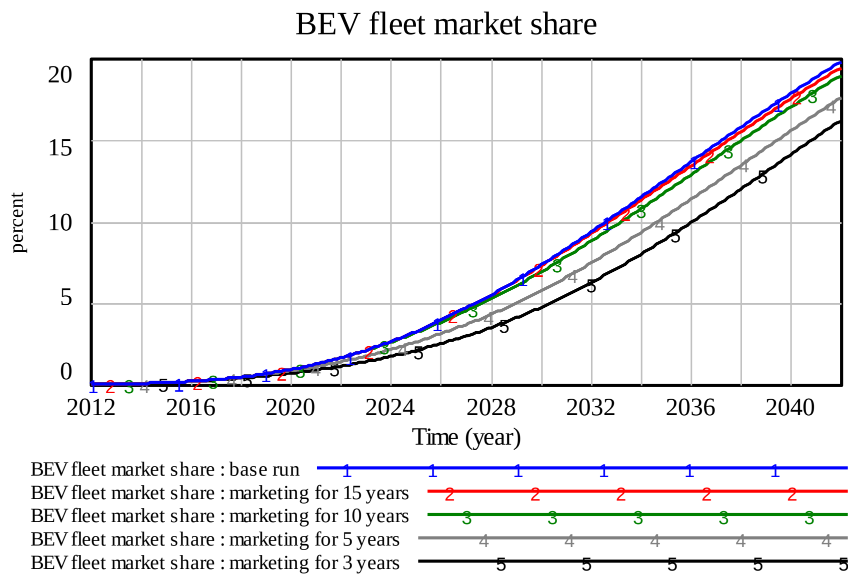

Figure 7.41. Fleet market share of BEV under different marketing strategies.

The summarized results of every marketing policy are given in Table 7.9.

Table 7.9. The results of different marketing policies.

	Market Share 2012 (%)	Market Share 2042 (%)	Total sales until 2050 (Million)
Base Run			
CV	99.99	59.47	6.987
BEV	0.003	19.76	1.036
HEV	0.007	20.77	1.129
Policy 3_1	No marketing activities		
CV	99.994	84.85	8.475
BEV	0.001	7.383	0.327
HEV	0.005	7.768	0.350
Policy 3_2	Less marketing activities		
CV	99.994	65.54	7.41
BEV	0.001	16.83	0.838
HEV	0.005	17.63	0.904
Policy 3_3	Marketing for 15 years		
CV	99.994	60.2	7.022
BEV	0.001	19.41	1.019
HEV	0.005	20.39	1.111
Policy 3_3	Marketing for 10 years		
CV	99.994	61.22	7.088
BEV	0.001	18.93	0.989
HEV	0.005	19.85	1.075
Policy 3_3	Marketing for 5 years		
CV	99.994	64.08	7.284
BEV	0.001	17.56	0.898
HEV	0.005	18.36	0.971
Policy 3_3	Marketing for 3 years		
CV	99.994	66.92	7.473
BEV	0.001	16.18	0.808
HEV	0.005	16.90	0.871

7.3. Combination of Scenario and Policies

Some scenarios and policies are examined in the previous two sections. In this section, three different scenario-policy combinations and one scenario-scenario combination are developed. Some scenarios or policies help to increase HEV penetration while some positively affect BEV penetration. They are combined to analyze their influences under situations different from the base run. In the first combination, marketing influences are assessed under high electricity price scenario. In the second one, combined effect of high gasoline price and bad infrastructure is analyzed. In the third combination, it is assumed that the BEV technology is improved at optimal level but there are no marketing activities for EVs. Lastly, tax regulation for HEV and advanced battery improvements is analyzed together.

7.3.1. High Electricity Price and Over Marketing Activities (Combination 1)

In this combination, marketing influence is examined under the Scenario 1_3. As stated in the Scenario 1_3, electricity cost increases and after a while, it becomes considerably higher than gasoline cost. In this situation, BEV sales begin to reduce. Besides, marketing policies in the Section 7.2.3 shows that marketing is a substantial policy to increase BEV diffusion rate. In this scenario, patterns of electricity and gasoline costs are assumed to be identical patterns in the Scenario 1_3. In addition, the intensity of marketing activities is doubled. In other words, number of advertisements, interviews on the both broadcast and printed media are doubled. Effects of this combination are given in Figure 7.42.

Figure 7.42 shows that if the electricity cost reaches greater values compared to the gasoline cost, even marketing, which is one of the most effective strategies to accelerate EV penetration, cannot stop fall of the BEV sales. Because marketing only provides people to be familiar with EVs. However, if customer is not satisfied with EV attributes such as operating cost, then they do not prefer EVs.

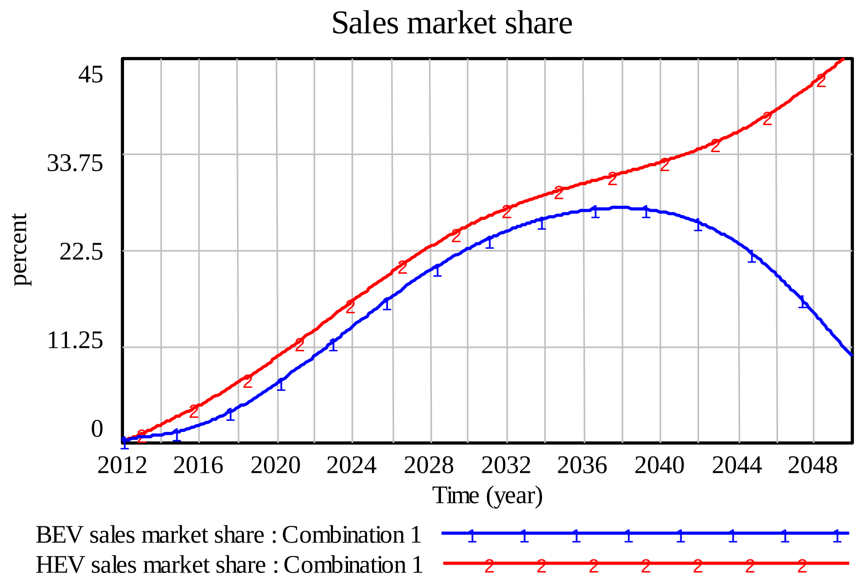

Figure 7.42. Sales market share of BEV and HEV under the Combination 1.

7.3.2. High Gasoline Cost and Bad Recharging Infrastructure (Combination 2)

In this combination, it is assumed that electricity and gasoline costs behave exactly same as the ones in Scenario 1_4. In other words, electricity cost increases normally (9% annually), while gasoline cost rises rapidly. Moreover, it is assumed that there is bad recharging infrastructure that is same as the bad infrastructure mentioned in the Scenario 3. Under these conditions, sales market shares of BEV and HEV are analyzed. The results of this combination and the Scenario 1_4 are given in the Figure 7.43.

The Scenario 1_4 results show that if gasoline cost begins substantially higher than electricity cost, then after a while, the BEV sales exceed the HEV sales. However, the Combination 2 results show that even the cost gap occurring between gasoline and electricity becomes too much, the HEV sales become notably higher than the BEV sales without sufficient recharging points.

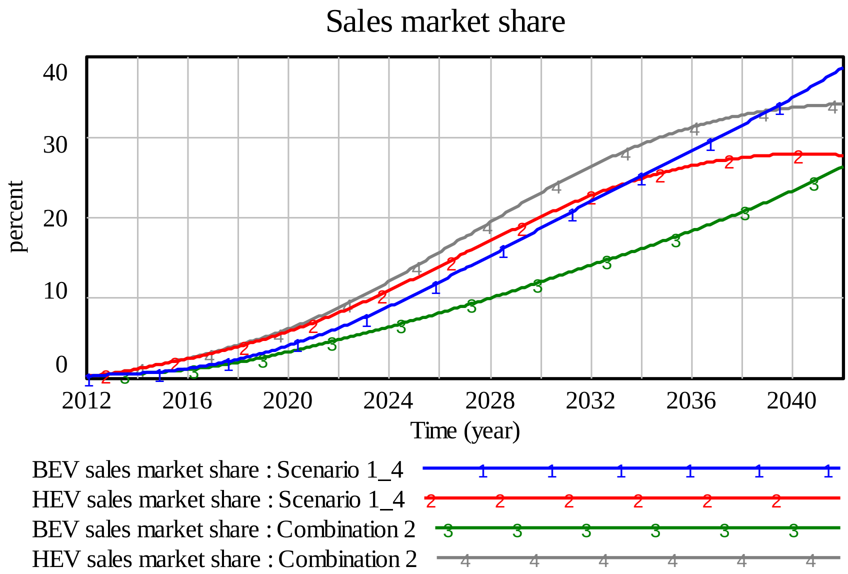

Figure 7.43. Sales market share of BEV and HEV under the Combination 2.

7.3.3. Advanced Improvement and No Marketing (Combination 3)

In this section, the Scenario 2_2 and the Policy 3_1 are combined. In other words, it is assumed that technological improvements would be advanced level and there would be no waiting induced by the recharging infrastructure. However, no marketing activity is applied in this combination. Under these conditions, the BEV sales market share and the HEV sales market share are analyzed. The results of this combination are given in the Figure 7.44.

As is seen from the Figure 7.44, even if technology is improved at advance level and obstacles related to infrastructural are eliminated, penetration of BEV is delayed by about a decade without marketing activities.

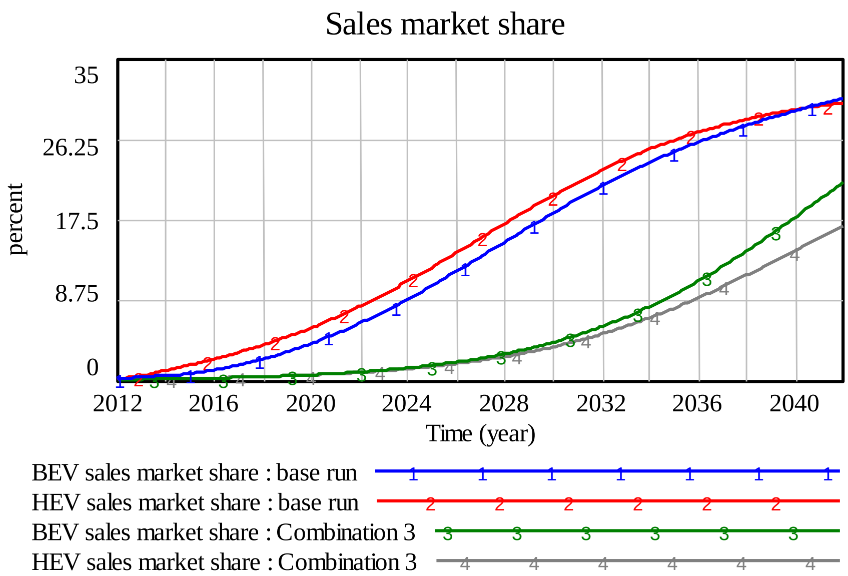

Figure 7.44. Sales market share of BEV and HEV under the Combination 3.

7.3.4. Tax Regulation for HEV and Optimal Progress for BEV (Combination 4)

In this section, the Scenario 2_2 and the Policy 2 are combined. To clarify, private consumption tax (PCT) for HEVs is assumed to be 3% instead of 37%. This value is equal to the PCT of BEVs. Moreover, improvement level of BEV is assumed to be at advanced level. In addition, it is assumed that there would be no waiting induced by insufficient recharging point. Under these conditions, sales market share of BEV and HEV are analyzed. The results of this combination are given in the Figure 7.45 and the Figure 7.46.

The figures show that even if the BEV technology is improved at advance level and the number of recharging points is adequate to meet the charging demand; new tax regulation for HEVs does not cause important change on the HEV sales.

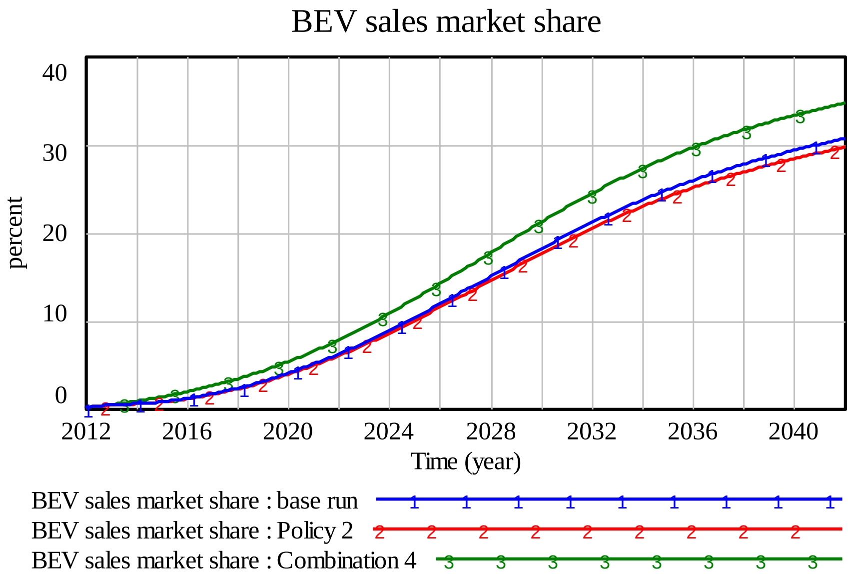

Figure 7.45. Sales market share of BEV under the Combination 4.

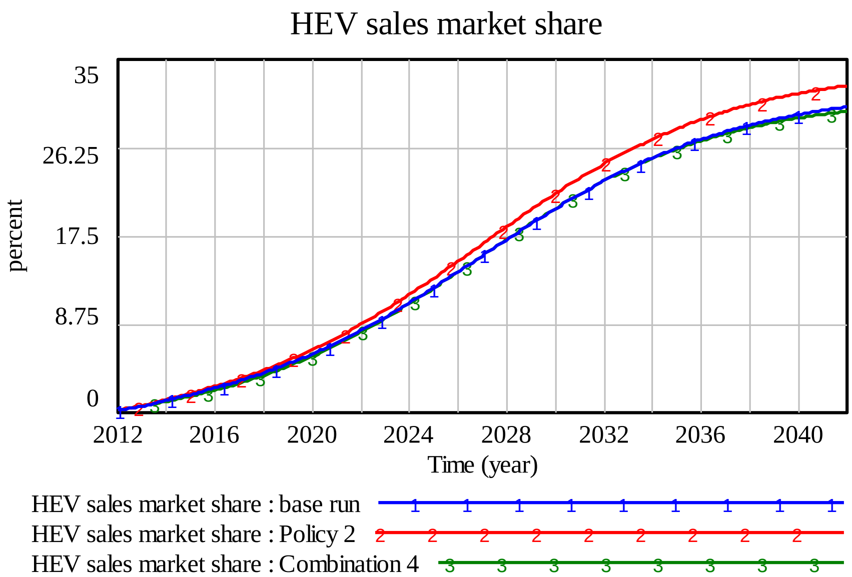

Figure 7.46. Sales market share of HEV under the Combination 4.

Results: The simulation results show that sales volumes of both BEV and HEV are always lower than CV sales throughout the simulation period in the base case. Moreover, after three decades, each of BEV and HEV shares in the sales reaches only around 30% while CV sales manage to capture 40% of the market at 2042. Furthermore, BEVs and HEVs reach respectively 19.76% and 20.77% shares in the fleet in Istanbul by 2042. There are two main reasons why EV sales are lower than CV's even after 3 decades. Firstly, although the percentage of potential customers increases gradually, there are still people who do not recognize EVs. These unaware customers buy CVs due to the perception of the unavailability of other choices. The number of unaware people is substantially high in the first years of the simulation. Therefore, EV sales are also relatively lower at the beginning of the simulation. As to the second reason, although BEVs and HEVs may display advantages compared to CVs, some of attributes still remain less efficient than CVs'. For example, BEVs and HEVs are profitable in terms of operating cost, and emissions. However, the driving range of BEVs is lower, and the refueling time of BEVs is longer than CV. Also, the maintenance cost of BEVs is markedly higher compared to the CVs throughout the simulation period. In addition, the purchase price of HEV is also higher than both BEV and CV. So, even after familiarity with EVs greatly increases in the public, the market shares of BEVs and HEVs still fail to reach the market share held by CVs due to the perception that conventional vehicles have more preferable properties. Apart from these, the sales market share of HEVs is slightly higher than the BEVs market share in throughout majority of the simulation period. This means that certain attributes of HEV, which are maintenance cost utility and time utility, are seen as more preferable than BEVs' from the viewpoint of the customers. However, in the last years of simulation, the BEV finally begins to be more preferable compared to the HEV due to improvements about battery technology.

Total number of every vehicle type within Istanbul increases in the first 10 years of simulation. However, the sales market share of CVs persistently declines throughout the simulation. The reason why the total number of CVs increases while its sales market share decreases is the result of growth in the automobile market. In addition to this, after the first decade, while the number of sold BEVs and HEVs keeps increasing, the number of CVs begins to decline.

The percentage of potential EV customers has an S-shaped behavioral pattern. It begins with a 1% potential EV customer among all drivers in Istanbul, and converges to 100% near the end of the simulation. It grows slowly in the beginning of the diffusion due to the low number of adopters compared to high number of non-adopters. Moreover, the majority of the population among the non-adopters does not have adequate knowledge about EVs in the beginning of the penetration process. Therefore, information about EVs spreads very slowly during the first few years. After a while, the percentage of potential EV customers grows faster because of the increase of non-adopters who become familiar with EVs, and the adopters. This portion of aware people who drive EVs on the road, talk about them, or mention them on the internet and in conversation, this then leads to a positive rise of further potential EV customers.

Another important point about EVs is the reduction level of greenhouse gas emissions, which is one of the major reasons of why EVs are proposed as a necessary replacement for CVs. The results indicate that the fleet market shares of BEVs and HEVs reach 19.76% and 20.77%, respectively by 2042 in the base run. When this observation is regarded, CO_2 reduction in the transportation sector reaches around 17.32% in 2042. Moreover, cumulative CO_2 reduction reaches $17.07 x 10^6$ tons by 2042.

The results also imply that both gasoline costs and electricity costs pose an influence on vehicle sales, and thus EV diffusion. However, it must be noted that these influences are mainly related to the driving cost gap between the use of gasoline and electricity. In other words, even if electricity cost increases; this situation would not significantly affect BEV sales; unless electricity cost comes close to gasoline cost or exceeds it. Similarly, the rapid increase in gasoline cost would not heavily influence BEV and HEV sales unless the gap between electricity and gasoline costs becomes notably large.

Moderate or optimistic improvements in battery technology can cause BEV sales volumes to increase. In addition to this, moderate or optimistic technological improvements ultimately lead to greater BEV sales over HEVs. However, despite of the advanced improvements, BEV would achieve to reach 23.46% of the market by. In other words, these progresses do not cause a significant raise of the BEV market share unless battery technology keeps pace with or exceeds CV technology in terms of driving range, refueling time, and maintenance cost. The results also show that even if there would be no technological improvements, no fall in purchase price, and no progress in recharging time for BEVs, the battery electric vehicles still succeed to capture 10% of the market. This means that BEVs may survive with their current technology. Finally, if no progress is made in BEV technology, this situation results in HEV sales to increase. We can deduce from these consequences that although both BEVs and HEVs are categorized as electric vehicles and CVs is supposed to be their competitor, these two distinct electrical vehicles also compete with each other.

If the number of recharging points becomes sufficient to meet consumer electricity demands, EV diffusion speeds up and captures a higher share in the market. If recharging points are not adequate, BEV penetration is delayed. Therefore, the government should prioritize to the construction of new recharging stations in order to increase BEV sales. It is important to point out that inadequate charging infrastructure for BEVs results in HEVs having a higher market share, this is not the case with sufficient infrastructure in place. In other words, sufficient BEV recharging points cause HEV sales to decline. This situation encourages the inference that BEVs and HEVs may inhibit each other sales.

The results show that if only BEVs are launched to the market, then the BEV fleet share would likely be about 7.5% more than its base run value in 2042. However, in this case, the CV fleet share becomes around 72%. This share is 12% more than the CV share in the base run. Moreover, CO_2 reduction is about 0.07% higher than its value in the base run. These results show that even though not launching HEVs to the market may be profitable for BEV sales; this situation causes a higher rise in CV sales compared to a rise in BEV sales. This is mainly due to the fact that most of potential HEV customers choose CVs instead of BEVs. In addition, the amount of CO_2 released from CVs is greater than the gas stemming from BEVs or HEVs. In this regard, it can be deduced that not introducing HEVs to the market does not cause significant change to the climate, in terms of CO_2 reduction.

According to the simulation results, word of mouth (WoMs) of both EV drivers and non-EV drivers has a remarkable impact on EV penetration. WoM influence strengthens particularly between 2016 and 2038 because the number of EV users and aware non-EV drivers are very low in the first years of diffusion. Thus, even if all of them talk about EVs, drive them on the road, or mention them in the social media, their total impact still remains quite small in the opening years. However, when the number of aware people increases, the amount of exposure also increases. Hence, more people recognize EVs between 2016 and 2038. However, after 2038, the influence of WoM on EV market share begins to decline because the number of people who are not familiar with EV becomes considerably lower. As unaware people diminish, WoM does not then cause a huge number of people to gain awareness about EVs. Moreover, exposure coming from non-adopters may be more influential compared to adopters of the technology due to a greater number of non-EV drivers.

If the repurchasing rate increases in Istanbul, this situation would likely cause BEV and HEV penetration to gain speed. The rise of repurchasing rates also affects CVs negatively. This observation shows that policies aimed to increase the repurchasing rate may accelerate both BEV and HEV diffusion.

Subsidies have a relatively small impact on the sales of both BEVs and HEVs in Turkey. Because even with 5000 TL or 10000 TL subsidy, EV prices become higher compared to the CVs throughout the majority of the simulation. In addition, there is low number of potential EV customers in the beginning of the simulation. However, influence of 5000 TL subsidy regime on EV sales begins to increase gradually but slightly after 2035. Because potential EV customers increase and EV prices come close to CV prices due to both subsidies and decrease in EV price coming from learning by doing. Even so, implementation of subsidy strategies may not be adequate alone to provide for a rise of the market share of EVs. For this reason, subsidies do not show a considerable change in CO_2 reduction. In addition to its small impact, it is important to point out that subsidy regimes, which are mentioned in the Policy section, result in a huge total cost. Particularly ‘5000 TL for all EV subsidy-regime’ may prove to be very costly.

If the private consumption tax (PCT) for HEVs is set to 3% instead of 37%, HEV diffusion is positively affected by this tax regulation. HEV shares in the fleet in Istanbul reach to 22.27% by 2042 while it reaches 20.77% in the base run. Therefore, even new tax regulation induces HEV sales to increase, it does not cause substantial change. According to the results, this tax regulation may be more effective if it is applied after 2023. This is mainly due to the fact that the influence of this policy gradually increases in parallel with the upward awareness level. Apart from that, the results indicate that when HEV sales go up due to this policy, BEV sales become lower compared to the base run even if just by a drop.

The results suggest that sufficient marketing activities are necessary to provide successful and rapid EV penetration. Inadequate marketing levels cause the penetration of

EVs to be delayed more than one decade. According to the simulation results, marketing is particularly important in the first 5 years of the diffusion process. If the marketing activities were stopped before the 5th year, certain amounts of people would less likely recognize EVs or learn information about them. This situation causes a low level of EV sales. However, after 5 years, the number of people who are familiar with EVs sufficiently increases to sustain an adequate level of social exposure. Thus, marketing duration needs to exceed a minimum of 5 years for EVs to be adequately self-sustaining. Additionally, after 10 years, marketing activities begin to lose their effect on EV sales since most people are already aware of EVs. Thus, after 10 years, marketing activities can be stopped or their level can be reduced to cut cost. In this regard, manufacturers should give importance to their marketing activities and these activities should not be removed before the market share is high enough to sustain a steady social exposure rate.

If WoM and marketing scenarios are considered together, it can be deduced that marketing is particularly important in the first 5 years of penetration. In the same years, WoM has a weak influence due to the small number of aware people. However, after 5 years, WoM get strong enough to sustain awareness without marketing.

If electricity costs reach greater values and the discrepancy between electricity and gasoline costs becomes considerably high, even marketing, which is one of the most effective strategies to accelerate EV penetration, cannot stop the fall of BEV sales. This is because of the fact that marketing activities can only provide people to be familiar with EVs. However, if customers do not feel satisfied with EV attributes such as operating costs, then they also do not prefer EVs. Similarly, even if gasoline costs grows increasingly and electricity costs increases normally, then the number of people who prefer HEVs or CVs instead of BEVs becomes higher when recharging points are insufficient.

Even if technological developments are progressed at an advanced level and recharging points become sufficient to meet the demand, the penetration of BEVs is still delayed by about a decade without marketing activities. The reason for this is that drivers would less likely notice BEVs, and their advanced attributes without marketing activities; no matter how advanced they are. If technological improvements of BEVs reach advanced level and a recharging infrastructure becomes adequate for drivers, the 3% private consumption tax (PCT) instead of the 37% PCT policy for HEVs has an ignorable impact on HEV sales.

8. CONCLUSION

Electric vehicles (EVs) have been proposed to replace conventional vehicles due to their potential advantages related to both the environment and energy consumption. However, certain technical and social obstacles will come with the adoption of EV technology. Besides, the eventual reduction of CO_2 emissions will heavily depend on the diffusion trajectory of electric vehicles. With regards to this, the study investigates the following two questions: Firstly, what are the plausible diffusion patterns of electric vehicles for Istanbul under different scenarios developed considering both local and global socio-economic, governmental, technological factors and their interaction with each other? Secondly, what is the expected extent of the diffusion rate for Istanbul after three decades?

In the study, a dynamic simulation model is constructed by employing system dynamics methodology. Subsequent to model construction, the model is validated with structural and behavior tests. After the validation, various scenario and policy analysis are performed.

It is observed that the sales volumes for EVs are always lower than the CV sales throughout the simulation period, which is from 2012 to 2042, within the base case. After three decades, both of the BEV and HEV shares in annual sales reaches only around 30% while CV sales captures 40% of the market at 2042. There are two main reasons why the EV sales market shares are lower than CVs' even after 3 decades. Firstly, although the percentage of potential EV customers goes up gradually, there are still people in the market who do not consider EVs as an option. These unaware customers directly buy CV due to the perception of the unavailability of other choices. Secondly, although EVs may have preferable sides compared to CVs, they still have some attributes that remain less efficient than CVs'. For instance, BEVs and HEVs are advantages in terms of operating cost, and emission utility. However, the driving range of BEVs is lower, the refueling time of BEVs is longer and also the maintenance cost of BEV is higher compared to CVs. These attributes improves gradually but they fail to improve enough to capture higher market share than CVs. In addition to these setbacks, the purchase price of HEVs is much higher than both BEVs and CVs. Hence, even after familiarity with EVs significantly increases, market share of neither BEVs nor HEVs succeeds to reach the market share of CVs, simply due to the more preferable properties of conventional vehicles. Moreover, according to the results, CO_2 reduction in the transportation sector would still only reach around 17% in 2042 and cumulative CO_2 reduction in Istanbul will be around 17.10^6 tons by 2042.

Gasoline costs and electricity costs have influence on EV diffusion. However, it is important to point out that their impact on diffusion is mainly associated with a mobility cost discrepancy between gasoline and electricity. For instance, even marketing, which is regarded as one of the most influential strategies used to raise BEV sales, cannot stop BEV sales to decrease if electricity cost exceeds gasoline cost and it continues to rise. Furthermore, moderate or optimistic improvement of battery technologies would lead to BEV shares in annual sales to increase. However, if battery technology does not keep pace with or exceed CV technology in terms of driving range, refueling time, and maintenance cost; then technological improvements cannot create a significant raise in the BEV market share. Contrary to expectations, even if no technological improvements were realized, BEVs would still succeed to penetrate around 10% of the market based solely on its current technology within the 30-year span of the model. Apart from this, a sufficient number of recharging points may lead to faster diffusion of BEV's as well, causing higher fleet market share overall. For example, even if electricity cost increases normally and gasoline cost grows increasingly as well, the number of consumers who prefer HEVs or CVs over BEVs still becomes higher when recharging points are insufficient. Therefore, the government should attach importance to new recharging point constructions if it wants to ensure a successful BEV diffusion. If only BEVs are introduced to the market as an electrical vehicle, both BEV and CV sales increase compared to the cases when all three types are active in the market. However, this strategy causes a higher rise in CV sales over BEV sales. For this reason, not introducing HEV to the market would be less likely to create a significant drop in CO_2 emission compared to the market conditions when all three types are available.

Two basic mechanisms help customers to gain awareness about EVs, which result in being potential EV customer. These two mechanisms are marketing and word-of mouth (WoM). Both marketing activities and word of mouth have a remarkable impact on rapid EV diffusion. For instance, an inadequate marketing level causes significant penetration of

EVs into the market to be delayed by more than one decade even there would be optimistic technological and infrastructural improvements about BEVs. In the first years of diffusion, WoM has a weak influence due to the small number of aware consumers active in the marketplace. Therefore, marketing activities should continue to spread information about EVs in order to guarantee consumer recognition, particularly in the first years of the diffusion process. However, after the first 5 years, the number of people who are familiar with EVs increases and WoM becomes strong enough to sustain an adequate social exposure without marketing. Moreover, after the 10^{th} year of the penetration process, the effectiveness of marketing activities on EV sales begins to decline since most of people are already aware of EVs. So, after the 10^{th} year, stopping marketing activities or reducing its level would be profitable in terms of cutting the costs for the government and automobile companies. Accordingly, the government and automobile companies should allocate an adequate amount of their budgets to the marketing activities until the market share of EVs is sufficient enough to be self-sustaining.

Policies that focus on raising the repurchasing rate may also result in faster EV penetration. For instance, the government currently withdraws vehicles older than 20 years from the market. This age can be decreased. Although subsidy regimes are proposed as an effective way to speed up EV penetration by some manufacturers and academic authorities, subsidies will have a small impact on the sales of both BEVs and HEVs in Turkey. Because of this, subsidies would less likely create considerable change on CO_2 reduction. Apart from its low impact on sales, subsidy regimes also are likely to bring about a huge overall cost. When the little impacts of subsidy regimes on diffusion process and CO_2 reduction are regarded, allocating this huge amount of money to subsidy regimes seems unprofitable from the perspective of the society as a whole. Thus, profit and loss accounts should be analyzed in detail by the government before implementation of any subsidy regimes. Beside subsidies, setting the private consumption tax to 3% instead of 37% may be supportive for HEV diffusion. However, it does not cause significant increase in HEV sales, particularly in the first years of diffusion. Besides, if battery technology and a recharging infrastructure for BEVs are improved at optimistic level, this tax regulation has ignorable impact on HEV sales.

Finally, both BEVs and HEVs are categorized as electric vehicles; while CVs are considered to be their basic competitor within the transportation sector. It is believed that HEVs are crucial to attract CV customers in EV diffusion process. However, if HEVs are supported too much by the government or manufacturers, this situation may inhibit BEV penetration in Istanbul because BEVs and HEVs also compete with each other. Therefore, after HEVs succeed to attract attention of CV customers, the government and automobile firms may reduce or stop incentives for HEVs to provide broader BEV penetration.

As future research, different type of alternative fuel vehicles such as plug in hybrid vehicles, and fuel cell vehicles, may be included in the model. Moreover, adding new vehicle attributes may enrich the model. In the study, it is assumed that CVs do not have technological progress throughout 3 decades. Improvement in CV technology can be regarded in future researches. Finally, marketing is an exogenous variable in the study. It may be turn into an endogenous variable with a good extension of the model.

APPENDIX A: MODEL EQUATIONS

AFV number per station=((total number of BEV)/(Number of Recharging Stations of
BEVs))/Reference vehicle number per station
Units: Dmnl
BEV electricity unit cost= Electricity unit price
Units: TL/km
BEV discard rate=total number of BEV*BEV discard fraction
Units: vehicle/year
BEV driving range=190*("Smoothed learning ratio for R&D"^Alpha for BEV driving range)
Units: km
BEV fleet market share=
total number of BEV/(total number of CV+ total number of BEV+total number of HEV)
Units: Dmnl
BEV emission utility for A= BEV emission rate*BEV weight of emission utility for A
Units: Dmnl
BEV emission utility for B=BEV emission rate*BEV weight of emission utility for B
Units: Dmnl
BEV operating cost utility for A=BEV electricity unit cost*BEV weight of refueling cost for A+BEV maintenance cost*BEV weight of maintenance cost for A
Units: Dmnl
BEV operating cost utility for B=BEV electricity unit cost*EV weight of refueling cost for B+ BEV maintenance cost*EV weight of maintenance cost B
Units: Dmnl
BEV perceived utility for A=BEV emission utility for A+BEV operating cost utility for A
+BEV purchase price utility for A+BEV time utility for A
Units: Dmnl
BEV perceived utility for B=BEV emission utility for B+BEV operating cost utility for B
+BEV purchase price utility for B+BEV time utility for B
Units: Dmnl
BEV purchase price=BEV purchase price before taxes *(1+BEV private consumption tax)*(1.18)
Units: TL
BEV purchase price before taxes=38261*(EV learning ratio for cost^Alpha forBEV purchase price)
Units: TL
BEV purchase price utility for A= (BEV purchase price/5000)/

(LN(BEV annual income level of household for A))*BEV weight of purchase price A
BEV purchase price utility for B=(BEV purchase price/5000)/(LN(Allocated money per car for B)) *BEV weight of purchase price B
Units: Dmnl
BEV refueling time=(0.95)*("Smoothed learning ratio for R&D"^Alpha for BEV refueling time)
Units: hour
BEV sales=BEV sales market share*market growth+"Total re-purchase"*BEV sales market share
Units: vehicle/year
BEV sales market share= BEV sales market share for A*percentage of group A+BEV sales market share for B*percentage of group B
Units: Dmnl
BEV sales market share for A=(EXP(BEV perceived utility for A)/(EXP(CV perceived utility for A) +EXP(BEV perceived utility for A)+EXP(HEV perceived utility for A)))*Percentage of potential customers for EV
Units: Dmnl
BEV sales market share for B=(EXP(BEV perceived utility for B)/(EXP(CV perceived utility for B) +EXP(BEV perceived utility for B)+EXP(HEV perceived utility for B)))*Percentage of potential customers for EV
Units: Dmnl
BEV sales market share in potential EV customers=percentage of group A*BEV sms in potential EV customers A+percentage of group B*BEV sms in potential EV customers B
Units: Dmnl
BEV sms in potential EV customers A= BEV sales market share for A/Percentage of potential customers for EV
Units: Dmnl
BEV sms in potential EV customers B= BEV sales market share for B/Percentage of potential customers for EV
Units: Dmnl
BEV time utility for A= (Max range/BEV driving range) *BEV refueling time*Effect of infrastructure on BEV refueling time
Units: Dmnl
BEV time utility for B=(Max range/BEV driving range)*BEV refueling time *Effect of infrastructure on BEV refueling time*BEV weight of time B
Units: Dmnl
Current number of stations= Number of BEV stations planned to be constructed + Number of Recharging Stations of BEVs
Units: station
construction=Municipality criteria*Effect of desired constraction on nmb of recharging stations
Units: station/year

CV fleet market share=total number of CV/(total number of CV +total number of BEV+total number of HEV)
Units: Dmnl
CV discard rate=total number of CV*CV discard fraction
Units: vehicle/year
CV emission rate=1*("CV learning ratio for R&D"^Alpha for CV emmision rate)
Units: Dmnl
CV emission utility for A=CV emission rate*CV weight of emission utility for A
Units: Dmnl
CV emission utility for B=CV emission rate*CV weight of emission utility for B
Units: Dmnl
CV number per refueling point=((total number of CV+total number of HEV)/(Number of refueling stations of CV*CV number of refueling point in every station))/Reference CVnumber per refueling point
Units: Dmnl
CV operating cost utility for A=CV gasoline unit cost*CV weight of refueling cost for A
+CV maintenance cost*CV weight of maintenance cost for A
Units: Dmnl
CV operating cost utility for B=CV gasoline unit cost*CV weight of refueling cost for B+CV maintenance cost*CV weight of maintenance cost for B
Units: Dmnl
CV perceived utility for A=CV emission utility for A+CV operating cost utility for A+CVpurchase price utility for A+CV time utility for A
Units: Dmnl
CV perceived utility for B=CV emission utility for B+CV operating cost utility for B+
CV purchase price utility for B+CV time utility for B
Units: Dmnl
CV purchase price=CV purchase price before taxes*(1+CV private consumption tax)*(1.18)
Units: TL
CV purchase price before taxes=25000*(CV learning ratio for cost^Alpha for CV purchase price)
Units: TL
CV purchase price utility for A=(CV purchase price/5000)/(LN(CV annual income level of household for A)) *CV weight of purchase price for A
Units: Dmnl
CV purchase price utility for B=(CV purchase price/5000)/(LN(CV Allocated money per car for B))*CV weight of purchase price for B
Units: Dmnl

CV sales=CV sales market share *market growth+"Total re-purchase"*CV sales market share
Units: vehicle/year
CV sales market share=Percentage of potential customers CV*(CV SMS comes from PAFVC for A*percentage of group A+CV SMS comes from PAFVC for B*percentage of group B+"CV SMS for A comes from non-PAFVC"+"CV SMS for B comes from non PAFVC")
Units: Dmnl
CV SMS comes from PAFVC for A=
(EXP(CV perceived utility for A)/(EXP(CV perceived utility for A) +EXP(BEV perceived utility for A)+EXP(HEV perceived utility for A)))*Percentage of potential customers for EV
Units: Dmnl
CV SMS comes from PAFVC for B=
(EXP(CV perceived utility for B)/(EXP(CV perceived utility for B) +EXP(BEV perceived utility for B)+EXP(HEV perceived utility for B)))*Percentage of potential customers for EV
Units: Dmnl
"CV SMS for A comes from non-PAFVC"=
"Percentage of potential non-EV customers"*percentage of group A
Units: Dmnl
"CV SMS for B comes from non-PAFVC"=
"Percentage of potential non-EV customers"*percentage of group B
Units: Dmnl
CV time utility for A=(Max range/CV driving range)*CV refueling time*
Effect of infrastructure on CV refueling time*CV weight of time for A
Units: Dmnl
CV time utility for B=(Max range/CV driving range)*CV refueling time*Effect of infrastructure on CV refueling time*CV weight of time for B
Units: Dmnl
Desired constraction=Number of BEV stations planned to be constructed/Construction delay
Units: station/year
Effect of desired constraction on nmb of recharging stations=LOOKEXTRAPOLATE("Graph of desired cons. on nmb of rec. sta.", Desired constraction/Municipality criteria)
Units: Dmnl
Effect of infrastructure on BEV refueling time=LOOKUP EXTRAPOLATE(Graph of effectof infrastructure on BEV refueling time,AFV number per station)
Units: Dmnl
Effect of infrastructure on CV refueling time=LOOKUP EXTRAPOLATE(Graph of

effect of queue on CV refueling time, CV number per refueling point)
Units: Dmnl
Effect of infrastructure on HEV refueling time=
LOOKUP EXTRAPOLATE(Graph of effect of queue on HEV refueling time, HEV number per refueling point)
Units: Dmnl
Electricity unit price=Current electricity unit price
Units: TL/km
Emission level of one HEV=Emission level of one CV*(1-HEV improvement)
Units: g/(km*vehicle)
Emission level of total BEVs=Annual range of BEV*Emission level of one BEV
*total number of BEV
Units: g/year
Emission level of total CVs=Annual range of CV*Emission level of one CV*total number of CV
Units: g/year
Emission level of total HEVs=Annual range of HEV*Emission level of one HEV
*total number of HEV
Units: g/year
EV Customer Awareness Gain=Total social exposure*(1-Percentage of potential customers for EV)
Units: Dmnl/year
EV customers awareness loss=Percentage of potential customers for EV*EV awareness loss fraction
Units: Dmnl/year
EV learning ratio for cost="Total BEV sales (Total experience in Istanbul)"/EV reference experience
Units: Dmnl
EV sale accumulation=BEV sales
Units: vehicle/year
EV total sales market share=BEV sales market share+HEV sales market share
Units: Dmnl
expectation formation of EV=(total number of BEV-Expected number of BEV in Istanbul)/
EV estimation time
Units: vehicle/year
expectation formation of HEV=
(total number of HEV-Expected number of HEV in Istanbul)/HEV estimation time
Units: vehicle/year
Expected number of BEV in Istanbul= INTEG (expectation formation of EV,1)
Units: vehicle
Expected number of HEV in Istanbul= INTEG (expectation formation of HEV,1)

Units: vehicle
Gap=MAX(0, Desire number of BEV stations-Current number of stations)
Units: station
"Graph of desired cons. on nmb of rec. sta."([(0,0)-(1.6,1.5)],(-0.2,0),(0,0),(0.197248,0.243421), (0.408257, 0.473684),(0.683486,0.736842), (0.963914,0.907895), (1.2156,0.980263),(1.5,1),(1.6,1))
Units: Dmnl
Graph of effect of infrastructure on BEV refueling time ([(1,0)(12.5,4)],(0,1),(1,1),(2.61774,1.38596),(4.05963,1.92982),(5.04434,2.49123),(6.72783,3.12281),(8.40979,3.57895),
(9.78593,3.80702),(11.1009,3.9),
(12.5,4),(12.7523,4))
Units: Dmnl
Graph of effect of queue on HEV refueling time([(0,0)(5,1.5)],(0,1),(1,1),(1.66667,1.04386),(2.23242,1.09649),(2.70642,1.20175),(3.18043,1.2 561),(4,1.3),(5,1.3))
Units: Dmnl
Graph of effect of queue on CV refueling time([(0,0)(5,2)],(0,1),(1,1),(1.66667,1.04386),(2.23242,1.09649),(2.70642,1.20175),(3.21101,1.31579),(4,1.4),(5,1.4))
Units: Dmnl
HEV discard rate=total number of HEV*HEV discard fraction
Units: vehicle/year
HEV driving range=CV driving range*(1+HEV improvement)
Units: km
HEV emission rate=1*(1-HEV improvement)
Units: Dmnl
HEV emission utility for A=(HEV emission rate)*HEV weight of emission utility for A
Units: Dmnl
HEV learning ratio="Total HEV sales in Istanbul (total experience)"/HEV initial experience
Units: Dmnl
HEV emission utility for B=(HEV emission rate)*HEV weight of emission utility for B
Units: Dmnl
HEV fleet market share=total number of HEV/(total number of CV
+total number of BEV+total number of HEV)
Units: Dmnl
HEV gasoline prices=CV gasoline unit cost*(1-HEV improvement)
Units: TL/km
HEV number per refueling point=CV number per refueling point
Units: Dmnl
HEV operating cost utility for A=(HEV gasoline prices)
*HEV weight of refueling cost for A+HEV maintenance cost*HEV weight of maintenance cost for A
Units: Dmnl

HEV operating cost utility for B=(HEV gasoline prices) *HEV weight of refueling cost for B+HEV maintenance cost *HEV weight of maintenance cost for B
Units: Dmnl
HEV perceived utility for A=HEV emission utility for A+HEV operating cost utility for A
+HEV purchase price utility for A+HEV time utility for A
Units: Dmnl
HEV perceived utility for B=HEV emission utility for B+HEV operating cost utility for B+HEV purchase price utility for B+HEV time utility for B
Units: Dmnl
HEV purchase price=HEV purchase price before taxes*(1+HEV private consumption tax)*(1.18)
Units: TL
HEV purchase price=HEV purchase price before taxes*(1+HEV private consumption tax)*(1.18)
Units: TL
HEV purchase price before taxes=36500*(HEV learning ratio^HEV alpha)
Units: TL
HEV purchase price utility for A=(HEV purchase price/5000)/(LN(HEV annual income level of household for A)) *HEV weight of purchase price for A
Units: Dmnl
HEV purchase price utility for B=(HEV purchase price/5000)/(LN(HEV Allocated money per car for B))*HEV weight of purchase price for B
Units: Dmnl
HEV refueling time=CV refueling time
Units: hour
HEV sales=HEV sales market share*market growth+"Total re-purchase"*HEV sales market share
HEV sale accumulation=HEV sales
Units: vehicle/year
HEV sales market share= HEV sales market share for A*percentage of group A
+HEV sales market share for B*percentage of group B
Units: Dmnl
HEV sales market share for A=
(EXP(HEV perceived utility for A)/(EXP(CV perceived utility for A) +EXP(BEV perceived utility for A)+EXP(HEV perceived utility for A)))*Percentage of potential customers for EV
Units: Dmnl
HEV sales market share for B=
(EXP(HEV perceived utility for B)/(EXP(CV perceived utility for B) +EXP(BEV perceived utility for B)+EXP(HEV perceived utility for B)))*Percentage of potential customers for EV
Units: Dmnl

HEV sales market share in potential EV customers=percentage of group A*HEV sms in potential EV customers A+percentage of group B*HEV sms in potential EV customers B
Units: Dmnl
HEV sms in potential EV customers A=
HEV sales market share for A/Percentage of potential customers for EV
Units: Dmnl
HEV sms in potential EV customers B=
HEV sales market share for B/Percentage of potential customers for EV
Units: Dmnl
HEV time utility for A=(Max range/HEV driving range)*HEV refueling time
*Effect of infrastructure on HEV refueling time*HEV weight of time for A
Units: Dmnl
HEV time utility for B= (Max range/HEV driving range)*HEV refueling time
*Effect of infrastructure on HEV refueling time*HEV weight of time for B
Units: Dmnl
Number of BEV stations planned to be constructed= INTEG (planned construction
-construction ,0)
Units: station
Number of Recharging Stations of BEVs= INTEG (construction,13)
Percentage of EV drivers= (total number of BEV+total number of HEV)/total number of vehicle
Units: Dmnl
Percentage of potential customers for EV= INTEG (EV Customer Awareness Gain-EV customers awareness loss,0.005)
Units: Dmnl
Percentage of potential EV customers=Percentage of potential customers for EV*Percentage
Units: {%}
Percentage of non-EV drivers"= Percentage of potential customers for EV*(total number of vehicle-(total number of HEV +total number of BEV))/total number of vehicle
Units: Dmnl
"Percentage of potential non-EV customers"=1-Percentage of potential customers for EV
Units: Dmnl
planned construction=Gap/Planning delay
Units: station/year
Population in Istanbul= WITH LOOKUP (Time, ([(2010,0)-(2050,2.2e+007)],
(2010,1.4e+007),(2013.75,1.50526e+007),(2019.1,1.64561e+007),

(2025.63,1.79649e+007),(2031.62,1.90 77e+0 7),
(2039.54,2.03158e+007),(2045,2.1e+007),(2050,2.1e+007)))
Units: person
Reduction of CO2= (Total emission level when all cars are CV - Total emission level)/Total emission level when all cars are CV
Units: Dmnl
"Smoothed learning ratio for R&D"=
DELAY1("EV learning ratio for R&D", "Time delay for R&D")
Units: Dmnl
"Social exposure of non-EV drivers"=
"Effectiveness of word of mouth of non-EV drivers"*"Percentage of non-EV drivers"
Units: Dmnl/year
"Total BEV sales (Total experience in Istanbul)"= INTEG (EV sale accumulation,20)
Units: vehicle
Total emission level=
Emission level of total CVs+Emission level of total BEVs+Emission level of total HEVs
Units: g/year
Total emission level when all cars are CV= Annual range of CV *Emission level of one CV*(total number of CV + total number of BEV + total number of HEV)
Units: g/year
"Total HEV sales in Istanbul (total experience)"= INTEG (HEV sale accumulation,100)
Units: vehicle
total market share=CV sales market share+BEV sales market share+HEV sales market share
Units: Dmnl
total number of BEV= INTEG (BEV sales-BEV discard rate,20)
Units: vehicle
total number of HEV= INTEG (HEV sales-HEV discard rate,100)
Units: vehicle
total number of CV= INTEG (CV sales-CV discard rate,1.99506e+006)
Units: vehicle
total number of vehicle= INTEG (market growth,1.99506e+006)
Units: vehicle
"Total re-purchase"=CV discard rate+BEV discard rate+HEV discard rate
Units: vehicle/year
Total social exposure= Marketing influence on EV+Social exposure of EV drivers+
"Social exposure of non-EV drivers"
Units: Dmnl/year
Total vehicle demand=motorization rate*Population in Istanbul
Units: vehicle

APPENDIX B: PARAMETER VALUES

Table B.1. Parameter values.

Parameter	Value of parameter	Unit of Parameter
Alpha for BEV driving range	0,023	Dmnl
Alpha for BEV purchase price	-0,015	Dmnl
Alpha for BEV refueling time	-0,015	Dmnl
Alpha for CV emission rate	0	Dmnl
Alpha for CV purchase price	-0,029	Dmnl
Annual range of BEV	18000	km/year
Annual range of CV	18000	km/year
Annual range of HEV	18000	km/year
BEV allocated money per car for B	80000	Dmnl
BEV annual income level of household for A	60000	TL
BEV discard fraction	0,08	1/year
BEV emission rate	0,386	Dmnl
BEV estimation time	2	Year
BEV maintenance cost	1	Dmnl
BEV private consumption tax	0,03	Dmnl
BEV reference experience	5000	Vehicle
BEV reference experience R&D	5000	Vehicle
BEV weight of emission utility for A	-0,07	Dmnl
BEV weight of emission utility for B	-0,09	Dmnl
BEV weight of maintenance cost for A	-0,085	Dmnl
BEV weight of maintenance cost for B	-0,12	Dmnl
BEV weight of purchase price A	-0,4	1/TL
BEV weight of purchase price B	-0,42	1/TL
BEV weight of refueling cost for A	-0,17	km/TL
BEV weight of refueling cost for B	-0,11	km/TL
BEV weight of time utility for A	-0,17	1/hour
BEV weight of time utility for B	-0,155	1/hour
Construction delay	1	year
Current electricity unit price	0,11262	TL/km
CV allocated money per car for B	80000	TL
CV annual income level of household for A	60000	TL
CV discard fraction	0,08	1/year
CV driving range	700	Km
CV number of refueling point in every station	8	Point
CV private consumption tax	0,37	Dmnl
CV refueling time	1/12	Hour
CV weight of emission utility for A	-0,07	Dmnl
CV weight of emission utility for B	-0,09	Dmnl

Table B.1. Parameter values (cont).

CV weight of maintenance cost for A	-0,085	Dmnl
CV weight of maintenance cost for B	-0,12	Dmnl
CV weight of purchase price for A	-0,4	1/TL
CV weight of purchase price for B	-0,42	1/TL
CV weight of refueling cost for A	-0,17	km/TL
CV weight of refueling cost for B	-0,11	km/TL
CV weight of time utility for A	-0,17	1/hour
CV weight of time for utility B	-0,155	1/hour
Desired station per vehicle ratio	0,05	Station/vehicle
Effectiveness of word of mouth of EV drivers	0,25	Dmnl/year
Effectiveness of word of mouth of non-EV drivers	0,15	Dmnl/year
Emission level of one BEV	72,56	g/(km*vehicle)
Emission level of one CV	188	g/(km*vehicle)
EV awareness loss fraction	0,01	Year
HEV allocated money per car for B	80000	Dmnl
HEV alpha	-0.015	Dmnl
HEV annual income level of household for A	60000	Dmnl
HEV discard fraction	0,08	1/year
HEV estimation time	2	Year
HEV improvement	0,25	Dmnl
HEV initial experience	50000	Vehicle
HEV maintenance cost	0,5	Dmnl
HEV private consumption tax	0,37	Dmnl
HEV weight of emission utility for A	-0,085	Dmnl
HEV weight of emission utility for B	-0,09	Dmnl
HEV weight of maintenance cost for B	-0,09	Dmnl
HEV weight of maintenance cost for B	-0,12	Dmnl
HEV weight of refueling cost for A	-0,17	km/TL
HEV weight of refueling cost for B	-0,11	km/TL
HEV weight of purchase price for A	-0,4	1/TL
HEV weight of purchase price for B	-0,42	1/TL
HEV weight of time for A	-0,17	1/hour
HEV weight of time for B	-0,155	1/hour
marketing influence on EV	0,01	Dmnl/year
Max range	300	Km
Municipality criteria	1000	Station/year
motorization rate	0,145	Vehicle/person
Number of refueling stations of CV	1000	Station
percentage of group A	0,88	Dmnl
percentage of group B	0,12	Dmnl
Percentage of potential customers CV	1	Dmnl
Planning delay	2	year
Reference CV nbr per refue. p.point	240	Vehicle/(station*point)

Table B.1. Parameter values (cont).

Reference vehicle number per station	20	Vehicle/station
time delay	1	Year
Time delay for R&D	2	Year

APPENDIX C: SENSITIVITY RESULTS

Table C.1. Final values of key variables in Sensitivity Experiments.

	Base run value (at 2042)	**Sensitivity Results (2042) (min, max)**
Sensitivity parameter: Motorization rate (vehicle/person) **Sensitivity range (minimum value, base run value, maximum value) :** (0.13, 0.145,0.17)		
BEV fleet market share (%)	19.76	(19.67, 19.77)
HEV fleet market share (%)	20.77	(20.74, 20.9)
CV fleet market share (%)	59.47	(59.6, 59.4)
Sensitivity parameter: Effectiveness of WoM of EV drivers (dmnl/year) **Sensitivity range (minimum value, base run value, maximum value):** (0.2,0.25,0.3)		
BEV fleet market share (%)	19.76	(19.07, 20.24)
HEV fleet market share (%)	20.77	(20.11, 21.42)
CV fleet market share (%)	59.47	(60.82, 58.34)
Sensitivity parameter: Effectiveness of WoM of non- EV drivers (dmnl/year) **Sensitivity range (minimum value, base run value, maximum value):** (0.12,0.15,0.18)		
BEV fleet market share (%)	19.76	(18.04, 21.03)
HEV fleet market share (%)	20.77	(18.97, 22.32)
CV fleet market share (%)	59.47	(63, 56.65)
Sensitivity parameter: Maximum range (km) **Sensitivity range (minimum value, base run value, maximum value):** (240,300,360)		
BEV fleet market share (%)	19.76	(20.43, 18.96)
HEV fleet market share (%)	20.77	(20.48, 21.11)
CV fleet market share (%)	59.47	(59.09, 59.93)
Sensitivity parameter: Estimation time of vehicles (year) **Sensitivity range (minimum value, base run value, maximum value):** (1.6,2,2.4)		
BEV fleet market share (%)	19.76	(19.77, 19.61)
HEV fleet market share (%)	20.77	(20.78, 20.83)
CV fleet market share (%)	59.47	(59.45, 59.56)
Sensitivity parameter: Annual range of vehicles (km/year) **Sensitivity range (minimum value, base run value, maximum value):** (14400,18000,21600)		
CO_2 reduction (%)	17.3	(17.3, 17.3)
Sensitivity parameters: Weight of emission utility for A (dmnl)& Weight of emission utility for B (dmnl) **Sensitivity range (minimum value, base run value, maximum value):** (-0.084,-0.07,-0.056) for A market segment (-0.108,-0.09,-0.07) for B market segment		
BEV fleet market share (%)	19.76	(19.6, 19.8)
HEV fleet market share (%)	20.77	(20.8,20.8)
CV fleet market share (%)	59.47	(59.6,59.4)

Table C.1. Final values of key variables in Sensitivity Experiments (cont).

<table>
<tr><td colspan="3">Sensitivity parameters: Weight of time utility for A & Weight of time utility for B
Sensitivity range (minimum value, base run value, maximum value):
(-0.20,-0.17,-0.14)for A market segment
(-0.185,-0.155,-0.125)for B market segment</td></tr>
<tr><td>BEV fleet market share (%)</td><td>19.76</td><td>(19.04,20.35)</td></tr>
<tr><td>HEV fleet market share (%)</td><td>20.77</td><td>(20.52, 21.08)</td></tr>
<tr><td>CV fleet market share (%)</td><td>59.47</td><td>(60.44,58.57)</td></tr>
<tr><td colspan="3">Sensitivity parameters: Weight of purchase price utility for A & Weight of purchase price utility for B (1/TL)
Sensitivity range (minimum value, base run value, maximum value):
(-0.5,-0.4-0.3) for A market segment
(-0.51,-0.42-0.34) for B market segment</td></tr>
<tr><td>BEV fleet market share (%)</td><td>19.76</td><td>(19.6,19.77)</td></tr>
<tr><td>HEV fleet market share (%)</td><td>20.77</td><td>(20.39, 21.21)</td></tr>
<tr><td>CV fleet market share (%)</td><td>59.47</td><td>(60.01,59.02)</td></tr>
<tr><td colspan="3">Sensitivity parameters: Weight of maintenance cost utility for A & Weight of maintenance cost utility for B (dmnl)
Sensitivity range (minimum value, base run value, maximum value):
(-0.1,-0.085-0.07)for A market segment
(-0.144,-0.12-0.096)for B market segment</td></tr>
<tr><td>BEV fleet market share (%)</td><td>19.76</td><td>(19.55, 19.82)</td></tr>
<tr><td>HEV fleet market share (%)</td><td>20.77</td><td>(20.78, 20.82)</td></tr>
<tr><td>CV fleet market share (%)</td><td>59.47</td><td>(59.67, 59.36)</td></tr>
<tr><td colspan="3">Sensitivity parameters: Weight of refueling cost utility for A & Weight of refueling cost utility for B (km/TL)
Sensitivity range (minimum value, base run value, maximum value):
(-0.20,-0.17,-0.136) for A market segment
(-0.132, -0.11,-0.088) for B market segment</td></tr>
<tr><td>BEV fleet market share (%)</td><td>19.76</td><td>(19.22, 20.11)</td></tr>
<tr><td>HEV fleet market share (%)</td><td>20.77</td><td>(20.8,20.81)</td></tr>
<tr><td>CV fleet market share (%)</td><td>59.47</td><td>(59.98, 59.08)</td></tr>
<tr><td colspan="3">Sensitivity parameters: Time delay for R&D (year)
Sensitivity range (minimum value, base run value, maximum value): (1.6, 2,2.4)</td></tr>
<tr><td>BEV fleet market share (%)</td><td>19.76</td><td>(19.68, 19.69)</td></tr>
<tr><td>HEV fleet market share (%)</td><td>20.77</td><td>(20.8,20.8)</td></tr>
<tr><td>CV fleet market share (%)</td><td>59.47</td><td>(59.5, 59.51)</td></tr>
<tr><td colspan="3">Sensitivity parameters: Annual income level of household & Allocated money per car
Sensitivity range (minimum value, base run value, maximum value):
(48000, 60000,72000) for A market segment
(64000,80000,96000) for B market segment</td></tr>
<tr><td>BEV fleet market share (%)</td><td>19.76</td><td>(19.68,19.69)</td></tr>
<tr><td>HEV fleet market share (%)</td><td>20.77</td><td>(20.77, 20.83)</td></tr>
<tr><td>CV fleet market share (%)</td><td>59.47</td><td>(59.55,59.48)</td></tr>
</table>

Table C.1. Final values of key variables in Sensitivity Experiments (cont).

Sensitivity parameters: Reference vehicle number (vehicle/station) **Sensitivity range (minimum value, base run value, maximum value):** (16, 20,24)		
BEV fleet market share (%)	19.76	(19.27,19.96)
HEV fleet market share (%)	20.77	(20.96,20.7)
CV fleet market share (%)	59.47	(59.77,59.34)
Sensitivity parameters: Marketing influence (dmnl) **Sensitivity range (minimum value, base run value, maximum value):** (0.008, 0.01,0.012)		
BEV fleet market share (%)	19.76	(18.76,20.42)
HEV fleet market share (%)	20.77	(19.8, 21.6)
CV fleet market share (%)	59.47	(61.44, -57.98)
Sensitivity parameters: Discard fraction (1/year) **Sensitivity range (minimum value, base run value, maximum value):** (0.064, 0.08,0.96)		
BEV fleet market share (%)	19.76	(18.31, 31.56)
HEV fleet market share (%)	20.77	(19.44,31.42)
CV fleet market share (%)	59.47	(62.25,37.02)
Sensitivity parameters: Municipality criteria **Sensitivity range (minimum value, base run value, maximum value):** (800, 1000,1200)		
BEV fleet market share (%)	19.76	(19.55, 19.77)
HEV fleet market share (%)	20.77	(20.87,20.76)
CV fleet market share (%)	59.47	(59.58, 59.47)
Sensitivity parameters: Planning delay (year) **Sensitivity range (minimum value, base run value, maximum value):** (1.6, 2,2.4)		
BEV fleet market share (%)	19.76	(19.76,19.61)
HEV fleet market share (%)	20.77	(20.78,20.83)
CV fleet market share (%)	59.47	(59.46,59.56)
Sensitivity parameters: Construction delay **Sensitivity range (minimum value, base run value, maximum value):** (1, 1,1.2)		
BEV fleet market share (%)	19.76	(19.7,19.56)
HEV fleet market share (%)	20.77	(20.8,20.84)
CV fleet market share (%)	59.47	(59.5,59.6)

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