Electric vehicles in China: Past, Present and Future

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Abstract

As the world's major car-producing countries and companies are increasing research and development efforts on vehicle electrification, electric vehicles (EVs) are developing rapidly from the development and testing stage to commodity production and application stage. As the largest global vehicle manufacturer and new vehicle market, China has considered the EV as one of the key tools to solve the increasing energy security issues and environmental pollution issues in the road transport sector. However, as a new market, what the challenges and key factors are in the EV promotion process is still not clear. The main objective of this dissertation is to answer this question through evaluating the effectiveness of EV development in China on energy savings, environment protection and policy demonstration. Instead of covering all determinants, this dissertation mainly focuses on four key aspects: the current statues and issues surrounding China’s EV development and promotion; the energy consumption and carbon emissions of EVs based on the power mix both at the state level and regional level; the potential diffusion trend of the EV penetration and the sensitivities of the key impact factors; and the evaluation of the effectiveness of the EV demonstration program in China.

Applying a mix of qualitative and quantitative research methods (such as lifecycle analysis, diffusion model and evaluation framework), this dissertation found that, in addition to the technology limitation of the EV, there are still many issues surrounding

the environmental, industry, infrastructure and policy aspects, which have hindered EV development in China. To accelerate EV promotion, more comprehensive and diversified policy strategies should be developed instead only focusing on the financial subsidies. The charging infrastructures, for example, showed a more important role in EV penetration than the pricing factors, based on current market conditions. For the energy and environmental motivations, although the pure battery EV (BEV) can achieve a great reduction in fossil energy consumption, its benefits in carbon emission savings is not obvious due to China's heavy reliance on coal-fired power generation. The plug-in hybrid EV (PHEV) seems to be the right choice as a transit technology, according to its performance with emission savings in the current market situation. An evaluation framework has been developed in this dissertation to discuss the effectiveness of the EV demonstration program in China, and help to guide a more balanced development of EVs by considering comprehensive aspects, which include the EV industry, market conditions, policy support, and environmental impacts. Ultimately, this dissertation provides recommendations for the policy implementation for developing a diversified and flexible policy strategy for the EV penetration in China based on different technology choices (EV types), different situations (national and regional) and different timelines (short-term, mid-term and long-term).

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ACRONYMS

AFV: Alternative Fuel Vehicle

ANL: Argonne National Laboratory

BEV: Battery Electric Vehicle

CATARC: China Automotive Technology and Research Centre

CO_2: Carbon dioxide

DoE: Department of Energy (US)

EU: European Union

EV: Electric Vehicle

FCV: Fuel-Cell Electric Vehicle

GDP: Gross domestic product

GHG : Greenhouse Gas

GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportation

HEV: Hybrid Electric Vehicle

ICE: Internal Combustion Engine

ICEV: Internal Combustion Engine Vehicle

IEA: International Energy Agency

LCA: Life-cycle Analysis

MCA: Multi criteria analysis

MIIT: Ministry of Industry and Information Technology (China)

MOF: Ministry of Finance (China)

MOST: Ministry of Science & Technology (China)

Mtce: Million tonnes of coal equivalent

Mtoe: Million tonnes of oil equivalent

NDRC: National Development and Reform Commission (China)

Ni-MH: Nickel-Metal Hydride

PHEV: Plug-in Hybrid Electric Vehicle

PM: Particulate Matter

PTW: Pump to Wheel

R&D: Research and Development

UK: United Kingdom

US: United States

VRLA: Value-regulated Lead-acid

WTP: Well To Pump

WTW: Well To Wheel

Chapter 1: Introduction

1.1 Background

1.1.1 Energy demand and CO_2 emissions in the transport sector

World primary energy demand in 2012 was the equivalent of 13361 million tonnes of oil (Mtoe), a 45.5% increase from the 2000 level (9179 Mtoe) (IEA, 2002; 2014). Considering the existing and planned government policies, the global energy demands will increase by 37% by 2040, and Asia will account for 60% of that growth (IEA, 2014). In addition, the human influence has been considered the dominant cause of climate change since the mid-20th century. According to the latest assessment report from the International Panel on Climate Change (2014), the global average temperature increased 0.85℃ from 1880 to 2012. Through the rapid increase in fossil energy use, the severity of climate change caused by energy-related greenhouse gas (GHG) emissions has reached a critical level (Yong et al., 2015). World energy-related CO_2 emissions in 2012 were 31.6 billion metric tonnes, an increase of 4000 million tonnes compared with 2011 (International Energy Agency [IEA], 2014). Although major

governments worldwide have all announced policies to limit the average global temperature increase to 2℃ by 2050 (Yong et al., 2015), the IEA mentioned in its 2014 World Energy Outlook that the current policies and other measures are insufficient to meet the 2℃ target and that energy-related CO_2 emissions will further increase to 38.0 billion metric tonnes by 2040 (20% increase) (IEA, 2014).

The transport sector is a major contributor to worldwide final energy use and CO_2 emissions. The total oil demand in 2013 was 90.1 millions of barrels per day (mb/d), of which 48.7 mb/d was from the transport sector (accounting for 54% of the total oil demand) (IEA, 2014). Based on current trends, transport-related oil demand will increase to 104 mb/d by 2040. Despite increased fuel efficiency and the use of alternative fuels, the projected share of the transport sector in oil demand will still increase from 54% today to more than 60% by 2040 (IEA, 2014). The transport sector was also responsible for 23% of energy-related carbon dioxide (CO_2) emissions (Travesset-Baro et al., 2015). Road transport is a major contributor to total energy-related CO_2 emissions in transportation. In Japan, 19% of the total CO_2 emissions are

from transport sector, where the emissions caused by private passenger vehicles account for more than 50% of the transport sector's CO_2 emissions, and 10% of the total (Yabe et al., 2012). Passenger cars in the United States (US) were responsible for 43.1% of transportation GHG emissions in 2012 (Onat et al., 2015). The CO_2 emissions from road transport increased by nearly 23% between 1990 and 2010 in the European Union (EU) (European Commission, 2013). This figure is considered to be even higher if the effects of the economic downturn are controlled for (Travesset-Baro et al., 2015). The energy consumption and GHG emissions from road transport are not only expected to be significant in developed countries, but they are also expected to increase dramatically with the growth of the personal vehicle fleets in rapidly developing countries such as China, India and Brazil (Karplus et al., 2010). According to the IEA (2014), Asia accounts for about 60% of the global energy demand in 2013. China will be the dominant force behind the energy demand growth in the coming decades and will account for approximately 1/3 of the growth (See Figure 1-1).

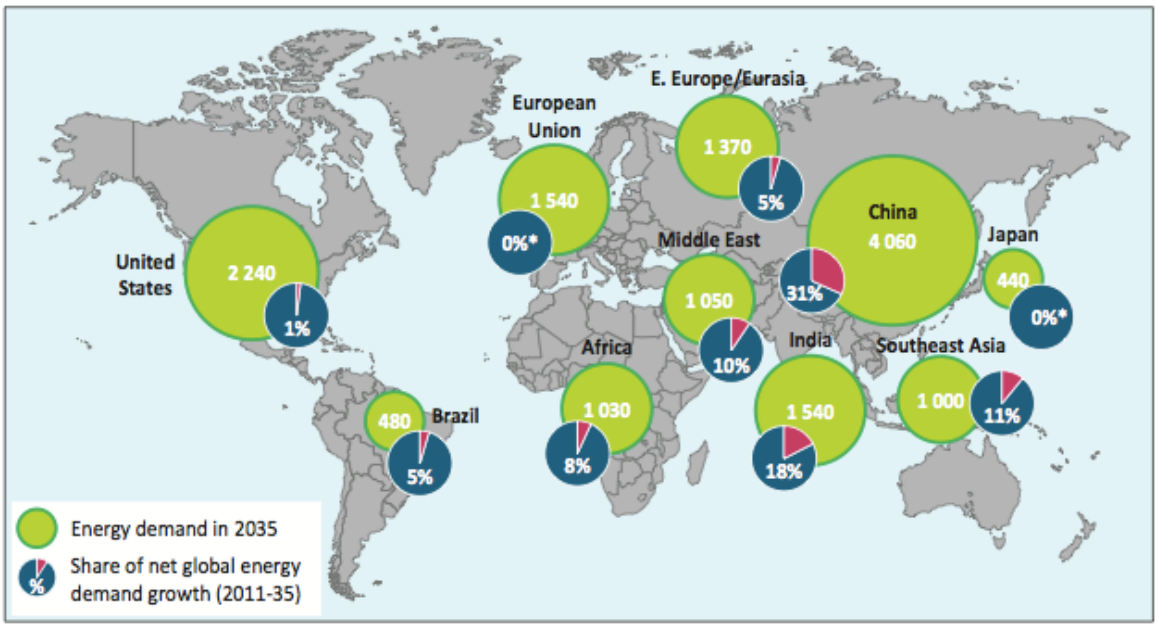

Figure 1-1 The global primary energy demand in 2035 (Source from IEA (2013))

1.1.2 Energy demand and CO_2 emissions in China

Since the economic reform began in 1978, the Chinese economy has achieved a long period of sustained growth, and it has become the fastest-growing economy and the second largest economy in the world (Shen et al., 2012). Gross domestic product (GDP) grew from 364.5 billion CNY (38 billion GBP)[1] in 1987 to 47.2 trillion in 2011 (National Bureau of Statistics, 2010; National Bureau of Statistics, 2012). The average economic growth rate in China's 11th Five-Year Plan period (2006-2010) was 11.2% (Zhou et al., 2013). Accompanying this dramatic economic growth, the energy demand and the energy-related GHG emissions in China have also increased

[1] Exchange rate used in this dissertation is 1GBP = 9.6 CNY

tremendously. Energy consumption in China surged from the equivalent of 571 million tons coal (Mtce) in 1987 to 3480Mtce in 2011 (National Bureau of Statistics, 2012). China was responsible for 12% of the total global energy demand in 2002. This figure increased to 22% in 2012 and will further increase to 24% by 2025 (IEA, 2014). China has been considered the dominant force in global energy demand growth and is expected to account for nearly 40% of the growth by 2025 (IEA, 2013). The IEA (2013) announced that China would become the largest oil importer and the largest oil consumer in the world by 2030. In addition, China is the world's largest coal consumer, producer and importer, accounting for more than 85% of demand growth between 2002 and 2012 (IEA, 2014)

From the environmental perspective, China produced roughly 7050 million tonnes (Mt) CO_2 in 2008, and it has overtaken the US to become the largest emitter in the world (Shen et al., 2012; Yan and Crookes, 2010). China was responsible for 23.7% of the world's total CO_2 emissions in 2009, compared with 5.7% in 1973 (IEA, 2011; Zhou et al., 2013). China will still remain the largest emitter in the world in the next two

decades. In 2012, China's CO_2 emissions were 60% greater than those of the US, and the country's emissions are expected to be more than twice the US levels by 2035 (IEA, 2013). Because of the increasing climate concerns in recent years, China is facing great pressure from international public opinion, and the government has already promised to reduce the CO_2 per unit of GDP by 40-45% by 2020 compared with the level in 2005 (Yan and Crookes, 2010). On 30th June 2014, the Chinese government sent the report "Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions" to the United Nations Framework Convention on Climate Change. The report announced China's intended nationally determined target contributions by 2030 and stated that China will reach peak CO_2 emissions by the year 2030 or so, and it will make its best efforts to peak early, reduce CO_2 emissions per unit GDP by 60% to 65% compared with the 2005 level, and increase the share of non-fossil fuels in primary energy consumption to roughly 20% (Department of Climate Change, 2015).

1.1.3 Transport sector in China

The transport sector is considered the fastest-growing contributor to the energy consumption, GHG emissions and air pollution in China. Energy demand in China's transport sector achieved an average annual growth rate of 7.0% between 1980 and 2007 (Wang 2009, Ou et al., 2010a). The transport sector accounts for 40%, 95% and 60% of petroleum, gasoline and diesel consumption in China, respectively (Ou et al., 2012). Accompanying the rapid economic growth, the number of vehicles in China increased dramatically, with an annual average growth rate of 15.09% between 1997 and 2007, and this has made China the world's largest vehicle market since late 2008 (Zhang et al., 2010). Because of the dramatic growth in car use, oil demand in China has also significantly increased. China was an oil-exporting country until 1993. However, because China is a poor oil country, the slow growth of China's domestic oil supply has increased its dependency on imported oil since 1993, and this ratio rose from 7.5% in 1993 to over 53.5% in 2009 (Tien, 2010; Ou et al., 2010a). The CO_2 emissions from the transport sector have increased to 524.85 Mt in 2008, nearly 4 times greater than in 1990 (International Transport Forum, 2011). It is considered that

there is still a huge potential increase in energy consumption and GHG emissions from transportation because of the potential growth in China's vehicle market. According to the IEA (2008), this oil import dependency will further increase to 74% by 2030 in the Business As Usual scenario, with road transport accounting for 43% of the total oil demand.

Although China has already become the largest new vehicle market worldwide, vehicle ownership in China is still low compared with that in developed countries and with the global average level. Vehicle ownership in China reached 81.5 per 1000 population (2012), compared with roughly 808 per 1000 in the US and 600 per 1000 in the EU and Japan (JAMA, 2012; Department of Energy (DoE), 2014; Wu et al., 2012). Even the global average level was 170 per 1000 population in 2013 (Ward's, 2014), still more than 2 times the Chinese level. Therefore, the vehicle stock in China will continue to grow substantially over the next two decades (Huo and Wang, 2012; Ou et al., 2010b; Wang et al., 2011; Wu et al., 2012). According to forecasting by BP (2014), the vehicle ownership per 1000 persons will increase to 360 in China by 2035.

This high growth of vehicle stock over the next several decades will cause China to face the increasing pressures from energy security and CO_2 mitigation as well as urban air quality improvement. The emission of NO_X from vehicles has contributed over 70% of ambient air pollution in urban areas of China (Zhang et al., 2008; Zhang et al., 2010). Smog is also a major problem in China's urban areas. More than 25% of the territory in China has been blanketed by smog since 2013, and more than 600 million people are affected by this issue (Zheng et al., 2014). One of the major reasons for the smog is the finer particulate matter (less than or equal 2.5 μm) (PM2.5) emission, and the PM2.5 emissions from the road transportation sector account for 25% of the total of PM2.5 emissions (Wang et al., 2015). Because of the growing energy security, environmental and health-related concerns about the impacts of road transport, the government and the automotive industry are facing great pressure to develop cleaner and more fuel-efficient vehicles. The focus so far has been on developing new fuels and introducing clean technology.

1.1.4 Electric vehicles (EVs) around the world

In recent years, because of the increasing concerns surrounding the oil crisis, climate change and air pollution, more and more countries are looking for alternative fuel vehicle (AFV) technology to replace the traditional internal combustion engine vehicle (ICEV). Various advanced vehicle technologies (including hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), battery electric vehicle (BEV) and fuel cell vehicle (FCV)) have been developed. Because of the potential for low emissions and high fuel efficiency, automotive power train electrification is widely considered an effective way to mitigate the energy shortage and air pollution brought by road transportation (Wu et al., 2015; Onat et al., 2015; Lorf et al., 2013; Li et al., 2012; Travesset-Baro et al., 2014; Wang et al., 2015). Electric vehicles (EVs) include grid-independent vehicles such as HEVs and grid-dependent vehicles such as BEVs and PHEVs (Midler and Beaume, 2010; Harding, 1999; and O'Brien et al., 1997).

It is not only the advantages for energy security and low emissions but also the potential leadership in the new global EV market that have motivated many countries

(especially those with advanced vehicle manufacturers) to vigorously develop EVs. According to the US climate action plan presented by President Obama in 2013, developing advanced EV technology is a prioritised strategy for reducing the energy consumption and environment impacts of the transport sector (Onat et al., 2015). Many states in the US have also launched their own policies to promote EVs. For Example, California has carried out the “Zero Emission Vehicle” and “Low Carbon Fuel Standards” regulatory programs to support the deployment of EVs (Elkind, 2012; Wu et al., 2015). Japan has proposed developing EVs as the core content of its “low carbon revolution” (2009), and it has begun efforts to increase its EV market share to 50% by 2020 (New Energy Development Organization, 2010). The Ministry of Economy, Trade and Industry (METI) in Japan launched the “Next-Generation Vehicle Plan 2010”, which sets the development target of its HEV sales share at 20%-30% and its BEV and PHEV sales shares at 15-20% by 2020 (METI, 2010; Yabe et al., 2012).

1.1.5 Motivations of EV development in China

China began to consider AFV development as a key component of national strategy in

the 1990s, and it has allocated great importance to developing AFVs, especially EVs, over the past 20 years. Similar to Germany and the US, the combination of scarce oil reserves and rich coal reserves makes China a prime candidate for pursuing the application of technologies to convert coal to power for vehicles (Shiau et al., 2009; Ou et al., 2010a; Ou et al., 2010c; Vallentin, 2008a; Vallentin, 2008b). As a result of the large coal reserves and coal-based energy mix in China, the BEVs and PHEVs there use grid electricity for power, and this has significantly contributed to improved energy security. Because of the low, even zero, emission of EVs in the operation process, EV development in China is also expected to reduce local air pollution from road transport, especially in urban areas. Although China has already become the largest vehicle manufacturer in the world, the level of ICEV technology in China is still far behind international advanced levels because of the lack of some key technologies relating to engines, automatic transmission, and electronic control systems. Therefore, developing BEVs that use the battery and motor system instead of the traditional internal combustion engine system has been considered the best option for narrowing the gap between China's automobile industry and global technologies.

In addition to ignoring the weakness in the traditional automotive technology, developing EVs in China also has some unique advantages. For example, China is very rich in important material resources used in manufacturing batteries, and this provides protection for developing the battery industry. Lead reserves in China rank second in the world just behind Australia's, and at present, China is the world's largest exporter of refined lead (Group of Electric Vehicles Project, 2008). In addition, China's proven lithium reserves are 17 million tons (calculated in accordance with LiCl), accounting for 79% of the total worldwide lithium reserves (Electric Vehicle Industry Development Strategy Research Group, 2009). Furthermore, the manganese reserves in China are 566 million tons, and the country's manganese ore production accounts for 35% of the world total. Because of these substantial resources, the development of batteries such as lead acid batteries, lithium iron phosphate batteries and lithium manganese oxide batteries is guaranteed (Group of Electric vehicles project, 2008). Based on all of these background conditions, EV technology, especially BEVs, has been seen as a great opportunity for China to seize the high ground in automotive innovation.

1.1.6 Policy strategy for EV development in China

In order to accelerate the development of the domestic EV industry, the Chinese government has implemented a number of actions to develop EV technology and promote the commercial EV market, including incentive policies, funding for research and development (R&D), and market demonstration programs (Ou et al., 2010; Zhang et al., 2011). The main plans and strategies directions of China's economic development are mainly based on the five-year planning cycle released by the government every 5 years. The development of alternative fuel vehicles was first mentioned in the 8th Five-Year Plan (1991-1995). Subsequently, the Chinese government continued to support EV R&D and marketing over the last 20 years (the details of the policy background of EV development in China will be introduced in Chapter 4). In 2012, Chinese government launched the "Energy-effective and Alternative Fuel Vehicle Industry Development Plan (2012-2020)", which clearly stated that developing BEVs and PHEVs is the main focus for transforming China's auto industry, and other AFVs (such as FCVs) will be continuously developed as a potential

future technology roadmap (State Council, 2012; Zhou et al., 2013). This plan also set a new target for EV development in which the combined production of BEVs and PHEVs should reach 500,000 by 2015 and approach 2,000,000 in 2020.

From the promotion perspective, the large-scale demonstration program “Ten Cities, Thousand Vehicles” was launched in February 2009 by four ministries: the Ministry of Finance, Ministry of Science & Technology (MOST), Ministry of Industry and Information Technology and National Development and Reform Commission. The demonstration program aims to promote at least 1000 AFVs (HEV, PHEV, BEV and FCV) for each city in at least 10 pilot cities by 2012. At first, 13 pilot cities were chosen, and then this figure was increased to 25 cities (August 2009). In this demonstration program, the subsidies from the central government were only provided to the public sector (buses, taxis, municipal vehicles, government fleets, etc.). In June 2010, 6 cities (Beijing, Changchun, Shenzhen, Hangzhou, Hefei and Shanghai) were chosen from the original 25 to provide subsidies for private buyers (the details of the demonstration project are introduced in Chapter 4). Although the Chinese government has

continuously invested in the AFV industry over the last two decades, “this demonstration program is distinctive in that it marks the beginning of official support for the mass deployment of AFV with substantial governmental financial subsidies” (Zheng et al., 2012).

In order to achieve the target established in the “Energy-effective and Alternative Fuel Vehicle Industry Development Plan (2012-2020)”, a second round of the demonstration program was launched from 2013 to 2015 that was called the Phase 2 program (the previous demonstration program (2009-2012) was Phase 1). In this round of demonstration projects, the subsidies are only provided to the new energy vehicles (BEV, PHEV and FCV), omitting HEVs. The Phase 2 program allows for joint application to urban clusters. Nine urban clusters were ultimately chosen as the pilot regions: in Inner Mongolia and in Zhejiang , Guangdong , Jiangsu , Guizhou , Jiangxi , Fujian , Yunnan and Hebei provinces (CATARC, 2014). Compared with the 25 cities in Phase 1, a total of 39 cities and regions were selected in Phase 2. In addition, the Phase 2 demonstration program does not divide the subsidy objectives into public vs.

private sector; all EV buyers in all pilot cities and regions can get the subsidies. These 39 cities and regions plan to promote over 300,000 EVs in total by the end of 2015 (CATARC, 2014).

1.2 Research Motivation

Although many countries are very optimistic about the development of electric vehicles，the potential future and diffusion trends are still uncertain. In fact, EVs have attracted interest from the auto industry many times over the last 130 years (in the late 19th and early 20th centuries and in the 1960s-1970s), but the result was that the EV lost its battle against the ICEV because of the technology limitations and the high price (Geels et al., 2012). However, the concerns regarding EV development are mainly concentrated on “where and how the electricity that will power electric motors will be generated and stored, rather than whether the electric motor will be used in power trains of future cars” (Nieuwenhuis et al., 2006).

Currently, EV development has once again become the focus of concern for

governments and major automobile manufacturers because of the increasing concerns over climate change, air pollution and oil prices. EV technology has been further enhanced compared with its performance in the last three decades. However, it still cannot be said that EVs will be successfully commercialised and widely promoted in the short term EV promotion still faces a number of issues related to technology, policy, infrastructure and consumer behaviour. Battery technology limitations, limited charging infrastructure, high initial consumer cost, safety and liability concerns are all considered as barriers to successful EV implementation (Romm, 2006; Zhang et al., 2011). Therefore, it is necessary to understand how will these factors affect EV diffusion and whether the currently policy support launched by these governments can effectively promote EV deployment.

However, because the EV market is a new technology market that has only been developed in the last several years, there is lack of data and experience to prove the effectiveness of EV development. The majority of current EV research is focused on how to overcome the technological barriers such as technical limitations and charging

infrastructure problems (Axsen et al., 2010; He et al., 2013; Sovacool et al., 2009). Few studies have evaluated the effectiveness of EV development from more comprehensive perspectives (including technology, social behaviour, market conditions, energy, the environment and policy) (Wu et al., 2015). Therefore, this dissertation evaluates the effectiveness of EV development from energy, environment, policy and market perspectives.

However, the different situations in different countries (such as auto industry development level, economic level, power generation structure, consumer behaviour and policy support and instruments) can also lead to different effects on EV development performance. Unlike the vehicle markets in developed countries (such as the US and the EU) that are already considered mature markets, the vehicle market in China is still in its growth period, and the market demands, conditions and consumer behaviour may be different to those in a more mature market. Although previous studies have focused on analyzing market diffusion and consumer behaviour with respect to EVs in the US, Japan, and Germany (Tanaka et al., 2014; Tomas, 2012;

Buhler et al., 2014; Propfe et al., 2013), the situation in China's vehicle market is different. China has been committed to developing EVs for 20 years. It is necessary and valuable to understand the key factors and issues for EV development in an emerging market such as China's, and how EVs will be deployed.

The policy support and demonstration scale in China for EV development make China one of the strongest political-institutional environments for EV development and promotion (McKinsey 2012), and it is also considered one of the most promising markets for EV development and promotion. Therefore, the EV development in China provides a prime case study for investigating the development and promotion of the new EV industry. The lessons and experience from China will provide reference for other countries on EV development policymaking and policy implementation, especially in terms of the adoption of incentive-based instruments in developing countries and emerging markets. At this point, it is worth noting that the current policy support and demonstration program in China is not considered to be very successful. For example, the targets of the Phase 1 demonstration program (2009-

2012) had not been achieved at the end of 2012. In the private passenger market, only 4400 EVs (include HEVs) has been bought, and this accounts for only 10% of the primary promotion target (CATARC, 2013). The lack of proper enforcement and implementation (especially at the local level) is considered to be the main reason for the ineffective command and control regulation in China (Blackman and Harington, 2000; Wachtmeister, 2013).

However, there is little literature that has investigated China's EV policies or studied quantitatively the development and performance of China's EV promotion, especially at the local level. Against the extensive background above, this dissertation investigates EV developments performance in China from the past through the present to the future. The impacts and effectiveness of the EV development and promotion process in China are analysed by considering the specific situations at both the national and regional levels, and this research also assesses the effectiveness of China's current policy incentives.

1.3 Research aim and questions

As stated above, there are four main reasons for China to develop EVs, namely, energy saving, environmental protection, market potential and industry development. Compared with the traditional internal combustion engine vehicle (ICEV), current EV performance is still far from competitive in cost, driving range, or maintenance, as well as the supporting infrastructure. Battery and EV technology breakthroughs are considered the key issues for EV development. However, other factors can also significantly affect the performance of EV promotion, such as energy mix, auto industry level, consumer behaviour, market conditions and policy environment. Although some existing studies have already studied the relevant determinants of EV development (See Chapter 2), they have not fully considered the Chinese situation in terms of China's political environment, auto industry conditions, power mix, consumer behaviour and market conditions, nor have they captured the country's economic situation and environmental pressures. Therefore, whether and how EV promotion can achieve good performance in China remains to be studied based. **This dissertation aims to evaluate the current effectiveness and the potential future of**

EV development in China and to determine a suitable development strategy based on the results. To achieve this research aim, four specific research questions were identified to cover energy, environment, market and policy aspects.

1. **What is the current status of and what are the main issues for EV development and deployment in China?**

EV development has been one of the Chinese government's core strategies, and considerable resources have been invested over several years. **To understand China's EV development status, this dissertation first investigates EV development history and the lessons from the country's previous promotion programs.** It is necessary to understand how the current policy incentives affect EV development and the main issues that hinder electric vehicle promotion in China from different perspectives such as policy, the environment, industry investment and infrastructure provision. To address this research question, this dissertation introduces China's existing policy strategy and instruments and analyses the success factors and the issues based on the experience of the previous and current demonstration programs.

2. How can EVs help to reduce fossil fuel use and GHG emissions given China's specific energy mix?

The policy strategy for EV development in China is to resolve the country's energy security and CO_2 emissions challenges; therefore, it is important to understand the energy and environmental aspects of the country's EV deployment performance. The electricity generation in China is coal based, with over 80% of total electricity-generating capacity coming from coal-fired thermal power. The increased demand on electricity caused by EVs could result in a significant increase in fossil energy consumption and GHG emissions. It is important to know the effectiveness of each kind of EV on energy saving and CO_2 reduction, given China's current energy mix. There is also a need to forecast how these situations might change when China's energy structure is gradually improved in the future. This research question is addressed in this dissertation by performing a comparative life cycle analysis of different drive trains in China within the regional context of the current energy mix.

3. How will EVs deploy in China, and what are the key influences on future EV diffusion?

This dissertation also investigates the EV market conditions to simulate the EV diffusion trend. Because the EV market is an emerging market and the auto industry is policy-oriented (See Chapter 2), it is important to understand how China's market situation and EV policies will affect EV diffusion. EV penetration can be affected by many factors such as battery technology, fuel cost, consumer behaviour, policy incentives, and infrastructure. Forecasting EV marketing potential can help the government to develop the most appropriate policies for different periods. In addition, clearly understanding how the EV diffusion trend can be affected by these factors based on China's market features will be very helpful in further improving the levels of EV penetration in China. In order to solve this research question, this dissertation uses the diffusion model to forecast the EV penetration in China by considering different variables, and it analyses the different effectiveness levels for the different impact factors.

4. How can China design an effective policy regime to promote mass EV adoption?

By investigating current EV development in China, this dissertation further analyses how to improve its effectiveness. To promote EVs in China, the government has provided a large amount of financial support for policy incentives, and the large-scale demonstration program was started (2009). The numbers of EVs and charging stations have increased significantly because of these policy instruments. However, progress is still considered to be a long way behind the initial target. Because of the lack of comprehensive evaluation and monitoring systems, there is a lack of understanding of the effectiveness of current EV promotion at the national and local levels (including varying requirements for technology, EV industry, infrastructure, appropriate business model and environment), and how the policy instruments might affect EV promotion. Evaluating the effectiveness of the EV policy instruments will provide a more effective means to improve EV penetration by using the most appropriate policy measures. This dissertation addresses this research question by discussing the effectiveness of the current policy instruments at the national level and also evaluating the different promotion efforts in the different pilot cities in China. Based on the findings resulting

from the evaluation, recommendations are given to improve the effectiveness of the EV deployment in China. The combination of these 4 research questions is expected to provide a comprehensive evaluation of the current EV development in China and also the potential future in the energy, environment, and market as well as the policy implications.

1.4 Thesis outline

1.4.1 The outline of chapters and their relationships with the research questions

The relationships between each core chapter and the research questions are shown in Table 1-1 and further explained below. In addition, there are other, more contextual chapters to introduce the research background, the literature review, the research methodology and the overall conclusions. The structure and the description of each chapter are introduced below:

Table 1-1 The outline of the dissertation

	Chapter (Paper)	Roles	Research Question
Background & Methodology	Chapter 1	Introduction, research background, motivations, and research questions	
	Chapter 2	Literature review	
	Chapter 3	Methodologies	
4 core Chapters	Chapter 4	The current status of EV development in China and the issues with EV promotion; recommendations	Q1 & Q4
	Chapter 5	The life-cycle energy consumption and CO_2 emissions for three kinds of EVs at the national (current situation and possible future) and local levels in China	Q2
	Chapter 6	The diffusion trend of BEVs in China in different scenarios and the effects from external factors	Q3&Q4
	Chapter 7	Evaluation of the electric vehicle demonstration program in China through a multi-criteria approach	Q1, Q2, Q3 & Q4
Synthesis & Conclusion	Chapter 8	Conclusion and summary of key findings from each chapter as each corresponds to the research questions and aims	

Chapter 1: Introduction

The Introduction aims to outline the research background and motivation for the dissertation and provide an overview of EV development in China. This chapter

explains the reasons for the EV development in China by describing the country's energy demand and CO_2 emissions resulting from transport, as well as the potential for auto industry development. The effectiveness of the EV development in China is discussed, and the potential benefits and main uncertainties of EV development in China based on China's own situations are introduced. This chapter also outlines the research aims and research questions, and it explains the role of each objective in the whole study. The research questions constitute four main aspects (energy, environment, market and policy) and correspond to the subsequent core chapters. The structure of the whole thesis is outlined.

Chapter 2: Literature Review

The literature review introduces the background of EV development pathways, including development history, EV classifications, and also the latest technological changes. In addition, the existing studies that focus on the energy and environmental impacts of the EV development are summarised, together with the current research gaps. The methodologies used in the existing studies are also introduced and

discussed. The history of the automobile industry development in China is analysed, and the status and relevant experience of EV development in advanced countries are described and discussed for comparison.

Chapter 3: Methodology

The methodology chapter introduces the research theories and overall analytical approaches that are applied in this research. It outlines the research methodologies used in the thesis and their relationships as they correspond to each research objective. Details of each research method are further discussed in the corresponding chapters.

Chapter 4: The main issues of EV promotion in China based on the experience from the exiting EV demonstration program

This chapter mainly corresponds to Q1 and Q4. It reports on the results of the demonstration program by the end of 2012. In accordance with the practical problems that occurred during the demonstration and the expert views collected

through the interviews, several issues relating to the promotion and implementation of EVs have been summarised and divided into four main aspects: vehicle issues, purchase behaviour, policy issues and infrastructure issues. In addition, further gaps between these issues and the new policies implemented in recent years (2013 and 2014) have been identified, for example the lack of monitoring and evaluation, the lack of policy support in infrastructure construction, and the reduced number of incentive types. Some recommendations have been given in response to these gaps in the strategy, and may help the government to further optimise EV development in the future.

This Chapter has provided an overview of the political background of the EV deployment in China, and evaluated the effectiveness of the existing demonstration program in the national level through the qualitative analysis (related to Q4). This chapter has been submitted to peer reviewed journal “Transport Policy” on August 2015.

Chapter 5: Electric vehicles in China: Life cycle energy consumption and CO_2 emissions for the different energy mixes now and in the future

Chapter 5 corresponds to Q2. It uses GREET model to evaluate the energy consumption and CO_2 emissions of different EVs in China, and this analysis is integrated with different hypotheses for the electricity production mix in the different regions, now and in the future. The results show that the Battery electric vehicle (BEV) can achieve clear reductions in fossil fuel use. But due to the continued dominance coal-fired power electricity, the BEV carbon profile will continue to be high, at least in the short term (2030). The BEV and Plug-in hybrid electric vehicle （PHEV） will not achieve their full potential in contributing to CO_2 emissions reduction compared with the Hybrid electric vehicle (HEV). Currently, the BEV can only show better CO_2 reduction than HEV in Southwest of China due to the abundant hydropower. On the contrary, the CO_2 emission of BEV is even higher than that of the conventional petroleum vehicle in Beijing and Shanghai, where coal-fired power accounts for more than 96% of the total mix.

This Chapter provides the investigation of the performance of different EVs on energy and environmental aspects, corresponding to the issues raised in Chapter 4 that China's power mix may affect the effectiveness of the EV development on energy saving and CO_2 emissions reduction. The findings in this Chapter are addressed in Chapter 7. This chapter was accepted and presented as an conference paper on the UTSG conference in London (January 2015), and It has been further submitted to the journal "Transportation Research Part D: Transport and Environment" for publication on August 2015.

Chapter 6: A diffusion analysis of BEV market penetration BEV in China through 2040

In order to address Q3, Chapter 6 evaluates the possible market potential of the Battery Electric Vehicle (BEV) in China up to 2040 under different scenarios, and it identifies the impacts on the diffusion trend resulting from the different factors. The diffusion model is based on the Generalized BASS model, and it has been used in this paper to evaluate the different diffusion trends for the BEV by considering the impact

factors and also the different scenarios resulting from these factor changes. The results of the study show that the charging infrastructures and the purchase price have the most significant impacts on BEV diffusion, but in the early development stage, increasing the infrastructure and driving range seem to be the most effective ways to enhance the potential market. It is concluded that it is difficult to achieve the levels of BEV take up proposed by the Government for 2020, unless the Government adopts more effective policy measures to build a positive environment for BEV development.

This chapter mainly focuses on the investigation of EV promotion from the market conditions perspective, and the different impacts of the EV technology, policy incentives and infrastructures. In contrast to the Chapter 4 and Chapter 7 that focus on the existing and current situations, this chapter uses the diffusion model to provide various possible future options for the EV deployment in China. This chapter has been submitted to the peer reviewed journal “Energy research & Social Science” on August 2015.

Chapter 7: Evaluation of China's EV demonstration program using a multi-criteria approach

As in Chapter 4, Chapter 7 also mainly focuses on Q1 and Q4, but provides a more quantitative-based study on the local level. This chapter has developed an evaluation framework using a multi-criteria approach, where technology-industry, market conditions, policy and environmental aspects are all considered. The different perspectives from the key stakeholders are included to provide the necessary context, and a set of market and environment scenarios were used for evaluation. Beijing, Shanghai, Hangzhou and Shenzhen were chosen as case studies to evaluate their specific performance in the demonstration program. The results show that Shenzhen ranked first in both evaluation scenarios based on its outstanding performance in techno-industry and on market conditions. Shanghai had the most balanced performance in that it showed good performance in most of the criteria. The main drawback in Hangzhou was that it prioritised the techno-economic aspects over all others, but Beijing performed worst amongst the cities in terms of the

environment aspects. The quantitative and contextual analysis suggests that in order to develop an effective EV program, both a comprehensive evaluation framework and related standards and plans need be developed and carried out by the central government. The results should be monitored continuously over 5 to 10 years to dynamically adjust key aspects of the program (policy, technology performance, etc.) in order to achieve multiple policy and industry goals.

This Chapter has combined the findings from Chapters 4, 5 and 6. The key impact factors of the EV deployment derived from Chapters 4 and 6 have been included in the evaluation framework; and the findings in Chapter 5 have been referenced to simulate the different performance of the pilot cities on environmental criteria. This Chapter has been submitted to the journal "Transportation Research Part A: Policy and Practice" on August 2015.

Chapter 8: Conclusion

The conclusion chapter summarises the research findings from each chapter and

brings together, and summarises the final achievements that correspond to each research question outlined in Chapter 2. The relationships between each core chapter are discussed, and the contributions of this dissertation are presented regarding both application and methodology approaches. Based on the policy recommendations given in each chapter, this chapter provides an integrated and comprehensive policy strategy route for improving EV development in China, and it also offers recommendations for future research.

1.4.2 Relationships between the core chapters (Chapter 4 to Chapter 7)

This dissertation follows the "four papers route". The four core dissertation chapters (Chapter 4-7) have been submitted as manuscripts to peer-reviewed journals. The combination of the 4 papers contributes to answering the 4 research questions and forms the core of this dissertation (see Figure 1-2).

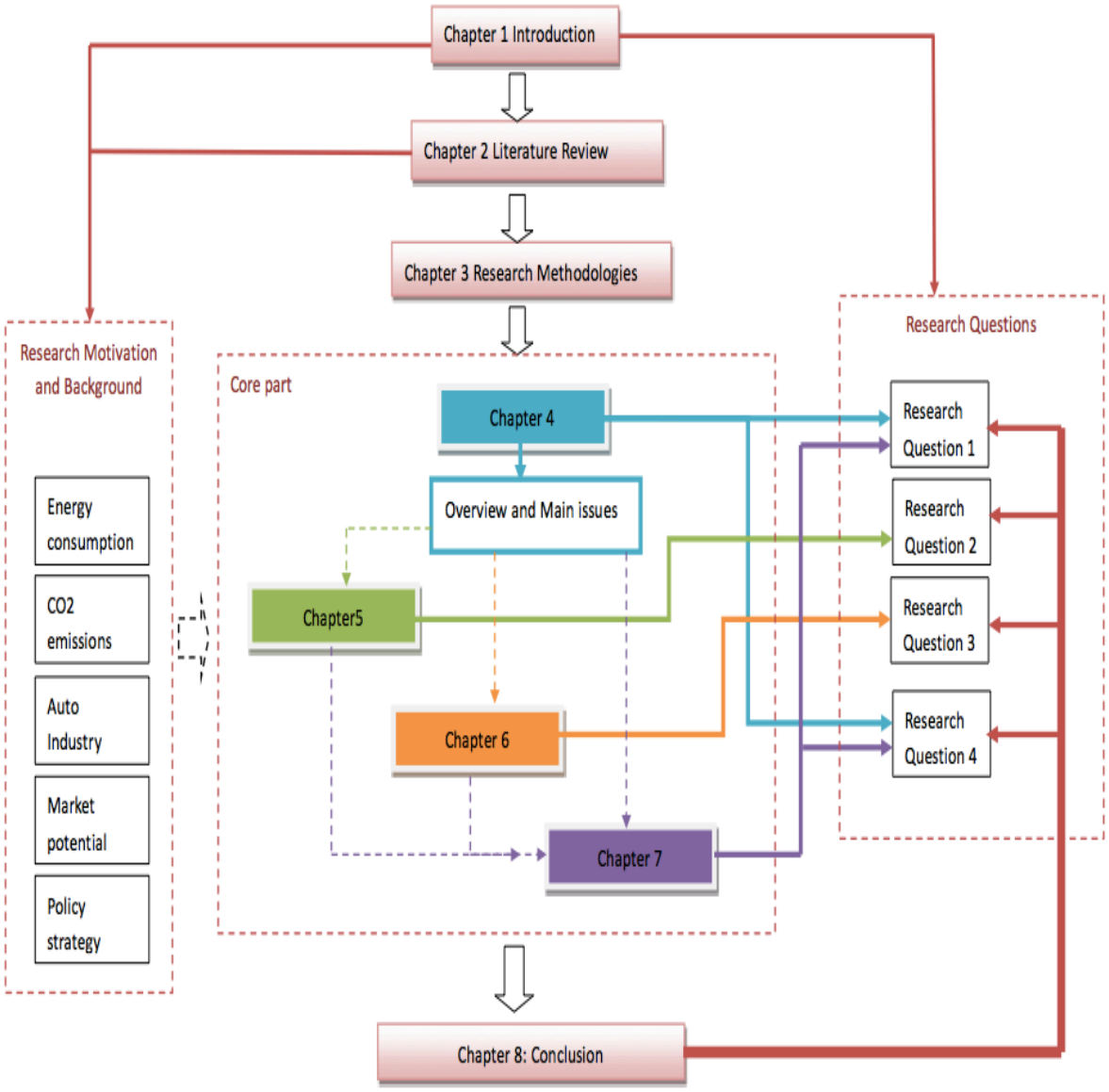

Figure 1-2 The structure of the dissertation

Based on the findings in Chapter 4, the main challenges of the EV development in China concentrate mainly on: the limitations of EV performance, specific market conditions and consumer behaviour, the effectiveness of EVs on energy consumption and pollution emissions under the current energy mix, the limitations of policy

incentives, the limitations of the charging infrastructure and the lack of an evaluation and monitoring system. These aspects are further discussed and analysed in the following Chapters. Chapter 5 corresponds to the energy and environmental aspects and evaluates the impacts of the EV in China on energy consumption and CO_2 emissions. For market conditions and consumer behaviour, Chapter 6 analyses the future BEV diffusion in China by considering different scenarios. The simulation considered the features of China's traditional ICEV market, and the key influencing factors in this chapter include EV performance, market conditions, policy incentives and infrastructure.

In order to resolve the lack of an evaluation and monitoring system in China's EV demonstration program, Chapter 7 developed a comprehensive evaluation framework to examine the effectiveness of the current demonstration projects at the local level. As the final core chapter, Chapter 7 is closely related to the other three core chapters, and it corresponds to all four research questions. For example, the main issues in the previous demonstration program are addressed in Chapter 4, and the key factors that

can affect the EV diffusion trend that are discussed in Chapter 6. These are all considered central to setting the criteria for the evaluation framework. In addition, the findings of the performance of different kinds of EVs in different regions on CO_2 emissions (discussed in Chapter 5) are treated as evidence and referenced in Chapter 7 to evaluate the environmental aspects. This chapter is combined with parts of the findings from previous chapters (Chapter 4-6) and provides a reference for the government's monitoring and evaluation of the EV development, and it addresses the issues identified in Chapter 4.

1.5 Intended contribution

This dissertation tries to provide a comprehensive analysis to help understand the process of the EV commercialization. As an emerging market, EVs have really only developed in the recent 20 years. Although the United States, Japan and Europe have all developed their national strategic plans to actively develop EVs (See Chapter 2), there is still lack of experience and lessons from the EV deployment process. China, as the largest vehicle manufacture and new vehicle market, has a history of EV

development over 20 years, and it has launched the strongest policy support and largest demonstration programs in the world. This dissertation details the case of the development of EVs in China not only through the timeline (from the past to the future), but also the geographic spatial scales (national level and local level). The impacts of the EV development process are also investigated through different perspectives (energy, environmental, industry, market and policy). Therefore, one of the main contributions of this dissertation is to give a comprehensive overview of the EV development process in China, and conclude the experience and lessons of EV deployment. The context and the methodological approach contribute evidence to provide the understanding of key factors and potential issues of the EV deployment process.

This dissertation tries to learn about the prospects for EVs, and to sketch out a clear and feasible roadmap for the future development. Although the EVs began to attract public attention in the last two decades, it is not new and has appeared several times in history, but disappeared in the market due to the lack of competitiveness (See

Chapter 2). In the current period, apart from the technological improvement of the EVs, the pressures from the energy saving and GHG emissions are the main drive for developing the EV. However, compared to the ICEV, the performance of the EVs still cannot fully meet the consumers' requirements, and this means that the support policies are needed for EVs to become more competitive. It is still uncertain whether EVs can succeed in the market in the nearly future, and how the support policies can help EVs achieve commercialization. This dissertation aims to find out the prospect of EVs through the current status and situations of the EV deployment, and find out whether the EVs can achieve successful this time or will disappear in the market again.

In addition, BEV, PHEV, HEV and FCV are all considered to be the major future options by governments and the automobile industry. However, there is still debated over which kind of technological routes may provide the best alternative that should be focused on； whether a certain kind of technology will replace ICEV in the future, or a variety of technologies will jointly divide up the automobile market. Through the study of the EVs in China, this dissertation is expected to investigate the different

potential of the different EV technologies, and give a clear roadmap for the EV deployment in China.

A comprehensive evaluation framework will be established to evaluate and monitor the process of EVs deployment. In order to accelerate the EV promotion, the governments and auto industry have launched a wide variety of policy instruments and demonstration programs. There are some studies focusing on the evaluation of the EV technology performance and the competitiveness of the EV industry. However, there is lack of study on evaluating the effectiveness of the EV promotion process. Although diversity of support policies is developed for the EV deployment, there is a lack of experience on how to effectively promote the deployment of EVs. Therefore, it is necessary and important to evaluate and monitor the progress of EVs promotion, to sum up experiences and shortcomings, and to adjust the policy instruments and plans based on the results of the evaluation. This dissertation develops an evaluation framework through the combination of qualitative research and quantitative research (See Chapter 3) to evaluate the effectiveness of the EV promotion progress. Although

this version of evaluation framework may still have some limitations, it is expected to provide a good basis and reference for the further development of the evaluation framework for EV deployment.

Chapter 2 Literature Review

This chapter reviews the relevant literature to introduce the research background and clarify the research gaps from the previous studies. To understand the previous status and issues of the EV development, this chapter begins with a brief review of the EV development history over the last 200 years to offer historical lessons for future EV promotion. The reasons for the EV's disappearance in the market have been analysed to provide experience and reference when focusing on the rise of electric vehicle development in recent years. This chapter then reviews the literature regarding EVs and EV batteries to give an overview of current EV technologies and the technological barriers for EV batteries. Through the review, the characteristics and limitations of the different EV types and batteries are introduced, and this helps to understand the current key issues of the EV and EV batteries from the technological aspect. This chapter also conducts an energy and environmental analysis of vehicle fuel pathways to show how the previous studies simulate the energy consumption and vehicle emissions through the different vehicle technologies and different fuel pathways. The gaps in the previous studies given China's specific power mix are discussed, and this

provides the research gap that can be focused on in this dissertation. This analysis forms the focus of the subsequent chapters. To understand the characteristics of China's auto industry, the chapter also reviews the industry's development history over the last 70 years. The current EV development status in developed countries is discussed, and this provides a comparison between China's EV development and a reference point for improving the effectiveness of China's current EV development strategy.

2.1 History of EV

The first ICEV (a gasoline powered three-wheeled vehicle) was designed and manufactured by German Karl Benz in 1886 (Lan and Huang, 2002), but in fact, the history of EV development is even earlier than the birth of the ICEV. Robert Anderson in Scotland developed the first prototype electric-powered carriage between 1832 and 1839; it was powered by non-rechargeable primary cells (Yong et al., 2015; Larmini and Lowry, 2012; Guarnieri, 2011a). At a similar time (mid-1840s), other lightweight electric vehicles also appeared in the US, the UK and the Netherlands.

Subsequently, electric vehicle development was stimulated by the developments of the direct current electric motor and the rechargeable battery between 1956 and 1981. Many researchers consider that the history of EVs could also be seen as the history of battery development (Wakefiels 1994; Westbrook, 2001; Anderson and Anderson, 2005; Yong et al., 2015). The Belgian Gaston Plante invented the first ground breaking rechargeable lead-acid battery in 1859. Then, an improved model was developed by Alphonse Faure in 1881 and used as a starter battery in all ICEVs and also as the power battery in most EVs in the following decades (Høyer, 2008; Guarnieri, 2011a). In the same year (1881), the first rechargeable battery-powered vehicle (a tricycle powered by lead-acid batteries) was invented by Gustave Trouve in France. Other similar electric tricycles with lead batteries were also demonstrated in both the UK and the US in the early 1880s (Høyer, 2008).

The most intensive period of EV development came then from 1880 to 1910, and many major technological breakthroughs were achieved in this period; many studies have considered this period the golden age of EV development (Westbrook, 2011;

Høyer, 2008; Anderson and Anderson 2005). Thomas Edison invented a more efficient battery-nickel-iron battery in 1901 that could store 40% more energy per weight unit than the lead battery (Høyer, 2008). The advanced zinc-air battery was also invented during this same period. In addition, Paul Pouchain made the first commercial EV in 1893, which could carry 6 passengers at 16km/h. The EV, named “La Jamais Contente” and driven by Camille Jenatzy in France in 1899, achieved the speed of 105.88km/h and is considered the first car to break the 100km/h barrier (Guarnieri, 2011b). Because of the technological advancements, EVs had been widely introduced into the market. For example, the first commercial EV in New York was introduced in 1897 as a taxi. Then, EVs became the favoured vehicle of choice, and in just 3 years accounted for 28% of the total road vehicles in 1900 (IEA, 2014; Yong et al., 2015). Between 1900-1910 or so, the electric car accounted for 38% of the US car market, with the steam vehicle accounting for 40% and the gasoline car for 22% (Guarnieri, 2011b).

Electric cars began to be challenged by ICEVs ever since the first gasoline ICEV was produced in 1886 (Yong et al., 2015). In fact, EVs were more competitive than ICEVs in

the early period because the gasoline car was considered to be “noisy, smelly, unreliable, fickle, vibrate heavily, had problematic gear change, and were dangerous to crank start” in the beginning. In contrast, EVs were considered silent, reliable, convenient to drive, easy to start and also exempt from gear changes. EVs’ disadvantages, however, were also seen to be as expensive, short driving range (30-60km) and low speed (24-32 km/h) (Guarnieri, 2011b). However, because of the technology improvements, ICEVs started to achieve greater reliability and comfort, and they gained an increasingly competitive advantage, especially on price. For example, in 1912, EVs in the US were priced at around US$1750 to $3000 against the gasoline Ford Model T price of US$650. In addition, ICEV prices further fell significantly after 1915 when Henry Ford introduced assembly lines (Guarnieri, 2011b). The large crude oil reserves found around the world caused the price of gasoline to fall, and this also resulted in the lower usage cost of ICEVs compared with EVs (Yong et al., 2015). The expansion of highways in the US required the EV technology to provide increased driving ranges. In 1896, the electric starter was first applied to a Benz car in England, and this solved the issues of the difficulty and

dangers of starting the engine. Because of all these factors, gasoline ICEVs developed dramatically, and were widely accepted by the market, whereas EVs gradually disappeared after 1920 (Guarnieri, 2011b; Yong et al., 2015, Høyer, 2008).

The disappearance of EVs from the market did not mean that they had disappeared from the public's mind. Because of concerns about the environment and the non-renewable energy consumption of ICEVs, EVs began to gain renewed attention during the 1960s. Midler and Beaume (2010) also observed that the re-emergence of EVs in the 1960s was caused by innovations in fuel cells and their potential to store energy for EVs. However, because of the lack of any technological breakthroughs, EVs were not successfully introduced into the market at that time. In addition, the increasing concerns of limited non-renewable resources and air pollution and also the lessons from the oil crisis in 1973 all combined to make EVs important in the 1970s and the early 1980s (Wakefield, 1994; Høyer, 2008; Yong et al., 2015). Since the 1990s, increasing attention has been focused on developing alternative fuel resources and technologies in the transport sector. For example, California launched the first zero-

emissions regulations in 1990, which then sparked electric vehicle development. The General Motors Company released the EV1 model in 1996. After this, the world's first commercial HEV, the Prius, was introduced by Toyota in Japan in 1997, and this car has become the world's best selling HEV. More than 18,000 Prius HEVs were sold in the first year of production (Yong et al., 2015). As the concerns over oil prices and climate change continued to increase, more and more automobile manufacturers released BEVs and PHEVs, such as the BMW i3/i8, the Mitsubishi i-MiEV, the Nissan Leaf, the Tesla Model S, the BYD e6/Qin, and the Chevrolet Volt.

EV technology is not new to the market—it has appeared a number of times in history—but it disappeared because of its lack of competitiveness compared with ICEVs. Today, the battery technology and EV technology have been improved, but some limitations such as driving range, charging time and cost still do not meet consumers' requirements. However, considering the rapid development of technology, support policies, and restrictions on traditional cars, EVs are considered to have the potential to be widely accepted in the future. Therefore, it is very valuable to

study whether EVs can now achieve successful commercialisation and gradually replace ICEVs based on the current development situations (including technology, industry, consumer behaviour and policy). This dissertation investigates how impact factors such as vehicle performance, infrastructure, cost and policy incentives might affect EV diffusion in terms of the current status and the potential future (Chapter 6). In addition, the effectiveness of the different policy incentives and instruments on EV penetration are also discussed in Chapters 4 and 7.

2.2 EV classification

There are different ways to classify EVs. In many studies, EVs have been divided into two main types based on their fuel, pure electric and hybrid electric vehicles. Pure electric vehicles are entirely powered by the battery and the electric motor, and HEVs are powered through a combination of an internal combustion engine and an electric motor (Harding 1999; O'Brien et al., 1997; Midler and Beaume, 2010). PHEVs, which use both an internal combustion engine and batteries is a type of HEV (Midler and Beaume, 2010). Another classification of electric vehicles considers fuel-cell vehicle to

be electric vehicles, and EVs have been divided into three categories: BEV, HEV and FCV (Åhman, 2006; Maggetto and Mierlo, 2001; Campanari et al., 2009). In recent years, as PHEVs have received increasing attention, they have come to be considered an independent category of EV. Yong et al. (2015) divided EVs into 3 types based on the vehicle hybridisation ratio: HEV, PHEV and BEV. Some studies also divide EVs, based on their electricity dependency, into two main types: plug-in vehicles that use a wall outlet to charge from the grid system (BEVs and PHEVs) and grid-independent vehicles that do not use electricity from the grid, such as traditional HEVs and FCVs (Gnann and Plötz, 2015). Based on all of these classifications, this research divides EVs into four classes: pure battery electric vehicles (BEVs), hybrid electric (grid-independent) vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell vehicles (FCVs). This study focuses mainly on BEVs and PHEVs.

2.2.1 Hybrid electric vehicle

An HEV is defined as a vehicle that has two or more major sources of propulsion power. Normally, HEVs are considered to combine an internal combustion engine and

one or more electric motors (Campanari et al., 2009; Schell et al., 2005). The main feature of HEVs is the reversible energy storage system (Guardiola et al., 2014). The motor in HEVs can perform as a generator when the vehicle is slowing down or braking, and the regenerate braking energy is converted into electrical energy during this process. The battery can be recharged by the reversible energy, which brings a significant benefit to the fuel economy of HEVs (Moreno et al., 2006; Guardiola et al., 2014). Based on the topology, HEVs can be further divided into two basic configurations: series and parallel (Muñoz-Aguilar et al., 2013). Series HEVs are entirely driven by an electric motor. In contrast, the parallel hybrid power train is one with two separate power sources that can directly drive the vehicle's wheels, which would normally be driven by either the internal combustion engine or the electric motor (Hutchinson et al., 2014). In addition, there is an advanced configuration of HEV called a series-parallel hybrid electric vehicle that combines both the series and parallel modes. It contains two motors, a complex transmission system, and an intelligent control system that can work in either the series or the parallel mode. By combining the advantages of series and parallel configurations, the series-parallel

mode is considered to make engines, motors and other components match optimally and to achieve more emissions reduction and energy savings (EV project group, 2008).

Since the release of the first commercial HEV, the Prius, in 1997, the majority of global automobile manufacturers have introduced hybrid electric models. For example, Honda introduced its Insight in the US market in 1999 and then released the Civic Hybrid in 2002. General Motor (GM) introduced two hybrid SUV models named Sature VUE and Chevrolet Equinox in 2005 and 2006, respectively, and then further launched the mid-class HEV Chevrolet Malibu in 2007. Ford introduced the Hybrid SUV “Escape” in 2005, and the Mercedes S-class HEV was released by Mercedes-Benz in 2006(EV project group, 2008). The market share of HEV in the US passenger car market has grown from 0% in 1997 to 3.2% in 2012, where the sales of Prius accounted for almost 70% of the hybrid passenger car sales in 2012 (Hutchinson et al., 2014). The fuel economy of the HEV is about 48% more efficient than the fuel economy of the ICEV (Elgowainy, 2010), which effectively reduces the oil consumption and the CO_2 emissions. However, because of the combined power system (ICE and

electric motor), the cost of HEV is higher than the ICEV. For example, the conventional ICEV Toyota Corolla is around 15,300 USD, while the Toyota Prius is sold around 20,000 USD (Granovskii et al., 2006). In addition, two power systems also add to the weight of the car, and this reduces the overall energy efficiency of the vehicle (Tomas, 2009).

2.2.2 Battery electric vehicle

The major source of propulsion power of the battery electric vehicle (BEV) (also called pure electric vehicle) is only provided by electricity (batteries). The power-train system of the BEV consists of batteries for energy storage and supply, and an electric motor to drive the wheels. Because of the diversification of primary energy generation, the BEV can use many sources of energy, such as hydropower, nuclear power and other clean power. The significant advantages of the BEV are considered to be the high energy efficiency and zero emissions during operation process, making the BEV suitable for personal mobility in urban areas (Rangaraju et al., 2015). The fuel economy of the BEV can achieve 280% more efficient than the one of the ICEV

(Elgowainy, 2010). In addition to the energy efficiency and emissions, low noise levels, low fuel costs, and the multiple energy resources available are also considered as the advantages of the BEV. Furthermore, as with the HEV, the regenerative braking system is also applied in the BEV to recoup energy (Wai et al., 2015).

However, there are also many limitations for the BEV to be widely accepted by the market. Although there are no emissions from the operation process, BEV has a substantial amount of emissions from the fuel generation and vehicle manufacturing process (Rangaraju, 2015). In addition, the high cost, limited driving range, long charging time and lack of charging infrastructures are considered as the 4 main disadvantages from consumers' point of view (Hayes et al., 2011; Wai et al., 2015). The cost, driving range and charging time can all be related to the performance of the batteries. Through adding more battery packs into the vehicle can help the vehicle to achieve the longer driving range, but the bulky and heavy battery packs will result in more energy consumption. In addition, the cost of the vehicle would rise dramatically. Technological breakthrough of the battery is considered as key to the success of the

BEV. Currently, there are some automotive manufacturers have already introduced some commercial BEV models, such as BYD e6, Tesla Model S, BMW i3 and i8.

2.3 Plug-in hybrid electric vehicle

The components and vehicle architecture of the PHEV is similar to the conventional HEV (Amjad et al., 2010; Bradley and Frank, 2009). The PHEV is a hybrid vehicle powered by both an ICE and a battery that can be recharged by plugging it into the power grid (Srivastava et al., 2010), which can replace a substantial fraction of the fuel to the grid electricity (Bradley and Frank, 2009; Galus et al., 2010; Björnsson and Karlsson, 2015). The PHEV is considered to combine the strength of both the BEV and the HEV, as it can use the electricity from the grid to achieve a diversification of energy resources. It can also avoid the problems caused by the BEV such as the short range of the vehicle and the lack of charging infrastructure. In the PHEV, there is a smaller battery than the BEV to supply a certain share of the driving distance between recharging, while an ICE can provide alternative power to extend the range when the battery is out of power (Björnsson and Karlsson, 2015). Therefore, there are two main

modes for the PHEV operation. One is the pure charge-depleting (CD) mode where the battery is supposed to provide the energy to propel the vehicle, and the battery state of charge (SOC) that is controlled to continually decrease during the vehicle operation(Bradley and Frank, 2009；Björnsson and Karlsson, 2015). Normally, the electricity is considered to be the only power in the CD model, which is further identified as “electric vehicle mode” (Bradley and Frank, 2009). The all-electric range (AER) presents the maximum possible range of the battery driven in CD model. However, some PHEV models also use a blended CD mode which uses liquid fuel and electricity for propulsion at the same time (such as the Prius PHEV) (Björnsson and Karlsson, 2015). When the energy of the battery is consumed for the long distances, the driving mode of the PHEV can turn into the charge-sustaining (CS) hybrid mode, which is the mode that the conventional HEV operates most of the time (Amjad et al., 2010; Bradley and Frank, 2009). In this mode, the battery state of charge is not changed by time, and the fuel is the only energy source to apply the power to the vehicle.

The PHEV provides high performance and fuel efficiency in both electric and hybrid model, and it is considered as a good option to shift energy consumption from fossil fuel to electricity using the existing infrastructures. It can offer most of the environmental and energy benefits of the BEV combined with the advantages of the ICEV. (Srivastava et al., 2010; Amjad et al., 2010). According to Srivastava et al., (2010), the PHEV can reduce at least 70% of the liquid fuel consumption compared to the ICEV. From the consumer's perspective, the PHEV also can achieve large saving on the fuel cost without the range limitations of the BEV (Krupa et al., 2014). The PHEV received more and more attention in the recent years; many auto-manufacturers have also introduced some commercial PHEV models. China's BYD F3DM became the first commercial PHEV in 2008, and available to the general pubic in 2010(Srivastava et al., 2010); Then General Motors (GM) also introduced the Chevrolet Volt PHEV in 2010,which has 56km AER. Toyota also added the vehicle to grid capability to their original Prius, and released the PHEV Prius in 2012. Many other PHEV models are introduced to the market in the recent years, such as BYD Qin, Audi A3 e-tron, Volkswagen Golf GTE, and BMW 5 Series PHEVs.

2.3.1 Fuel cell vehicle

A fuel cell is defined as an electrochemical device in which the chemical energy is converted into electricity (Campanari et al., 2009). Instead of the rechargeable battery in a BEV, the main power of the fuel-cell vehicle is provided by the proton exchange membrane (PEM) fuel cells, which utilises a solid polymer electrolyte membrane. The fuel cell electric vehicle is considered to be more suitable for automotive applications in lower temperature operations [Schell, et.al, 2005]. The typical topology of the FCV always contains at least two power systems: a fuel cell system that provides stationary power and an energy storage system (battery or super capacitor) to deliver dynamic power (Xu et al., 2015). Hydrogen is considered an environmentally “green” fuel with zero emissions, and the only output is pure water (Xu et al., 2015). However, there is a premise here that the hydrogen used in the fuel cell should be generated by electrolysis using renewable energy (López Cascales et al., 2015). Compared with BEVs, FCVs can provide sufficient range, but there are energy losses during the generation of hydrogen followed by an energy demand for compression and

distribution. In addition, although FCVs have huge potential for energy savings and emissions reduction, there are still many barriers to its applications, such as high cost, fuel-cell safety, production, and hydrogen storage and transportation (Liu and Liu, 2015).

FCVs are still considered far from the market, conceptually even further away than BEVs, HEVs and PHEVs (Cipollone et al., 2014). However, many studies find FCVs to be similar to BEVs in that they are both good choices for the mobility fuel transition in the future (Xu et al., 2015; López Cascales et al., 2015; Larsson et al., 2015). “Battery electric and hydrogen fuel cell vehicles should not be regarded as antagonistic, either/or options but that both should be pursued and supported” (Offer et al., 2010; 2011). The first FCV was introduced by Honda in the US in 2002; it was a four-seat vehicle with 150km/h speed and a 270km driving range (Lowry and Larminie, 2012). Toyota introduced its latest commercial FCV, the “Mirai”, in December 2014. According to the news by Xinhua net (2015), Toyota received 1500 orders for its FCV in Japan in January 2015 (after officially having been listed for sale for only one

month).

This section introduced the four main EVs that are cover feasible EV types and that have already been tested in the vehicle market. However, because grid-independent HEVs still use gasoline or diesel as their only power source, it is considered a good technology option to increase the fuel efficiency of traditional gasoline vehicles, but not an innovative alternative fuel vehicle that can use a variety of other energy sources (especially clean power) rather than oil. Therefore, the HEV is considered as a providing a fuel-efficient vehicle that can help to achieve the energy saving and emissions reduction. However, for the long-term future, the government is looking for an alternative vehicle that moves from the oil-based fuel into the other clean energy resources. The BEV and PHEV use electricity power and they are considered to have more potential for the future development. FCVs are also good potential AFVs because they have high fuel efficiency and environmentally friendly performance. However, the fuel-cell technology is considered immature because there are still technical and security issues regarding the hydrogen production, transportation, and

storage. There are few practical examples of FCVs because they have not been commercialised to public consumers by the major vehicle manufacturers (except for Toyota). Therefore, in this dissertation, the FCV is only considered as a potential EV technology in the future. The focus here is the development status and future of the BEV and the PHEV, which not only have good potential in solving energy and environmental issues, but also already have begun their commercialization process.

2.4 EV energy storage technologies

The battery is the most important component in EVs because it determines the costs and driving performance, especially for BEVs and PHEVs (Pan, 2004; Taniguchi, 2001; Huth, 2015). Battery technology is considered to be the main technological constraint to the commercialisation of EVs (Egbue and Long, 2012). In order to satisfy consumer demand, EV driving performance must catch up with and overtake ICEV performance at no additional cost (Moseley, 1999). However, current battery technology levels still cannot meet consumers' requirements; the high cost of the battery is considered to be the most important hindrance to EV promotion (Delucchi, 2001; Egbue and Long,

2012). A study by Delucchi (2001) on the life cycle costs of BEVs compared with ICEVs showed that the battery is the most expensive component in the BEV life cycle. According to the IEA (2013), EV batteries are responsible for 50% of total EV costs. In addition to the cost, other battery characteristics also directly affect EV performance such as power storage, life cycle, power density, self-discharge rate and operating temperature range (Nelson, 2000). Similarly, Axsen et al. (2010) concluded that the limitations of the battery technology are caused by the trade-offs between five major attributes: cost, power, energy, longevity and safety. Among these, power storage and energy density are the two main indicators that determine the range and mass of the battery, respectively. In addition, battery maintenance, environmental impacts and recyclability are also considered important for EV production (Jiang and Tan, 2009). Based on the different emerging materials, processes and technologies, a number of different energy storage technologies have been used in EVs.

2.4.1 Lead-acid batteries

Lead-acid batteries use lead dioxide for the positive electrode and spongy matallic

lead for the negative electrode, and these are “separated by a micro-porous material and immersed in an aqueous sulfuric acid electrolyte” (Divya and Østergaard, 2009). Lead-acid battery development has been on-going for more than 100 years; the first rechargeable lead-acid battery was invented in 1890 in France (Sun et al., 2002; Malcolm, 2011). Lead-acid batteries have been widely used in the auto industry as providing the energy to start the ICEV (Sun et al., 2002). In addition, the lead-acid battery has also been considered a candidate battery for EV use since it was introduced (Høyer, 2008; Guarnieri, 2011a). Gross (1976) conducted a review of the candidate EV batteries at that time and proposed alternatives such as lead-acid batteries, nickel-iron batteries and nickel-hydrogen batteries, all of which are suitable for EV use. Among these, lead-acid battery performance is the best, and it has been expected that these batteries will continue to dominate in the near future. Through technology improvements, some significant advantages of using lead-acid batteries in EVs have been reported, including low cost (materials and manufacturing), high current capability, good reliability, and wide operating temperature range (Mou and Tang, 2009; Sun et al., 2002). The low cost of raw materials and production are

considered to be the most significant advantage, meaning that lead-acid batteries have the potential to be widely applied (Sun et al., 2002).

However, there are also drawbacks to using lead-acid batteries in EVs that were summarised by Rand (1979) as follows: low energy density, short life cycle, long recharging time and high maintenance requirements. Among these, the low energy density and short life cycle are the major drawbacks that limited the application of lead-acid batteries in Evs (Mou and Tang 2009). According to Tie and Tan (2013), the current lead-acid specific energy is between roughly 35Wh/kg to 45 Wh/kg, and the energy density is 100 Wh/L or so. The life cycle of lead-acid batteries is limited to 700 cycles, which also depends on the depth of the charge (Lory and Larminie, 2012). The valve-regulated lead-acid (VRLA) battery that was developed at the beginning of the 1990s (Moseley and Cooper, 1999) has achieved better performance than the traditional lead-acid battery. VRLA batteries are still low cost, but they have a longer life cycle and higher specific energy (50Wh/kg) (Tie and Tan, 2013; Nelson, 2000). VRLA batteries are capable of providing EVs with a 160km driving range in one charge

(Moseley and Cooper, 1999), and they have been demonstrated to provide good safety and reliability during operation (Gerssen-Gondelach and Faaij, 2012).

However, this driving range still cannot meet the requirements of BEVs. Lead-acid batteries are considered more suitable for use in HEVs (Nelson, 2000) and also some low-speed BEVs such as sanitation vehicles, postal vehicles and golf carts. Lead-acid batteries are also used in some commercial low-speed BEVs; the Cherry QQ3 EV is a good representative in China of a BEV that uses a lead-acid battery. It is a small BEV that can achieve a 100km driving range at the eco-driving speed (20km/h to 40km/h). Although it has limited driving range and low speed, the sales of the QQ3 EV reached 3129 in 2012, which was mainly attributed to its low price (50000 CNY (5,200 GBP))[1] (CATARC et al., 2013). However, it is difficult to achieve a fast charge in lead-acid batteries, and it may result in pollution during production and disposal (Tie and Tan, 2013), and this requires a highly developed battery recycling system (CATARC et al., 2013). Because of these limitations, lead-acid batteries and their lack of potential for

[1] Exchange rate used in this dissertation is 1GBP = 9.6 CNY

enhancement indicate that there is still debate on whether lead-acid BEVs should be developed in China. Currently, lead-acid EVs are not eligible for China's EV subsidies (CATARC et al., 2013).

2.4.2 Nickel-cadmium batteries

Nickel-cadmium batteries comprise a positive electrode of nickel oxyhydroxide and a negative electrode of metallic cadmium (Lory and Larminie, 2012). Compared with lead-acid batteries, nickel-cadmium batteries can be fast–charged, and they also have a much longer life cycle. A nickel-cadmium battery can achieve more than 1000 cycles, more than twice that of lead-acid batteries (Lory and Larminie, 2012; Nelson, 2000; Sun et al., 2002). In addition, nickel-cadmium batteries also have high specific power, a wide range of operation temperatures (-40°to +80°C) and low self-discharge. Because of these advantages, these batteries been considered good candidates for EVs, and they have already been used in some EVs, such as the Peugeot 106 electric version, Citroen AX EV and Renault Clio (Lory and Larminie, 2012).

However, there are still two main drawbacks of nickel-cadmium batteries for use in EVs. First, because of limited resources, the material cost of cadmium is several times than that of lead. In addition, the operation voltage of nickel-cadmium cells is low, which results in their requiring 10 cells in a nominally 12V battery compared with the 6 cells in lead-acid batteries. Therefore, the total cost of nickel-cadmium batteries is high (three times the cost of lead-acid batteries), which restricts their extensive use ((Gross, 1976; Lory and Larminie, 2012). Second, cadmium, as a heavy metal, is considered less environmentally friendly for wide use because it can cause serious harm to the environment and public health (Nelson, 2000; Sun et al., 2002; Zhang, 2010)

2.4.3 Nickel Metal-Hydride (Ni-MH) batteries

Ni-MH batteries were introduced commercially in the late 1980s and proposed as a competitor to lead-acid and nickel-cadmium batteries (Nelson, 2000). Ni-MH batteries perform similarly to nickel-cadmium battery (Nelson, 2000; Mou and Tang 2009; Lory and Larmine, 2012). The main difference with Ni-MH batteries is that they use

hydrogen absorbed in a metal-hydride for the negative electrode instead of cadmium. The Ni-MH cell is considered to have somewhat better performance than the nickel-cadmium battery in terms of specific energy and energy density (Nelson, 2000; Lory and Larmine, 2012). In addition, Ni-MH batteries charge more quickly than nickel-cadmium batteries (Lory and Larmine, 2012), and they also have fewer environmental hazards because of the absence of heavy metal cadmium (Mou and Tang, 2009). The specific energy of NiMH batteries is approximately 60-70 Wh/kg. However, Gerssen-Gondelach and Faaij (2012) commented that the specific energy of NiMH batteries is still far below the specific energy demanded for BEVs (150-200 Wh/kg). Because of the high nickel cost and the higher share of nickel in NiMH batteries, the cost of NiMH batteries is even higher than that of nickel-cadmium batteries. The cost of the standard cell in a Ni-MH battery is nearly twice that of a nickel-cadmium cell (Nelson, 2000). In addition to the high cost, the high self-discharge rate (Up to 5% per day) is considered another shortcoming that hinders Ni-MH batteries from being used in BEVs (Lory and Larmine, 2012). Combining these features, Ni-MH batteries are considered attractive candidates for HEVs, and they are widely used in HEVs today

such as the Toyota Prius, Honda Insight and Ford Escape Hybrid. The first commercial HEV, the Prius, which was introduced by Toyota, was powered with an Ni-MH battery pack (Giddord et al., 1999), and Toyota also announced in 2009 that they would use Ni-MH batteries in most of their HEVs after they had tested other alternatives (Lory and Larmine, 2012).

2.4.4 Lithium-ion batteries

Lithium-ion batteries are part of a family of rechargeable batteries with a cathode and an anode; lithium ions move between the anode and cathode to create a flow of electricity during discharge (Lory and Larmine, 2012; Divya and Østergaard, 2009). Because of the different cathode materials, there are different lithium-ion batteries with varying strengths and weaknesses (Gerssen-Gondelach and Faaij, 2012). Compared with other battery technology, the lithium-ion battery is the most promising energy storage technology for EVs, and it comprise the largest share of commercial BEV batteries today (Gerssen-Gondelach and Faaij, 2012; Diouf and Pode, 2015; Tie and Tan, 2013). These characteristics are mainly attributable to the

batteries' high specific energy, high specific power and high energy density, which make them much lighter and smaller than other batteries with the same energy storage capacity (Diouf and Pode, 2015; Tie and Tan, 2013).

The energy density of lithium-ion batteries is twice than that of Ni-MH batteries and 3 times higher than that of lead-acid batteries (Sun et al., 2002). In addition, different from other rechargeable batteries, lithium-ion batteries have no memory effect and a relatively long life cycle, and lithium-ion would not cause any additional environmental problems because it does not contain any poisonous metals such as lead or cadmium (Tie and Tan, 2013; Diouf and Pode, 2015). However, the cost of lithium-ion batteries is higher than that of nickel-cadmium and Ni-MH batteries, which is considered to be the main barrier to promoting lithium-ion batteries in the EV market (Lory and Larmine, 2012; Divya and Østergaard, 2009; Matteson and Williams, 2015). Lithium-ion battery can cost as much as 8 times the cost of lead-acid batteries and 4 times that of Ni-MH batteries. However, the cost of lithium-ion EV batteries is expected to drop significantly, which is attributable to market growth and

production scales stemming from the high demand for lithium-ion batteries in other electronics sectors (Diouf and Pode, 2015; Lory and Larmine, 2012).

Currently, most major automobile makers use lithium-ion batteries in their modern EVs, such as the Nissan Leaf, Tesla Model S, Mitsubishi MiEV, Chevy Volt and BYD e6. However, there is still concern about the safety of lithium-ion batteries. Because of the flammability of the material they use, lithium-ion battery malfunction can lead to fire risk and explosion (Nelson, 2000; Mou and Tang, 2009; Sun et al., 2002; Yong et al., 2015). The current lithium-ion battery technology is still not mature, but it is considered to have the potential to be improved and to satisfy the requirements for EV application (Yong et al., 2015).

Table 2-1 Comparison between different battery technologies

	Lead-acid	Nickel-cadmium	Ni-MH	Li-ion
Specific energy (Wh/kg)	30-45/50 (VRLA)	60-80	60-100	150-200
Cycle life (80% discharge)	200-300/700 (VRLA)	1000-1200	300-1000	500-2000
Operation temperature	-20 to +50 (℃)	-40 to +80 (℃)		-20 to +60 (℃)

Self-discharge	2% per day (normal)	0.5% per day (good)	Up to 5% per day (poor)	0.2-0.3 % per day (very good)
Cost	Low	High	Very high	Very high
Recharging time	Poor	Good	Good	Good
Safety	Very good	Good	Good	Normal
Toxicity	Very high	Very high	Low	Low
Current use in EV	Low-speed EV (Cherry QQ3 EV)		HEV (Toyota Prius, Honda Insight and Ford Escape Hybrid)	BEV and PHEV (Nissan Leaf, Tesla Model S, Mitsubishi MiEV, Chevy Volt and BYD e6)

Source from Lory and Larmine (2012); Gerssen-Gondelach and Faaij (2012); Diouf and Pode (2015)

Table 2-1 has summarised the main features between different battery technologies. Based on the review of the current EV batteries, a number of important indicators including life cycle, cost, operation temperature range, specific energy and energy density mainly determine battery performance. It can be seen different batteries have different performance characteristics, and there is no battery that can achieve good performance in all these major indicators. Among these four battery technologies, Li-ion battery has good performance on most of these indicators, and

this explained why Li-ion batteries are widely used in the BEVs and PHEVs globally. This dissertation discusses how a range ofEV performance factors will affect EV deployment in China, and how the EV market share might change if battery performance achieves a breakthrough in performance and costs in the future (Chapter 6).

2.5 Assessment of vehicles on energy and environmental impacts

As stated in Research Question 2, this dissertation investigates EV performance energy saving and CO_2 emissions reduction. In order to address this question, measures for evaluating the vehicles' energy consumption and emissions need to be understood. Assessing the energy and environmental impacts of vehicles is very important in the policy decision-making process (Domingues et al., 2015). Evaluating the energy consumption and environmental impacts of vehicles requires consideration of their complete life cycle. Because substantial energy consumption and environmental burdens are generated not only by use in th vehicle but also in the production process and fuel supply chain (Bauer et al., 2015; Egede et al., 2015). The

distribution of the energy consumption and emissions will be very different depending on the power train technologies and fuel production pathways (Bauer et al., 2015). Therefore, alternative fuel vehicles show their potential in energy saving and GHG emission reduction, but this potential must take into account the impacts over all stages of the vehicle life cycle, from the raw material extraction to the end of life (Zhang and Huang, 2005; Bauer et al., 2015; Domingues et al., 2015; Egede et al., 2015). For this reason, a comprehensive life cycle assessment (LCA) of a wide range of current and future vehicle technologies and alternative fuels has been simulated over the last two decades in a series of studies. The review of the LCA studies on the vehicle and alternative fuels has provided an overview of research directions of the existing LCA, and their characters in the different time periods. The gaps and findings of the existing studies in other countries have also provided a comparison to be contrasted with the experience in China (introducing in next section).

Period: 1990-1995

During 1991-1993, Delucchi (1991, 1993), who worked at the University of California,

Davis, completed the first evaluation research on a variety of transportation fuels and electricity production fuel cycle emissions. The pollutants he studied included carbon monoxide, methane, nitrous oxide (N_2O), nitrogen oxides (NO_x), and nonmethane organic gas. Focusing not only on the energy consumption and emissions in the fuel production process, Delucchi also considered the energy consumption and emissions that resulted from more extensive processes such as vehicle manufacturing, constructing an energy infrastructure and so on. Through subsequent research, this research model and databases were constantly improved, and Delucchi finally introduced the LEM (lifecycle emission model) in 2003 (Delucchi, 1997; Delucchi and Lipman, 2003; Zhang et al., 2008). According to Wang (1999), the developer of the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model, Delucchi's model theory had provided a basis on the development of GREET.

During the same period in Europe, scientists at Sweden's research centre (Ecotraffic) studied the fuel cycle emissions and primary energy consumption of the different transportation fuels (Ecotraffic, 1992). The research mainly focused on the fuel paths

based on natural gas and renewable energy, and included studies on cars, medium-duty trucks, and buses, and this was considered to have a wider scope than that other studies during that period (Ecotraffic, 1992; Zhang et al., 2008). Because the main sources of electricity in Sweden are hydro and nuclear power, the study results showed that using pure electric vehicles in this region is very helpful in reducing the urban air pollution and carbon dioxide emissions and that using renewable fuel lines can also achieve a more than 50% reduction in greenhouse gas emissions.

In order to determine the possibility of promoting high-proportion and low-proportion options in America, with the assistance of the Oak Ridge National Laboratory and the Pacific Northwest National Laboratory, the American National Renewable Energy Laboratory (NREL) conducted a full life cycle analysis of the E10 ethanol (low-proportion ethanol fuel: 10% ethanol and 90% gasoline) and E95 ethanol (high-proportion ethanol fuel: 95% ethanol and 5% gasoline) paths. This study used U.S. reformulated gasoline as a baseline, and the results showed that the ethanol fuel pathway can significantly reduce emissions (NREL, 1991, 1992). However, Zhang et al.

(2008) thought that the researchers in this study had very optimistic assumptions about the efficiency of future ethanol production.

Period 1996-2000

Because of the promising advantages of biofuels, some researchers began to focus on the biofuels that are currently used for transportation. Kaltschmitt et al. (1997) studied the life cycle analysis of biofuels under different environmental conditions in Germany in 1997. Their study chose sugar beet, wheat, and potatoes as the feedstock and compared bio-based systems, including cultivating and harvesting the raw materials through energy use to fossil systems, including mining and processing the raw materials through energy use. Their study showed some clear ecological advantages of bio-ethanol over fossil fuels, such as conserving fossil energy sources and reducing global warming potential, but bio-ethanol also has some definite disadvantages, such as high cost and low energy efficacy; in particular, N_2O and NO_X emissions are higher than the conventional fuels.

It is worth noting that the studies during this and the previous period purported to be only life-cycle-based and only concerned with energy and the environment. Cost analyses were not part of their main focus (Blottnitz and Curran, 2007). In order to provide an economic analysis of vehicle fuel life cycle, in 1998, Walter (1998) incorporated an economic, environment and energy (EEE) analysis into the LCA method and used this new method to study the actual life cycles of 7 different raw materials (renewable and non-renewable) for use in alternative motor fuel. In addition, according to Weiss et al. (2000), researchers from the Massachusetts Institute of Technology also added a cost analysis into what was called well-to-wheel (WTW) analysis and predicted and evaluated energy consumption, GHG emissions, and cost for the American alternative vehicle fuel pathway in 2020.

Also in this period, according to Li (2006), America's Argonne National Lab (ANL) began to develop a model, based on a spreadsheet, that could be used to assess the energy efficiency and emissions of the entire fuel cycle for alternative fuels and advanced vehicle technology. Soon, a model known as GREET was developed by the

Department of Energy (DoE) and ANL (Wang, 1999). It allowed researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis. (Li, 2006; Wang, 1999). Since then, the model has been continuously improved and widely appilied.

Period: 2001-2005

In 2001, ANL released version 1.6 of the GREET model software in which WTW was used to replace the previous fuel cycle concept (Wang, 2001). Zhang et.al (2008) considered that this change marked the maturity of the methods and models of WTW study. WTW as an effective fuel cycle analysis method has been proposed and widely used (Zhou et al., 2010; Song et al., 2008) (Wei et al., 2006; Torchio and Santarelli, 2010). It has been defined as the analysis of "a vehicle/fuel system covers all stages of the fuel cycle—from energy feedstock recovery (wells) to energy delivered at vehicle wheels (wheels)" (Torchio and Santarelli, 2010). WTW can be further divided into two stages: well-to-tank (WTT) and tank-to-wheels (TTW) (Zhou et al., 2010; Torchio and Santarelli, 2010; Song et al., 2008; Wang, 2002).

In support of General Motors and the three major oil companies (BP, ExxonMobil, Shell), ANL researched the greenhouse gas emissions analysis of alternative fuel vehicles in North America. The study chose the car as the research object, and the research result comprised 3 kinds of greenhouse gas emissions, oil consumption, fossil energy consumption and total energy consumption (Wang et al., 2001; Li, 2006; Zhang et al., 2008). In 2000, General Motors once again united the four oil companies (BP, ExxonMobil, Shell and Total Fina Elf) to support the German LSBT laboratory to study the WTW analysis of alternative vehicle fuel energy consumption and greenhouse gas emissions in the EU (Zhang et al., 2008). According to Choudhury et al. (2002), the research result of this study included 3 kinds of greenhouse gas emissions, oil consumption, fossil energy consumption and total energy consumption. In 2003, a research update was presented based on this study (Li, 2006).

In this period, hydrogen pathways and their use in proton exchange membrane fuel cell-based power trains received wide attention, and they were compared with other

fuels and power trains. Wang (2002) studied the impact of a fuel cell vehicle using the GREET model and evaluated the WTW for both energy and emissions. In addition, Hekkert et al. (2005) used the WTW of alternative fuel energy efficiency and CO_2 emissions to analyse replacing crude oil with natural gas. In their research, they compared 15 different technology options both traditional and new, and the study results indicated that fuel cells with compressed hydrogen (produced by steam reforming natural gas) led to the highest GHG reduction, and this was up to 40% less compared with current practices at the time. In addition, the fuel cells with compressed hydrogen were also considered to be among the most energy efficient; however, in the case of liquefied hydrogen, the GHG emissions rose dramatically. The hybrid internal combustion engine (ICE hybrid) fed by diesel also showed good performance in the results of this study: “it took first place for WTW efficiency and second place for GHG reductions” (Hekkert et al., 2005).

In addition, adding the cost analyses into LCA led to significant growth in the studies during this period; Gregory (2001) considered that economic analysis should be

added into LCA and used to give more information to and recommendations for product planning and development. In addition, Mizsey and Newson (2001) compared five power train and fuel combinations in their study considering WTW efficiency, GHG emissions and investment costs. The result of this research showed that the best efficiency was obtained for the ICE hybrid fed with diesel, whereas the best WTW GHG emissions rate was obtained for the fuel cell that operated with compressed hydrogen, which was produced at a centralised plant; the lowest investment costs were obtained for the ICE, and the on-board fuel-reformer solutions offered poor results in all aspects. Furthermore, in 2003, Conservation of Clean Air and Water in Europe, European Council for Automotive R&D and European Commission's Joint Research Centre jointly researched the WTW analysis of alternative vehicle fuel pathways in the EU (Edwards et al., 2004). This study introduced cost analysis into WTW analysis, completed a comprehensive analysis of fuel life cycle EEE, and calculated the WTW abatement costs of different pathways (Edwards et al., 2004; Zhang et al., 2008). It should be noted that in all of these projects after 2000, the concerned objectives were turning from the urban pollutant emission of the

alternative fuel path to greenhouse gas emissions and energy economy (Zhang et al., 2008). This demonstrates that the capacity to save energy and reduce greenhouse gas emissions had already become the focus of comparing the different fuel pathways.

2006-2010

In this period, the concerns regarding GHG emissions and energy economy are still high. Zhang et al. (2008) developed WTW cost analysis model in China. In their studies, fuel production and distribution costs were calculated using the technical and economic approach in the WTT phase; in the TTW phase, Zhang et al. (2008) introduced the concept of “ownership cost”, which reflects the total cost paid by car owners throughout the entire ownership “from purchase to disposal”. It included vehicle retail cost and fuel and maintenance costs. In addition, in 2010, Torchio et al. (2010) compared the EEE of different power train and fuel options using WTW assessment, energy and external costs based on the European market. The research established a global index, which was a useful tool for decision makers.

Wei et al. (2006) considered that although LCA was more systematic and comprehensive than other methods of assessing the environmental impact of energy use, it could not accurately evaluate the different environmental effects of alternative energy fuels. Because of the particularity of vehicle operating environment, in the study that compared alternative fuel vehicles, the equivalent emissions at different WTW stages caused very different level of environment damage (Wei et al., 2006). For example, the emissions emitted from the factories (production process) are easier to be controlled than the emission from the vehicle operation process. Therefore, based on the vehicle fuel life cycle assessment, this research proposed weight coefficients in different phases based on the marginal environmental damage cost and improved the analysis of the LCA of vehicle fuel, which could be "adapted to apply comparative analysis between different environmental impacts of different vehicle alternative fuels" (Wei et al., 2006). The result of this study demonstrated the value of this point of view. For example, in the empirical analysis, only considering the total pollutant life cycle emissions, the result showed that fuel vehicles were better than fuel-cell vehicles in sulphur oxide (SO_x) emissions; however, considering the environmental

damage caused by the pollutants, SO_x from hydrogen fuel was entirely generated during energy exploitation and preparation, and it achieved zero emissions in fuel use. Therefore, considering the actual environmental effects caused by SOx emissions, fuel cell vehicle performance exceeds that of gasoline vehicles (Wei et al., 2006).

In addition, in the last few years, increasing interest in biofuels has been observed because of their promising advantages: GHG reduction, renewability, fuel diversification, etc. An outlook on world biofuels was proposed by the IEA (2006), and an IEA report (2008) analysed the current and future developments in biofuel technology. With regard to the automotive sector, some very interesting features can be observed: the possibility of using traditional ICEs with little or no engine modification and the possibility of using the same distribution infrastructure as that for traditional fuels. However, according to the IEA (2008), the sustainability of the 1st generation biofuels is under review, and, at present, they are often an expensive option if the total production costs are taken into account excluding government grants and subsidies. In addition, Agarwal (2007) reviewed the current status of

biofuels for the transportation sector, in particular bio-ethanol and bio-diesel. The main factors analysed were the modifications required for existing engines (material compatibility, engine performance), environmental compatibility and costs (both investment cost for infrastructure and additional costs for the vehicle).

In 2008, Campanari et al. (2009) studied a specific energy analysis of electric vehicles that used batteries or fuel cells through WTW simulations. The result of this research showed that the performance of the different electric vehicles and fuel cycle pathways were seriously affected by existing energy sources. In addition, the study also found that although biofuel had lower carbon dioxide emissions, it showed very low efficiency over the full WTW analysis. Similarly, Bouvart and Prieur (2009) studied the comparison of life-cycle GHG emissions and energy consumption of combined electricity and hydrogen production pathways with carbon dioxide, capture and geological storage (CCS). The result showed that "CCS leads to significant GHG emissions reduction on the whole studied pathways of electricity and H_2 production", but this technology results in significant additional energy consumption because of

the CO_2 capture processes. “CCS technology thus meets the GHG reduction objective but goes against the optimisation of available fossil energy resource uses.” A similar study was also conducted by Ou et al. (2010) that analysed the impact of CCS in the life cycle GHG of coal-based fuel. The result of this research showed that using CCS could make the BEV achieve more CO_2 reductions compared to other vehicle technologies.

2010-2015

Through the technological improvements and their wide acceptance by the auto industry, BEVs and PHEVs have become the main focus in most of the LCA studies (Huo et al., 2015; Faria et al., 2013; Domingues et al., 2015). These studies found the performance of the BEV on the environmental impacts is highly depended on the electricity generation mix. The different electricity mix in different regions will significantly caused different environmental performance of the BEVs. Faria et al. (2013) conducted a LCA for ICEVs, BEVs and PHEVs that considered different energy mixes and driving profiles in Europe. The results showed that BEVs can be more

sustainable from the energy, economic and environmental perspectives but only with the following three main prerequisites: battery technology improvement, eco-driving profile, and environmentally friendly electricity power mix. Domingues et al. (2015) combined the LCA with the multi-criteria decision analysis to evaluate the environmental impacts of the ICEV, PHEV (10 and 40 mile battery range) and BEV in Portugal. The results showed that the BEV assessed the best performance in reducing the unban area air pollution and oil dependency. The overall performance of the BEV is also better than other vehicle types as it is the alternative with the best performance in 8 (out of 10) indicators in that study. Onat et al. (2015) also focused on a comparative analysis of the carbon and energy footprint of the BEV, PHEV, HEV and ICEV. Their study considered the state-based electricity generation mix in the US and compared the 4 vehicle types across 50 states. Based on the state-based average electricity generation mix scenario, the BEV is the least carbon-intensive vehicle in 24 states, while the HEV is the most energy efficient option in 45 states. If considering the state-based marginal electricity generation mix, "*widespread adoption of EVs is found to be an unwise strategy given the existing and near-future marginal electricity*

generation mix" (Onat et al., 2015).

2.6 The energy and environmental analysis of AFV in China

According to Torchio et al. (2010), because of geography influences source-to-fuel pathways (e.g. natural gas, biofuels) and the prevailing type and size of the power train options, the index results of WTW analysis are always area-sensitive. Based on the literature review of the existing studies, it can be concluded that the studies in different regions and countries also have different areas of focus because of their different situations. For example, the different studies have mainly focused on vehicles that represent the characteristics of their own vehicles and on the driving cycles in their own countries. To address Q2 from Chapter 1, this dissertation plans to evaluate the energy consumption and emissions of EVs in China given China's specific (power mix) situation. The previous studies that assessed vehicle energy and environmental impacts in China are reviewed and discussed in this section, and the gaps are identified.

In China, the earliest vehicle fuel WTW analysis began in 1997 (Li, 2006) (Zhu, 2006). Ford Motor Company, the National Science and Technology Commission, Tsinghua University, and a number of research institutions in Shanxi Province analysed the WTW of the coal-based methanol fuel pathway and PEV pathway by coal-based electricity generation. This research included a comprehensive evaluation of energy, urban pollutant emissions, carbon dioxide emissions and cost indicators (Kreucher et al., 1998) (Zhang et al., 2008).

According to Zhou et al (2010), most of the studies in China focus on a single fuel, such as coal-based vehicle fuel, hydrogen fuel, and biofuels. China's resource structure is characterised by “lack of oil, less gas, relatively rich in coal”. The ratio of coal in China’s entire energy consumption system is roughly 70%, and the coal-dominated energy consumption structure is difficult to change in the short term (Song et al., 2010). Therefore, many studies of WTW in China focus on coal-based fuel pathways (Song et al., 2010; Zhang and Huang, 2006). Some studies showed that compared with traditional internal combustion engine vehicles, electric vehicles

produced much less environmental pollution during the operating phase and even achieved zero emissions. However, because most of the electricity in China is produced by coal-fired thermal power, electric vehicles still can produce environmental pollution, even higher than that of conventional fuel pathway when considering the full LCA (Hu et al., 2002). In 2008, Song et al (2008) studied the WTW analysis of China's coal-based vehicle fuel energy consumption and carbon dioxide emissions. The result showed that carbon dioxide emissions from coal-based fuels were more prominent and that a great deal of carbon dioxide was generated in the WTT stage, which resulted in sharply rising carbon dioxide emissions throughout the WTW period (Song et al., 2008).

Zhang et al (2008) studied the LCA of alternative vehicle fuel in China. This research is more comprehensive, and the different fuel pathways have included petroleum fuels, natural gas, coal-based fuels, biomass, and electricity. Cost analysis was also added in this research, which found that the pathway of hydrogen produced through water electrolysis to supply FCEVs had similar fossil energy consumption to that of the

advanced gasoline vehicle pathway in WTW analysis; however, the GHG emissions from this FCEV pathway were approximately 15% higher than those for the advanced gasoline vehicle pathway. In contrast, using natural gas to centralise hydrogen gas production had good performance in reducing GHG emissions. GHG emissions from natural gas were lower than those in the advanced gasoline vehicle pathway even when the CCS system was not added (Zhang et al., 2008). Moreover, Ou et al. (2010) studied the energy demand and GHG emissions of China's alternative vehicles based on analysing different scenarios. Another study (Ou et al., 2010) compared the GHG emissions of coal-to-liquid (CTL) fuels with EVs powered with coal-to-electricity. CCS technology was considered in this research, and the results found that CTL fuels led to anywhere between 30% to 140% more GHG emissions than ICEVs and that EVs achieved 3-36% GHG emissions reductions without utilising CCS technology. Considering the CCS technology that is applied in power plants, EV GHG emissions reduction can achieve 60%-70% compared with ICEVs. Wu et al. (2012) studied the energy consumption and CO_2 emissions of EVs in three developed regions (Jing-Jin-JI, Yangtze-River-Delta and Pearl-River-Delta). This study highlighted the variable EV

performance in different regions of China, which were caused by the different electricity mix. The study found that HEVs were more suitable for the regions with high shares of coal power than were PHEVs and BEVs. In contrast, EV development achieved more significant CO_2 reductions in regions with much cleaner electricity mixes.

The main features and findings of the previous studies in China can be summarised as follows:

1. Because of the energy structure, most of the studies in China focused on a coal-based fuel pathway and on a single fuel.
2. Considering coal-fired thermal power, electric vehicles still can produce environmental pollution in China, sometimes even higher than that of conventional fuel pathway when analysed on a life cycle basis.
3. Whole WTW total energy consumption of coal based fuel vehicles is higher than that of gasoline and diesel vehicles
4. The coal-powered electric cars and plug-in hybrid vehicles still have the potential

to become the most suitable choices for China

Because of China's vast land area and the uneven distribution of resources，the different electricity mixes in different regions can significantly affect AFVs' energy consumption and GHG emissions performance. However, there are still only a few studies that focus on regional and local electric mixes. To consider the different performance of different types of EVs, it is necessary to understand the effectiveness of each EV type on energy consumption and CO_2 emissions in different regions in China. There are 6 inter-provincial power grids in China that are defined by the geographical distribution (North grid, Northeast grid, Northwest grid, Central grid, East grid and South grid). Due to the uneven distribution of the energy resources, the electricity mix in the different grids is totally different, but these grids are not strictly independent as they can mutually transmission among each other. Coal still plays the dominant role in all these grids. Especially in the North and Northeast, the coal-fired electricity can account for more than 95% of the total electricity generation. In contrast, the hydropower can account for more that 22% in South grid, Central grid

and Northwest grid. The nuclear power is mainly concentrated in the South and East grids, and that accounts for about 5% of the total electricity generation (Huo et al., 2010; National Statistics, 2009). It can be seen that the clean energy resource, such as solar, wind and hydro power, are mainly concentrated in the central grid, south grid and northwest grid, and there is lack of clean energy in the north, northeast and east of China. However, most of current pilot cities in the EV demonstration program are distributed in the north and east of China (such as Beijing, Tianjin, Hefei, Shanghai and Hangzhou) as the level of economic development and the level of automobile industry are relatively high in the these regions. Because electricity cannot be stored on a massive scale in an economic way, and because the output electricity of some clean energy such as wind and solar is intermittent, it is difficult to use this energy for the base load. It is necessary to balance the deployment of the EVs with the development of the power infrastructure in China. It will be a major challenge to optimize the energy and environmental impacts of the EV deployment by improving the power infrastructure and coordinating the demand and supply in the grid system. Based on the results of LCAs, the macro-effects analysis of implementing EV policy is

very important and valuable. However, current studies have mainly focused on comparing the results from WTW analyses of different alternative fuels, and they overlook any macro-effect policy analysis.

This dissertation considers these findings and data gaps from previous studies, and Chapter 4 will provide a more comprehensive analysis of EVs' energy savings and CO_2 emissions at both the national and regional levels. The different potential of BEVs and PHEVs for energy saving and CO_2 reduction need to be analysed more in-depth by considering the different power mixes at different times and in different regions. This study will also recommend macro-policy implementation for EV development based on the LCA results, and will also apply to a framework for further evaluating the effectiveness of EV promotion in China.

2.7 The Automotive industry in China

In addition to the energy savings and environmental protection, EV development has been considered a good opportunity for China's automobile industry to catch up with

and even to lead global production of EVs. This is an important reason for the government to support the development of electric vehicles in China. This section introduces the development history of China's automotive industry to provide an overview understanding of the current status of China's automotive industry and why EV development seems important for the industry and nationally. China's automotive industry started in the 1950s (Zhu et al., 2007), and there have been five main phases in the development of the industry over the past 60 years (Zhang, 2010; Gan, 2003).

Initial stage (1953-1958)

1953 to 1958 is considered the initial stage of the automobile industry in China. The construction of the First Automobile Works (FAW) in Changchun in 1953 marks the beginning of this phase (Lin, 2010). The FAW was completed in 1956, and the first domestic vehicle—the Jiefang truck—rolled off the assembly line in the same year. At this stage, the state government was the main promoter of and investor in the industry having invested roughly 1.1billion CNY (114.6 million GBP)[1] (Gan, 2003). The

[1] Exchange rate used in this dissertation is 1GBP = 9.6 CNY

unique characteristic of this period is that the construction work and the technologies were carried out with the assistance of the former Soviet Union as part of a technology collaboration program (Group of EV project, 2008; Gan, 2003). Industry development in this period was highly dependent on technology imports, product R&D and construction from the Soviet Union, and industry capacity was approximately 60,000 vehicles per year (Gan, 2003).

Independent stage (1958-1984)

1958 to 1984 is considered the second phase of China's automobile industry. The industry entered an "independent stage" after Sino-Soviet relations deteriorated in 1958 (Zhang, 2010; EV Industry Development Strategy Research Group, 2009). The construction of the Second Automobile Factory (which was renamed the Dongfeng Motor Corporation in 1992) was the benchmark achievement in this phase. Self-reliance was considered the main philosophy of auto industry development in this period. In addition, because of security considerations, the main automobile capacity development in this period was centred in western China, particularly in Sichuan,

Shanxi and Hubei provinces (Gan, 2003). For example, the Second Automobile Factory was first established in Shiyan, which is a small city located at the junction of Hubei, Chongqing, Henan and Shaanxi provinces, where mostly mountains and only a railway and highway pass through. The plants that were built in these remote regions lacked infrastructure, materials, energy and transport supply, which caused many difficulties for the industry development in this period. In addition, in the beginning, the automobile products in China mainly focused on heavy trucks that were mainly for military use (Gan, 2003). In the 1970s, the demand for passenger cars began to increase, which provided a good opportunity to expand production capacity.

Opening-up stage (1984-1998)

1984 to 1998 was a phase of adjustment and rapid development in China's auto industry (Gan, 2003). The Chinese government decided to strategically establish and develop a modern auto industry in which domestic automobile manufacturers could gradually develop competitive brands and technological capabilities in the global market (Nam, 2015). In order to learn advanced technologies, processes and

management methods from advanced foreign auto manufacturers, the foreign direct investment (FDI) regulation based on the strategy of trading market access for technology was devised and launched in this period (He and Mu, 2012). This strict FDI regulation required foreign auto manufacturers to establish an international joint-venture (IJV) partnership with China's domestic automobile company in exchange for its access to China's vehicle market (Nam, 2015). China wanted to use its large potential market to exchange advanced technology from global vehicle manufacturers. The first IJV vehicle company was founded in 1984 through cooperation between the Beijing Automotive Industry Corp. and Chrysler, which marked the beginning of the opening-up stage of China's auto industry (Zhang, 2010). After that, encouraged by the open-door policy and the large market potential, most of the international automobile manufacturers came into China's market by IJV, such as Volkswagen, BMW, Toyota, Mercedes-Benz, Honda, Nissan, General Motors, Ford and Mazda (Gan, 2003; Zhang, 2010). According to Gan (2003), the total investment was approximately 120 billion CNY (12.5 billion GBP) by 1998, and the output production was 298.7 billion CNY (31.11 billion GBP), which accounted for 0.8% of the

total GDP in China. The output production value of the auto industry increased 32.8 times from 1980 to 1998. However, the performance of the trading market access for technology strategy was not good and did not meet the government's expectations. According to Nam (2015), although many domestic auto companies had expanded output capacity through IJV partnership, efficacy and technological capabilities were still not being considered. A great deal of experience was learned from the IJV, and the vehicle market expended rapidly; however, the core technology in the auto industry was still controlled by the foreign manufacturers. China's domestic auto industry still lacked capacities such as independent development engines, electronic control systems, automatic transmission and also bodywork. (Zhang, 2010) The lack of self-development capacity is considered the main challenge to the further development of China's auto industry.

Market growth stage (1999-2008)

In order to accelerate the expansion of the vehicle market as well as to stimulate economic development, The Chinese government introduced a number of policy

incentives to encourage the ownership of private passenger cars in late 1998, including reducing tariffs and offering low-interest loans (Gan, 2003). The vehicle stock in China increased from 0.8 million in 1990 to 65.39 million in 2010 (Hu et al., 2010). In addition, because of fast-growing vehicle ownership, concerns about vehicle pollution and congestion problems in urban areas increased significantly, and vehicle fuel efficiency came to be a strict requirement of environmental regulations. The potential of alternative fuel vehicles such as EVs and natural gas and biofuel vehicles began to gain increasing attention from the government and vehicle manufacturers. EVs had begun gaining more attention than other after the 10th Five-year plan (2001-2005). The Chinese government considered developing EVs to be a core strategy for China's domestic auto industry to catch up to a global advanced level, and it invested a great deal to promote EVs. At the time, the policy incentives for EV development focused only on China's local manufacturers in order to resolve the lack of self-development capacity and to help the local EV makers create a competitive edge in the early introduction of the EV market (CATARC et al., 2013).

Current stage (2009-2015)

The development of the automobile market in China continues to grow rapidly. In 2009, the annual sales of the vehicles in China have reached more than 10 million vehicles and ranked 1st in the world. This number has increased to more than 23 million vehicles in 2014, which is more than 2 times of the level in 2009. The annual sales of the vehicles[1] in China has ranked 1st in the world for the last six consecutive years (2009-2014) (Netease Auto, 2015). However, China's auto industry is considered as “large” but not “strong”. Due to the lack of the core technology and the R&D capacity, China's domestic brand cars are still lack of competitiveness compared to the foreign more advanced brands. According to the report of Chinabaogao (2014), the market share of China’s own brand passenger vehicles was 40.28% in 2013, declined by 1.57% since 2012. The sales of China’s own brand passenger cars only accounted for 27.53% of the total car sales (2013), declined by 0.85% since 2012. There was no Chinese brand in the top ten sales auto brands in China for the last two consecutive years. Enhancing independent innovation capability and competitiveness

[1] The vehicles here include all kinds of business vehicle, passenger vehicle, agricultural vehicles and special vehicles, but do not include the motorbikes.

of the brand have become important tasks and challenges for China's domestic auto industry. The government and auto industry are committed to develop its own brand of electric vehicles, and to establish a strong position in the electric vehicle market. From 2009, with the start of "ten cities thousand vehicles" large demonstration program, the government further increased its efforts to support electric vehicles. Most of the domestic automobile manufacturers in China have developed their own EV passenger vehicles, such as SAIC, Changan, FAW, Dongfeng, Geely, Chery, BAIC, JAC and BYD. After the release of the "Energy-saving and new energy vehicle development plan for 2012-2020" by the State Council of China in 2012, these major manufacturers all accelerated the speed to launch electric car models. Since 2014, the government further introduced many new policies to build a relatively complete system of policy support for the EV development. Measures included industry management, tax incentives, technological innovation, and infrastructure construction (CATARC, 2014). According to MIIT (2015), the annual production and sales of the EVs in 2014 are 78499 vehicles and 74763 vehicles, and this level is 3.5 times and 3.2 times than the one of 2013, respectively. However, the EV ownership is

still well below the target set by the State Council in 2012, which promoted an EV ownership level of 500,000 by 2015. The main impact factors and challenges that occurred in the EV deployment process are the main focus for the detailed analysed in this dissertation.

In conclusion, although China is the largest vehicle manufacturer in the world with the largest vehicle market, the industry and technology levels of China's domestic auto manufacturers are still far behind the most advanced levels globally. Although the government has attempted to improve the domestic auto industry through trading market access for technology, this strategy was not fully successful in that China's auto industry still lacked core ICEV technology, manufacturing capability and independent innovation. Therefore, EVs as an emerging technology have been considered a useful area for China's auto industry to focus on. EVs are still in the development stage and are new to both the Chinese auto industry and advanced foreign automobile manufacturers. This also explains the government's electric vehicle policy actions and approaches. Although some advanced commercial EV

models have been developed by the major car manufacturers (such as Toyota, BMW and GM), the Chinese government remains committed to developing and promoting its own brand of electric cars. The government has launched many policy incentives and demonstration programs that have all been aimed primarily at supporting domestic EV manufacturers.

It can be seen that the different policy strategies in the different periods have significantly affected the direction and effectiveness of the auto industry development (such as trading market access for technology and the policy incentives to encourage private passenger car ownership). Therefore, in order to forecast the EV development trend in China, it is necessary to understand the role of policy in EV development and to evaluate the effectiveness of current policy support regarding EV deployment. This dissertation introduces the current EV development policies in China, discusses their effectiveness and issues based on the existing lessons, and it also provides recommendations for policy implementation to improve EV deployment.

2.8 Global EV development status

Because of the increasing pressures on energy and the environment caused by road transport, major countries around the world are working to reduce their overall carbon footprints and fossil fuel consumption in road transport. The US, the EU and Japan have all introduced more stringent regulations to push the automobile industry towards low- or zero-emission vehicles (Bakker et al., 2014). For example, the European Commission has adopted a roadmap that plans to reduce 60% of carbon emissions and imported oil dependence in the transport sector compared with its 1990 levels (European Commission, 2011), it and requires that auto manufacturers reduce the average CO_2 emissions of their passenger cars to 95g/km by 2020 (European Commission, 2012). In addition, the US also launched a variety of environmental standards to control vehicle emissions and energy consumption, including low-emission vehicle standards, ultra-low-emission standards and zero-emission standards (Lan and Huang, 2002). In order to achieve these requirements, most of the car manufacturers around the world have chosen EV technology, from

among the variety of technology options as their area of (Dijk et al., 2012; Bakker et al., 2014). Governments have also introduced EV development strategies based on their own situations.

2.8.1 EV development plans

Reducing imported oil dependence is the main objective of the EV development in the US. In 1993 (the Bill Clinton period), the Partnership for a New Generation of Vehicles" (PNGV) plan was jointly carried out by the US government and three major auto manufacturers: General Motors, the Ford Motor Company and Chrysler (CATARC, 2013). In addition to the automobile companies, the PNGV involved 7 federal agencies (the Departments of Commerce, Defense, Energy, and Transportation, the Environmental Protection Agency, the National Aeronautics and Space Administration, and the National Science Foundation), state laboratories, universities, suppliers and the United States Council for Automotive Research (Yang, 2004; Zhang, 2010). In 2002 (the George Walker Bush period), the US government launched the Freedom CAR project, which mainly focused on developing FCVs (CARATC, 2013). In 2006, President

George W. Bush proposed the Advanced Energy Initiative to increase government investment in advanced BEVs, FCVs and other clean energy technology (EV Project Group, 2008). After President Barack Obama took office in 2009, the US government granted 4.8 billion dollars (2.4 billion from state grants) for the development of advanced batteries, EV technology and industrialisation (EV Industry Development Strategy Research Group, 2009). President Obama called for putting one million EVs on the road by 2015 (Department of Energy, 2011).

Compared with the US, reducing GHG emissions has been the main factor for the EV development in European countries. In Germany, the federal government launched the National Electric Vehicle Development Plans in 2009, which stated that BEVs and PHEVs would be the main focus of the EV development strategy for energy and environmental conservation. The goal of the development plan is that EV (BEVs and PHEVs) stocks in Germany should achieve 1 million by 2020 (German Federal Government, 2009). In 2010, the Ministry of Environmental Protection further proposed the goal that the EV stock should reach 6 million by 2030 (CATARC, 2013).

In Japan, because of the lack of resources and the country's high imported oil dependence, the government is focusing more on developing energy-saving vehicle technology. The competitiveness of the automobile industry is considered to be the first target of EV development (including HEVs, BEVs, PHEVs and FCVs). In April 2009, Japanese Prime Minister Taro Aso proposed EV development as a "low-carbon revolution", and he planned to create 10 EV pilot cities, as well as to increase the electric car market share to 50% by 2020 (EV Industry Development Strategy Research Group, 2009). The Next Generation Vehicle Plan was released in 2010, one target of which is that the number of next-generation vehicles should account for up to 50% of the total vehicles by 2020 and that advanced eco-friendly vehicles (next-generation and eco-friendly conventional vehicles) account for up to 80% in 2020 (New Energy Development Organization (NEDO), 2010). In order to reach this target, the plan expected that at least 17 types of BEV and 38 types of HEV (PHEV) would be developed by 2020 (New Energy Development Organization, 2010).

2.8.2 Battery Research and Development

In order to achieve battery technology breakthroughs to overcome the limitations of EVs, governments in many advanced auto industry countries greatly increased their battery R&D investments (Zhang, 2010). The federal government in the US has invested almost 80 million a year for EV battery R&D (Malcolm, 2011). In 2009, the American Recovery and Reinvestment Act authorised 2.4 billion USD in grants to support vehicle battery manufacturing; In addition, in 2011, President Obama asked Congress to provide additional grants for battery and EV R&D (Malcolm, 2011). In addition, the High-Technology Strategy and Lithium-ion Battery Alliance: LIB 2015 was released in 2008, and it clearly ensured the continued support of lithium-ion battery development in Germany. The German government will provide 60 million euros for lithium-ion battery R&D, with 360 million euros more granted by the business sector (German Federal Government, 2009). The Japanese government also considered that advanced battery technology was key to controlling the EV industry (Åhman, 2006). The Ministry of Economy, Trade and Industry (METI) granted 24.5 billion JPY (126.3

million GBP)[1] for EV battery R&D in 2007-2011. According to the Next Generation Vehicle Plan (2010), Japan will mainly focus on improving the performance of lithium-ion batteries and developing innovative (post-lithium-ion) batteries (NEDO, 2010).

2.8.3 Policy incentives for EV promotion

The high R&D cost, production cost and lack of charging stations in the current period require that governments provide policy incentives to manufacturers and consumers to support EV market penetration. In the US, the government provided tax credits as policy incentives for implementing HEVs, BEVs, FCVs and PHEVs (EV Industry Development Strategy Research Group, 2009). For HEVs, based on the fuel economy, tax credits are available of between 250 to 3400 USD. For PHEVs and BEVs, based on the battery energy level, 2500 USD tax credits will be given to PHEVs and BEVs for which battery energy is not less than 4 kWh. The government will provide 417 USD per kWh in tax credits to vehicle batteries with energy over 4 kWh. In addition to the battery tax credits, the government also set different tax credits based on EV weight (CATARC, 2013). Furthermore, the US government also provided loans to EV

[1] Exchange rate used in this dissertation is 1GBP = 194 JPY

manufacturers. Ford, Nissan, and Tesla received approximately 8 billion USD loans for EV production (EV Industry Development Strategy Research Group, 2009). Germany levies an annual ownership tax on passenger cars based on their CO_2 emissions. In order to encourage EV deployment, EVs are exempt from the tax in their first 5 years and then taxed based on their weight after 5 years (still lower than the tax for traditional ICEVs). In France, the government began to provide subsidies for low-emissions in 2008. Consumers who purchased low carbon emission vehicles could receive up to 5000 EUR in subsidies, and this subsidy increased to 7000 EUR in 2012(CATARC, 2013; German Federal Government, 2009). In addition, Japan launched a "new green tax" in 2009 that tax credits to low-emission and low energy consumption vehicles (mainly focusing on BEVs, HEVs and PHEVs) (NEDO, 2010).

2.8.4 Policy support for charging infrastructure

In order to introduce EVs into markets, governments pay particular attention to building charging infrastructure. In 2009, the US Department of Energy announced that they would invest 100 million USD to upgrade the current electric grid to satisfy

the increasing charging demand of PHEVs and BEVs, and they also provided subsidies (30% of the total cost) to consumers and companies who invested in constructing charging stations (up to 1000 USD for private consumers and 30,000 USD for companies) (CATARC, 2013). The American Recovery and Reinvestment Act authorised the government to choose 8 regions for an EV demonstration program and intended to promote 13000 new energy vehicles and 20000 charging stations in these pilot regions by the end of 2013. The main EV charging station companies such as Coulomb Technologies and ECOtality all gained a sufficient amount of subsidies from the government for the charging station construction. Some EV manufacturers such as Tesla Motors also build many charging facilities in the US. By May 2014, there were a total of 9857 charging stations and 22935 charging spots built in the US (CATARC, 2014). In Europe, the UK government launched the government-oriented “Plugged-In Places” (PiP) program and built charging stations with a focus on BEVs and PHEVs. The government provided a 30 million GBP budget for this program (Cabinet Office, 2010). By March 2013, there were more than 4000 charge points built in the PiP program. In addition, the Office for Low Emission Vehicles also announced that it would provide

subsidies for constructing charging stations. The subsidies are provided not only to local governments and companies who build the charging facilities but also to the private consumers who purchase and install them. The subsidies could cover 75% of the cost of the charging station (CATARC, 2013). In France, more than 8000 charging facilities were built by the end of 2013 (CATARC, 2014). Japan plans to accelerate the construction of PHEV and BEV charging stations in order to further popularise next-generation vehicles. Japan's METI began offering subsidies to companies that built charging stations in 2006. The government announced in its Next Generation Vehicle Plan 2010 that it would build 2 million normal charging facilities and 5000 fast-charging facilities by 2020 (NEDO, 2010). In order to support this plan, the Japanese Parliament increased the budget in 2012 to provide an additional 100.5 billion JPY for charging station construction (CATARC, 2013). In 2009, the Tokyo Electric Power Company, Nissan, Mitsubishi and Fuji Heavy Industries formed CHAdeMO, a joint venture among 158 companies, including the Tokyo Electric Power Company, Nissan, Mitsubishi, Fuji Heavy Industries, and Toyota. After its establishment, many foreign companies also joined the organisation, such as the Swiss ABB, the German Bosch,

and Korean Samsung. By March 2014, CHAdeMO had installed 1922 fast-charging facilities and had nearly covered all Japanese prefectures and highways. In addition to Japan, CHAdeMO also installed many fast-charging facilities in the US and Europe. According to CATARC (2014), by March 2014, CHAdeMO had installed more than 3000 fast-charging facilities around the world.

In conclusion, these advanced countries have all launched clear alternative fuel vehicle development strategies, most of which focused on BEVs and PHEVs. Their EV development strategies are mainly concentrated in three perspectives: battery technology R&D, policy incentive support measures and charging stations. Regarding policy incentives, in addition to direct subsidies, tax credits for EV buyers are considered useful instruments and are widely used by many countries. For charging station construction, these countries provided abundant subsidies to encourage companies and local governments to build the charging stations by reducing their costs. Some countries such as the UK and the US have also provided direct subsidies to private consumers to encourage them to purchase EVs and install private charging

facilities. These experiences from the advanced countries can be compared with China's development strategy to show how policy incentives and instruments could work given China's own situation. China, as the largest vehicle manufacturer, has also launched a development strategy for alternative fuel vehicles. As stated in the introduction (Chapter 1), China has already committed to develop the EVs over 20 years, and the policy incentives and demonstration scale of the EV development in China has been considered as one of the strongest political-institutional initiatives in the world. Therefore, the experiences and lessons learned from the existing EV promotion process in China are also expected to provide reference and guidance to the rest of world. When considering China's specific situation, such as economic development, policy-oriented market, low vehicle ownership, high-density populations and monopoly power enterprises, whether the experiences from developed countries can be effectively used in China and how the current policy support the EV deployment in China will evolve in the future all need to be further analysed. This dissertation has evaluated the EV development in China from some of these perspectives. Chapter 4 will introduce China's EV policy background in detail

and will discuss the current status and challenges of EV promotion in China. Chapter 5 will simulate the life-cycle energy consumption and CO_2 emissions of the three types of EVs (HEVs, PHEVs and BEVs). Considering the gaps in the existing research, this dissertation will consider the different electric mixes at both the national and local levels and will simulate the relationship between the coal-fired power proportion and BEV emissions based on China's situation. Chapter 6 will forecast the EV diffusion trend in China by considering the national vehicle market features through the historic data on ICEV penetration in China. The potential impacts of the different policy-oriented scenarios are also discussed. Based on Chapters 4 to 6, Chapter 7 will develop a comprehensive evaluation framework to study the effectiveness of China's current EV promotion progress from the local level.

Chapter 3 Methodology

In order to address the research questions and the gaps introduced in the introduction and literature review, different research theories and methodologies are used in this dissertation. This research studied the interactions between EV development and related sectors, such as energy, environmental, policy and the market, and it evaluated the effectiveness of China's current EV promotion progress through both qualitative and quantitative methods. This chapter gives a general introduction of the main theory and methods used in this dissertation; the detailed and specific introductions to the methodologies used for each individual topic are described in each corresponding chapter (Chapters 4 to 7).

3.1 The overall approach

This dissertation investigates the EV development status in China through different timelines (past, present and future), different geographic spatial scales (the different situations and instruments at the national level (macro) and between local levels

(micro)) and different perspectives (energy, environmental, industry, market condition and policy). The overall approach is shown in Figure 3-1 below.

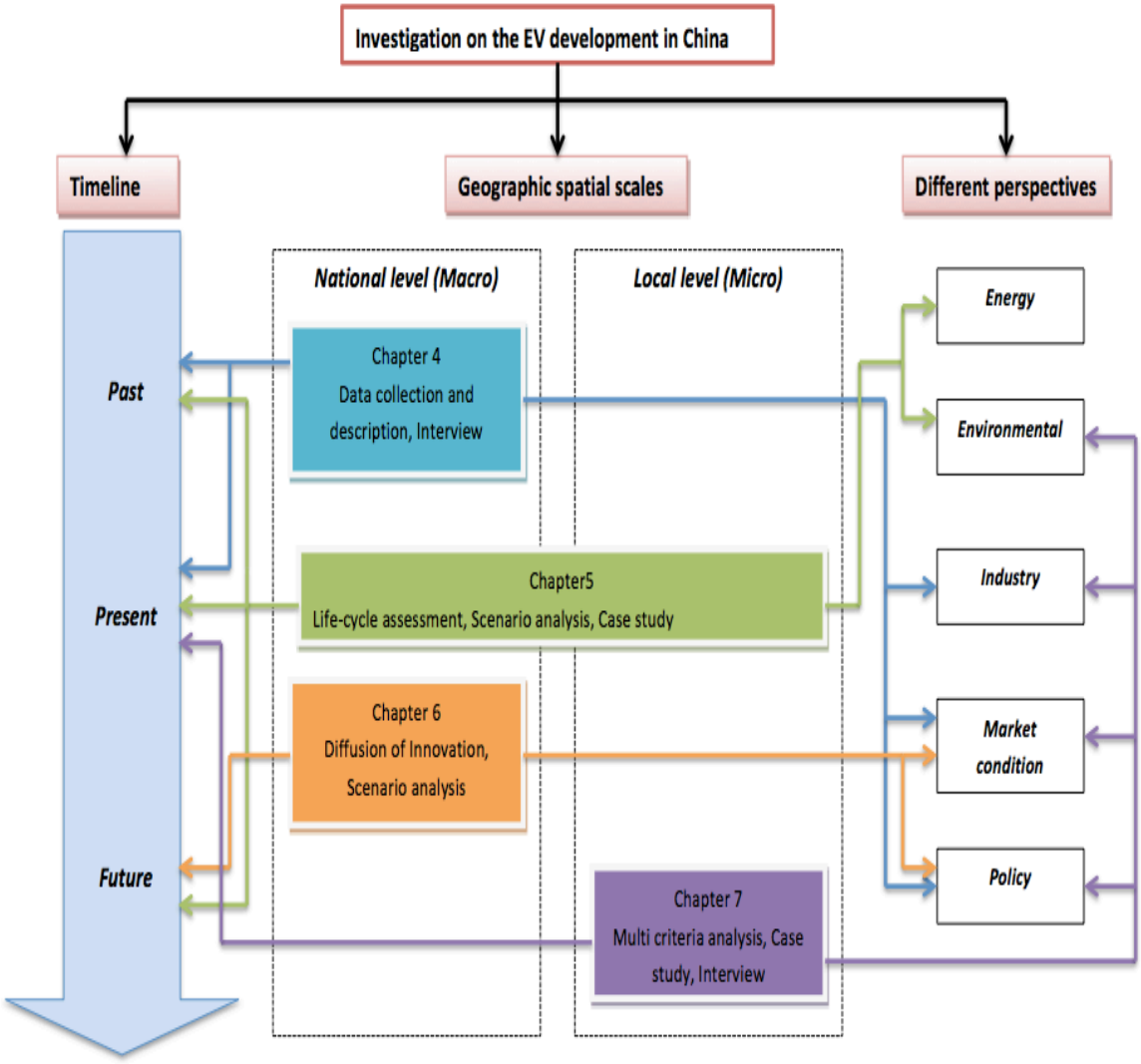

Figure 3-1 The overall approach and major methodologies used in this dissertation

To investigate the industry, market conditions and policy instruments, this dissertation collects data through fieldwork, interviews and document research to

understand the previous and current EV development status. The author conducted fieldwork in China on three separate occasions over 4 years and interviewed more than 20 high-level experts from various institutions, companies and governments in EV-related fields. Based on the data collection, Chapter 4 introduces China's current EV development strategy and policy instruments, and the results of the pervious EV demonstration program (2009-2012) are discussed and analysed (national level). By considering the latest data and local-level details (2013-2015), Chapter 7 further discusses and evaluates the market conditions, policy instruments and other aspects (technology, industry and environment) in different pilot cities (case studies) to show the latest EV development status and issues at the local level. Multi-criteria assessment (MCA) was chosen to establish a comprehensive evaluation framework in Chapter 7 by considering the various perspectives in this dissertation. In Chapters 4 and 7, the previous and present status of EV promotion are introduced and analysed. To forecast the potential future of EV deployment in China, the diffusion of the innovation theory is used in Chapter 6 to forecast EV diffusion trends and their relationships with the relevant impact factors (such as vehicle performance, cost, and

infrastructure). The different potential impacts from the policy instruments and market conditions are also considered through scenario analysis.

For the energy and environmental perspectives, this dissertation uses life cycle assessment (LCA) to simulate the impacts of EV development by considering the different EV types and the different power mixes along the timeline. The different potential power mixes are assumed using scenario analysis. According to gaps that were identified from the existing LCA studies in China (Chapter 2), this dissertation not only considers the national power mix but also the different mixes in different regions (Chapter 5). Five different cities from different geographic locations are chosen as case studies. Furthermore, the LCA results for EVs from the energy and environmental perspectives contribute to improving policy instruments and are applied to the evaluation framework in Chapter 7 as key criteria for the effectiveness of EV promotion in China.

3.2 Life Cycle Analysis

In order to understand the energy and environmental performance of EVs in China, this research uses life cycle assessments to evaluate the impacts of EV development on energy and the environment: “Life cycle assessment (LCA) is a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle” (Blottnitz and Curran, 2007). It included obtaining raw materials, production, use, and final disposition and an impact study of the consumption of environmental and other resources (ISO14040, 1997). LCA is also introduced as an environmental and resource evaluation of the full life cycle of a product from "cradle to grave" (Blottnitz and Curran, 2007; Zhang et al., 2008) According to Ahmad (1993), LCA as an environmental assessment method stresses that the overall analysis and evaluation of a product’s impact on the environment should cover the full product life cycle and ultimately seek to improve the methods and measures.

LCA has already been widely used in environmental impact assessments of energy and vehicles. Bouvart and Prieur (2009) highlighted in their research that "environmental assessments only make sense if they are conducted on the whole chain i.e., on the entire life cycle of the product or unit of energy service studied". If only a part of the chain is considered, the environmental improvement in this part may cause adverse effects in other parts such as the upstream or downstream parts of the chain. Therefore, studies based on LCA can avoid these pollution transfers, which are relevant and necessary. When automotive life cycle analysis is considered, two kinds of cycles can be distinguished: vehicle and fuel life cycle (Torchio and Santarelli, 2010) (Zamel and Li, 2006).

According to Zamel and Li (2005, 2006), vehicle life cycle follows the sequence: vehicle material production, vehicle assembly, vehicle distribution, vehicle maintenance, and vehicle disposal and recycling. Fuel life cycle can also be divided into five stages: primary energy extraction, transport and storage of raw materials, fuel preparation, fuel transport, storage and distribution, and fuel use (Torchio and

Santarelli, 2010; Zhou et al., 2010; Zhang and Huang, 2005). The lifecycle assessment approach to EVs is shown in Figure 3-2. Zamel and Li (2005) studied the LCA of fuel cell and ICE vehicles by considering both vehicle and fuel life cycles, and the research results showed that the material production step is greatly dependent on the average weight of the materials used in the vehicle and that the other three steps are dependent on the total weight of the vehicle. In addition, "the material production step is responsible for almost 75% of the energy consumption and emissions during the vehicle life cycle". That study also found that total energy consumption and total GHG emissions were lower with the use of recycled rather than virgin material: "The use of 100% recycled material results in a 45% decline of energy consumption and a 42% decline in carbon dioxide emissions." However, the result also showed that the energy consumption in the fuel life cycle occupied 80-93% of the total energy consumption. Because the weight in the fuel life cycle is much greater than that in the vehicle life cycle, most existing LCA studies of electric vehicles mainly focus on weight (Torchio and Santarelli, 2010; Wang, 2002) (see Chapter 2 Literature Review).

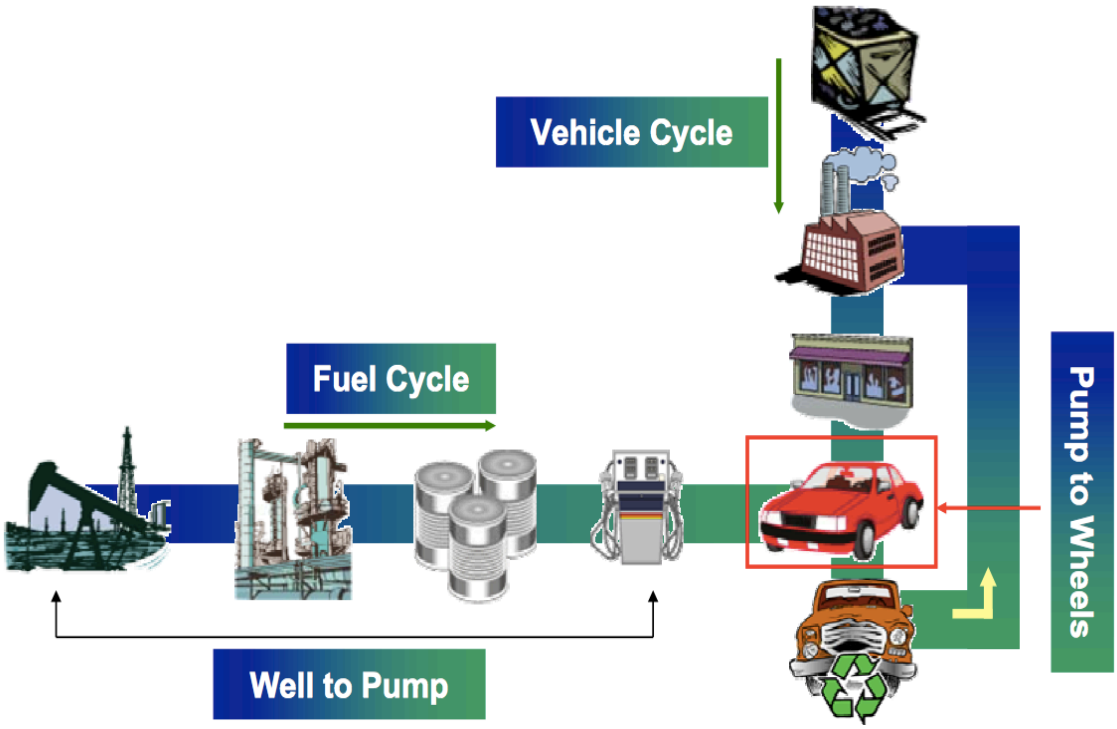

Figure 3-2 Vehicle life cycle assessment (example of petroleum-based fuels) (according to Wang (2003))

This dissertation has mainly focused on evaluating the energy consumption and CO_2 emissions of EVs given China's coal-based electricity mix. Therefore, the fuel life cycle analysis (wheel-to-wheel [WTW] analysis) is the main focus, for two reasons: First, the major emissions from EVs come from the electricity generation process, and as such, WTW analysis can effectively evaluate energy consumption and CO_2 emissions from the coal extraction to the final electricity used in the EV operation. Second, because fuel life cycle accounts for the majority of the total energy consumption and emissions, the differences in energy consumption and emissions between EVs and

ICEVs on the vehicle life cycle will be less. There is a lack of data on the life cycle of the vehicle manufacturing process. Therefore, the fuel life cycle provides the basis for simulating and comparing the energy consumption and CO_2 emissions of the different EVs and ICEVs in China.

The fuel life cycle of EVs (BEVs and PHEVs) can be divided into 5 stages: primary energy extraction, transport and storage of raw materials, electricity generation, electricity distribution, and electricity use (battery recharge). According to the literature review, many studies used LCAs to simulate vehicle fuel energy consumption and emissions over the past 25 years, and some models wer developed based on the life-cycle approach. For example, Tsinghua University developed the Tsinghua-CA3EM model to simulate compare the life cycle greenhouse gas (GHG) emissions of coal-to-electricity for EVs and for the petroleum-based fuels that are utilised in vehicles (Ou et al., 2010). However, most of these models were not publicly available. The GREET model, the most widely used public LCA model, is used in Chapter 5 to simulate the energy consumption and CO_2 emissions of different EVs in

different electricity mixes. The GREET model is a spread sheet based approach that was developed by the US Department of Energy (DoE) and Argonne National Laboratory (USA). The details of the GREET method as used in this study are fully introduced in Chapter 5. This study not only evaluated the energy consumption and CO_2 emissions of EVs under current power mixes but also considered the potentially different future power mixes in China. In addition, by considering the gaps that were concluded from the literature review, this study also simulated the different EVs based on different cities and it thoroughly assesses the impacts of the different regional power mixes in China.

3.3 Diffusion of Innovation Theory

To understand the market diffusion of EVs, existing studies on vehicle market forecasting focus on different modelling techniques. Agent-based models (ABMs) are models that can simulate the action and interaction of each agent by creating virtual environments. The agents in the model are entities or individuals that are supplied with internal characteristics and that dictate their interactions with other agents in

the environment (Al-Alawi and Bradley, 2013). Some existing studies have applied ABMs in the field of vehicle technology adoption. Eppstein et al. (2011) used an agent-based model to estimate PHEV adoption rate. This study only considered consumer agents, and it assumes that the costs and benefits of PHEVs will be considered by consumers based on their own behaviour and knowledge of the technology. In addition, McCoy and Lyons (2014) used an ABM to simulate the electric vehicle development in Ireland. The agents in this study focused on consumer preferences based on socioeconomic characteristics and environmental preferences. ABMs can model vehicle purchasing decisions at an individual level by considering agents' individual characteristics, needs, limits, and preferences. However, the disadvantages of ABM studies are their complexity and their data requirements, which make ABMs generally more difficult to verify and validate. The ABM requires determining the different agencies and collecting the data and different views from the different agencies. However, the EV diffusion is lack of historical data, which is difficult to determine agencies and collect the data. In addition, without the option of

assessing the sensitivities of the agent-level data and the elasticity, there may be instability implications for the overall modelling (Al-Alawi and Bradley, 2013).

Some studies used the consumer choice model (logit model) to simulate vehicle purchasing or holding decisions (Brownstone et al., 2000) (Batley et al., 2004) (Shepherd et al., 2012). These models used purchaser demographic data and past vehicle sales data. However, it should be noted that for some new technologies such as PHEVs and EVs, historical sales data do not exist. Therefore, the sensitivities of consumers' purchasing decisions to the attributes of these EVs must be indirectly derived from model assumptions, survey data, or other similar fields of consumer preference research. For these reasons, it is difficult to use conventional consumer choice models to assess the potential impacts of technological innovation, and also difficult for new products, such as EVs.

However, because EVs are an emerging technology in China, there are few sales data consumer survey data (especially in the private market) for forecasting. Therefore, it

is difficult to use ABMs and consumer choice models to forecast EV diffusion based on China's vehicle market. In addition, this dissertation wants to clarify the EV diffusion trend along the timeline by considering the different potential situations in the future. Therefore, a diffusion rate and time series model is more suitable for forecasting future EV diffusion. Innovations theory is used in this dissertation, and EVs, as an innovative product, can be predicted following the diffusion trend of innovations.

The diffusion of innovations can be described by an S-shaped pattern, and it was developed by Everett Rogers in 1962 (Heffernan et al., 2008; Wonglimpiyarat and Yuberk, 2005), He considered diffusion the process by which an innovation (an idea or product) is spread through communication channels over time among the participants in a social system (Rogers, 2003). According to Rogers (2003), the S-shaped curve of technology adoption always begins with the "innovators" and "early adopters" and ends with the "laggards" (see Figure 3-3). The blue line describes the

groups of consumers who adopt the new technology, and the yellow line represents market share. Rodgers (1962) established five adopter categories (Table 3-1).

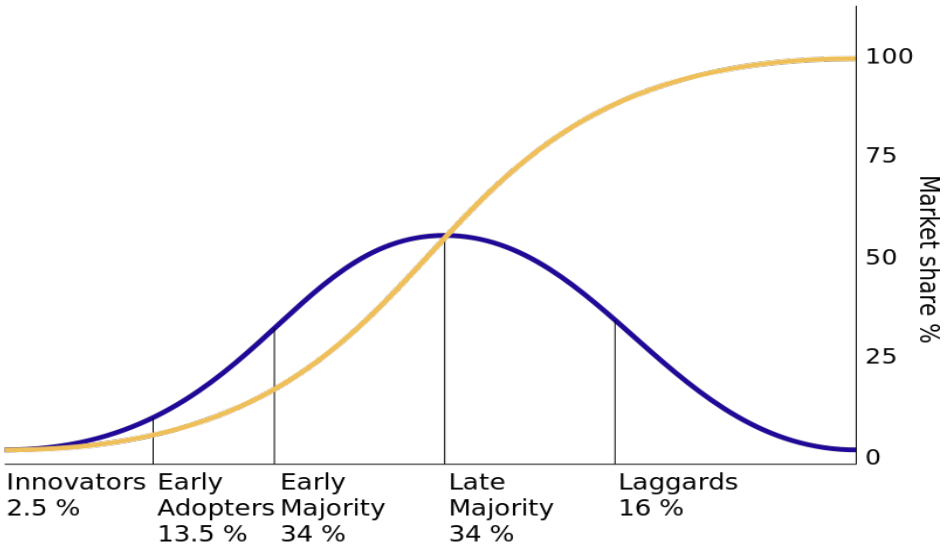

Figure 3-3 The diffusion of innovations (according to Rodgers (2003))

Table 3-1 The adopter categories identified by Rodgers (1962) (adapted in 2003)

Adopter categories	Definition
Innovators	These are people who are willing to take risks and to be the first to try an innovation.
Early adopters	These are people who have a high degree of opinion leadership among the adopter categories. They always enjoy leadership roles and are already aware of the need to change. There is no need for information to convince them to change.
Early Majority	These people are considered infrequent leaders who adopt innovations after varying degrees of time. They typically need evidence of success and information on an innovation before they adopt it.

Late Majority	These people are typically sceptical about innovations and only adopt them after the after the majority of society has done so.
Laggards	These people are the last to adopt innovations. They are very conservation and very sceptical of change and are often bound by tradition.

Based on diffusion theory, Frank M. Bass (1969) developed the first quantitative aggregate model of new product diffusion, which applied the theory to the marketing discipline (Radas, 2010). The Bass diffusion model is a model of "the timing of adoption of an innovation and will be central to subsequent developments", and it is widely used in product diffusion analysis (Norton and Bass, 1987; Lee et al., 2013; Park et al., 2011). The BASS model combined the external and internal influences to describe an S-shape diffusion curve of new products by using innovation and imitation factors (see Figure 3-4).

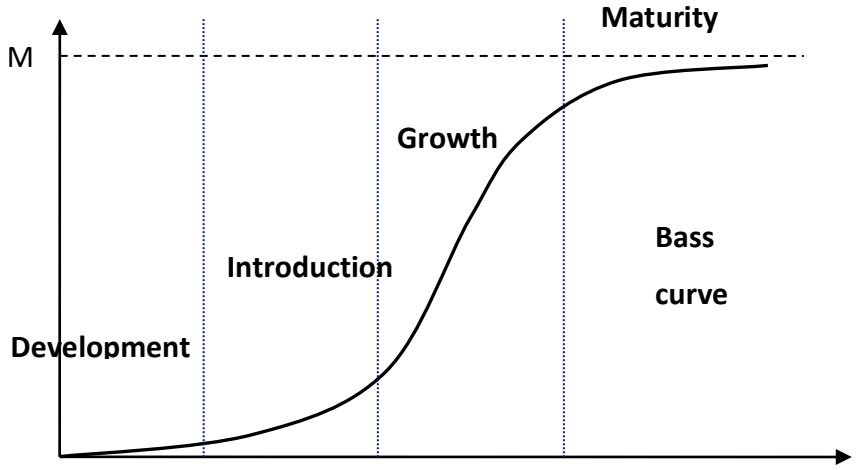

Figure 3-4 The S-shape diffusion curve of the BASS model

The basic function of the Bass diffusion model can be given as the mathematical formula below: (Bass, 1969; Mahajan et al., 1990; Nigel and Towhidul, 2006).

$$\frac{f(t)}{1-F(t)} = p + qF(t) \qquad (1)$$

where:

- $f(t)$ is the rate of change of the installed base fraction (the fraction of the potential market that adopts the new product at time t)
- $F(t)$ is the installed base fraction (the fraction of the potential market that has adopted the new product up to time t)

Thus:

$$\mathrm{F(t)} = \int_0^t \mathrm{f(t)dt}$$

- p is the coefficient of innovation

- q is the coefficient of imitation

The f(t) function has the shape of a bell, indicating that as time goes by, the number of new purchasers increases until it reaches a peak, and then it declines. Use of the Bass model requires estimating three parameters: the innovation coefficient p, the imitation coefficient q, and market potential M. If n(t) is the number of adopters at time t, it can be said that n(t)=Mf(t), Analogously, if N(t) is the cumulative number of adopters at time t, then N(t)=MF(t). Alternatively, it is possible to describe the behaviour of n(t)by the following equation:

$$\mathrm{n(t)} = \mathrm{p[M - N(t)]} + \frac{q}{M}\mathrm{N(t)[M - N(t)]} \qquad (2)$$

where, p [M-N (t)] represents the number of adopters who are not affected by those who are already using the new products; these are called the innovation adopters. In contrast, the term $\frac{\mathrm{q}}{\mathrm{M}}$N(t)[M-N(t)] represents adopters who are influenced by the number of previous buyers. If the initial conditions N (0) = 0, the equation above can be written as:

$$\mathrm{N(t)} = \mathrm{M}[\frac{1-\mathrm{e}^{-(\mathrm{p+q})\mathrm{t}}}{1+\frac{q}{p}e^{-(p+q)t}}]; \qquad (3)$$

$$n(t) = M\{\frac{p(p+q)^2 e^{-(p+q)t}}{\left[p+qe^{-(p+q)t}\right]^2}\}; \quad (4)$$

The coefficients of innovation and imitation remain constant over time in the BASS model; however, they can be changed in the real world by other factors such as technology improvement, policy effects and market conditions. Therefore, a generalised Bass diffusion model was developed to consider variables that can affect innovation and imitation over time (Bass et al., 1994; Park et al., 2011). This dissertation used the generalised Bass diffusion model to forecast the EV promotion trend in China. To consider more variables and their differing effects on the innovation and imitation factors, Chapter 6 developed a new diffusion model based on the generalised Bass model and used it to simulate the potential trend of EV promotion under different policy support and external market conditions. The details of the generalised Bass diffusion model and the diffusion model that was used in this study are introduced in detail in Chapter 6.

3.4 Multi-criteria Analysis

In order to evaluate the current effectiveness of the EV promotion progress and policy instruments in China, a decision-making approach should be established to evaluate the performances of the different EV promotions in different pilot cities and their different policy instruments. Cost-benefit analysis (CBA), cost-effectiveness analysis (CEA), economic-effects analysis (EEA) and MCA are all commonly used as decision-making evaluation methods for. However, many methods (including EEA, CBA and CEA) focus on comparing different forms of input or output by giving them monetary values, but with certain social issues, such as transport and the environment, it is difficult to achieve a monetary assessment of all criteria (Tudela etal.,2006). For example, Scannella and Beuthe (2003) observed in their study that some criteria such as promoting a public image are difficult to assess in monetary terms. Therefore, MCA is increasingly used in environmental policy and transport project evaluation in which the complexity of the issues and the limitations of economics-based methods (such as CBA and CEA) are apparent (Macharis and Bernardini, 2014; Browne and Ryan, 2011; Turcksin et al., 2011). MCA is a decision-

making approach based on deriving an overall score for the alternative options that are being analysed. It considers multiple criteria in decision-making environments and provides a highly structured decision-making technique (Department for Communities and Local Government, 2009; Nwokoagbara et al., 2015). MCA is more suited to performing comprehensive evaluations in transport because it can examine the social, economic and ecological aspects of sustainable transport projects in terms of measuring impacts against a wide range of criteria (Hickman et al., 2012; Vermote et al., 2014).

In this dissertation, MCA is used to evaluate the effectiveness of China's EV demonstration program because EV development covers such a wide range of factors. For the early EV introduction period, the primary objectives of the demonstration program were not economic benefits but environmental improvement and market penetration. MCA is mainly formed by 5 core components: goals, inputs, alternatives (options), criteria and weights. Setting criteria is used to evaluate the performance of alternatives in different aspects, and weights for the

relevant criteria are given to represent their relative importance. These factors are numerical and determined by stakeholder preferences based on background information and experience (Nwokoagbara et al., 2015). These factors are identified by the views of the experts who represent their stakeholder groups in the EV development, such as the national government, EV manufacturers, local governments, academic institutions and other service operators. The MCA decision-making approach is shown in Figure 3-4, and the details of the MCA process used in this dissertation are introduced in Chapter 7.

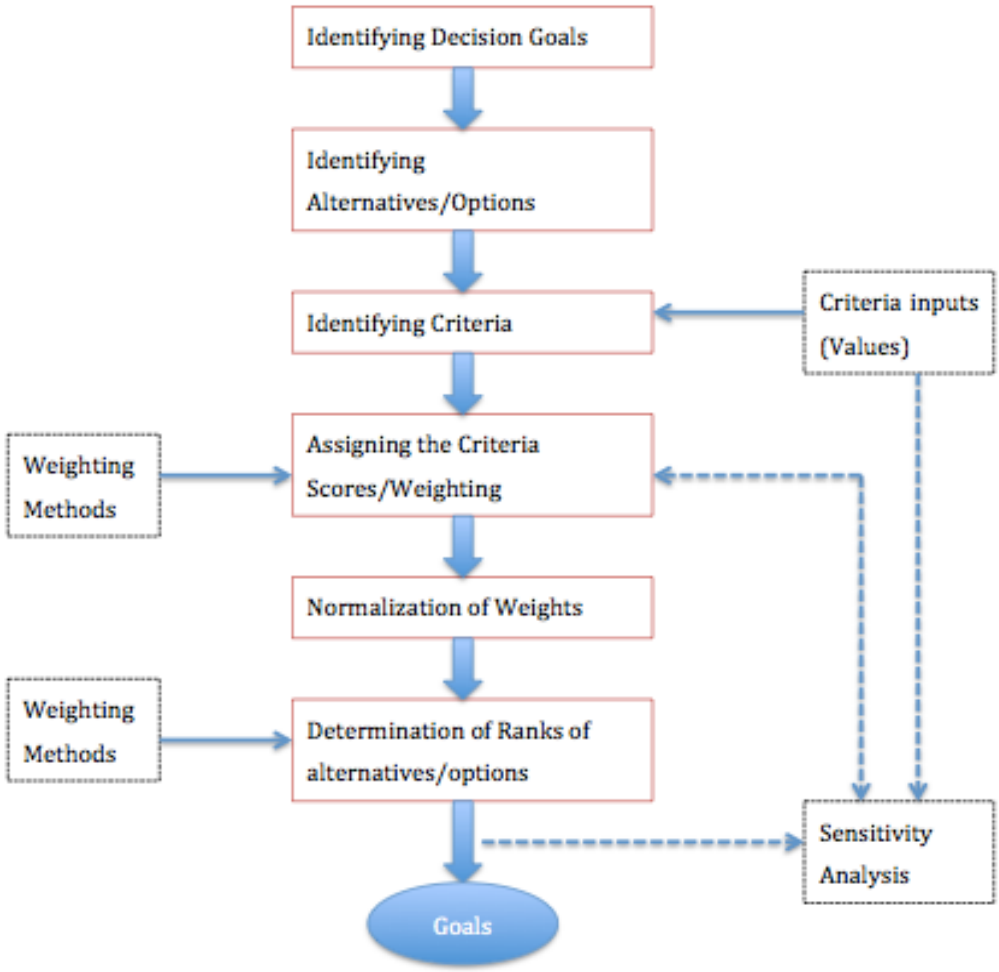

Figure 3-5 The steps in MCA

3.5 Scenario analysis

In order to analyse the possible future of EV development given alternative possible outcomes, and also based on the lack of historical data on EVs (because the technology is new), scenario analysis was used in this study. Scenario analysis does not rely on historical data and can be used to evaluate all potential outcomes and

their implications. Because the future of development policy and other situations is highly complex, work with scenarios can analyse possible future events by considering alternative possible outcomes. In addition, scenario analysis "*often integrates within itself different methodological manners of tackling issues, such as scientific techniques, evaluation techniques and decision-making techniques*" (Kosow and Gaßner, 2007).

In this dissertation, scenario analysis is used mainly for two reasons. First, as an emerging market, EV promotion in China lacks data. For example, EVs have only achieved commercialisation in the private user market in China in the last 5 years; there are fewer data and statistics on consumer attitudes and behaviours, and on actual vehicle driving performance. In addition, because of the limitations of existing policy incentives, it is also difficult to imagine how the different policy incentives and instruments will affect EV deployment. Therefore, some assumptions are required in establishing the scenarios for discussing these different situations. Second, this dissertation not only evaluates the past and present performance of EV deployment

in China but also investigates the country's potential future EV development. Because of the uncertainty and the flexibility of future conditions, scenarios analysis is necessary for considering the different possibilities.

Scenario analysis integrated with the evaluation and diffusion models is used in Chapter 5 and Chapter 6 in this dissertation. In Chapter 5, scenario analysis is used to analyse the potential future energy mix changes in China and their impact on EV development. Because it is difficult to accurately predict future power mix changes, the scenarios assume different potential electric generation mixes in 2020 and 2030. The scenario analysis in Chapter 6 is used to assume the possible changes in external factors and their implications for EV penetration. These external factors include technology improvement, vehicle cost, fuel cost, policy incentives and infrastructures. Because EVs in China have not been commercialised for long, and the current policy subsidies have only implemented for a short time, it is difficult to predict the future trends in EV promotion and related changes in policy incentives. To consider the different possible policy incentive changes and external situations, three scenarios

are developed in Chapter 6: one is based on the current situation by considering that vehicle performance, cost and infrastructure will not change in the future; one is more market based by considering that the impacts factors will change over time (commonly known as the business-as-usual scenario); and the last one considers a more positive environment for EV development, such as strong policy incentives, EV technology breakthroughs and rapid infrastructure growth (positive development scenario).

3.6 Case studies

Case studies are an ideal methodology for in-depth investigation (Feagin et al., 1991), and they can be used to analyse problems from actual cases and the viewpoint of the participants (Tellis, 1997). A case study is an "investigation and analysis of a single or collective case, intended to capture the complexity of the object of study" (Stake, 1995; Hyett, 2014), and case studies have been widely discussed and developed by many researchers (Creswell, 2013; Flybjerg, 2006; Stake, 1995; Yin, 2009). There are two main advantages to case study research. First, case studies can capture the

complexity of a social phenomenon because they can evaluate changes and innovations in an event or process and allow for thorough exploration by considering multiple perspectives (Peck et al., 2001; Li, 2013). Second, case studies offer substantial flexibility in the use of multiple data sources (Li, 2013; Yin, 1993; Creswell, 2009). According to Li (2013),

> "*Unlike a quantitative research which heavily relies on a single source of data, case studies favour the used of various data sources, such as documentation, interview and observation, in addition to quantitative data*".

In this research, considering the research gaps that were identified in the literature review, this dissertation focused on local-level studies of the EV development in China in addition to the national level. Because of the differences in China's regional conditions and complexity, case study research is used for in-depth local-level investigations. In Chapter 4, in consideration of the different regional electricity mixes, Beijing, Shanghai, Changchun, Chongqing and Shenzhen are chosen for case studies to simulate the differences in EV development and the effects of the differences on energy saving and CO_2 emissions in the different cities. In Chapter 7, the case studies of 4 pilot cities (Beijing, Shanghai, Hangzhou and Shenzhen) are used

to evaluate and compare the effectiveness of the current EV demonstration program by considering the different local-level conditions and policies. The varying regional complexity factors (including policy environments, market conditions, industry bases, power mixes) are considered in the case studies, and multiple sources of information are collected through documentation, interviews and observation. The investigations of these case studies are expected to describe the features and real-life performance of local EV development in China.

3.7 Interviews and Fieldwork

Both primary and secondary data are used in this study for simulation and analysis. The secondary data in the study are mainly collected from documental research and also from unpublished internal institutional resources that were collected during the fieldwork. The primary data used in this study are all collected from the interviews in the field. In order to understand the specific, timely and authoritative information in China, fieldwork and interviews are the two main methods used in this study for the information and data collection, and opinions were also collected from experts for

the data setting (especially in Chapter 7). The findings presented in this dissertation are the result of 4 years of research, and the author conducted 3 major sets of fieldwork: in July-August 2012, January 2014, and September-October 2014. The first two sessions were conducted in Beijing and Tianjin, and for the final session, the author visited four pilot cities (Beijing, Shanghai, Tianjin, and Shenzhen).

EV development involves a variety of elements including technology R&D, the vehicle industry, policy, consumer behaviour, infrastructure and the grid system. Therefore, in this dissertation, the interviews focus on the multiple stakeholders in the EV development process, including the national government ministry, local government departments and NGOs (such as the NDRC and the local government EV promotion offices), grid companies (such as State Grid), academic institutions (such as Tsinghua University and the Beijing Institute of Technology), government-related institutions (CATARC, China Electric Power Research Institute, China Electricity Council and so on), EV manufacturers (such as BYD and BAIC) and other EV-related companies (such as EV taxi companies). A total of 22 people were interviewed, all of whom were high-level

specialists in their fields. They included chief engineers and managers from EV manufacturers, university professors, directors (or deputy directors) and EV project leaders from institutions, and a director from a local government office. Among these interviewees, there were 6 experts from the Experts Group of the National 863 Electric Vehicle key project, and these experts were also involved in the Expert Inspection Group for evaluating the EV demonstration program; that group was organised by 4 government ministries (MOF, MIIT, NDRC and MOST). The details of the interviewed organisations and agencies and the distribution of the interviewees are introduced in Table 3-2.

Table 3-2 The information on the interviewees in this dissertation

Organisations	Number of interviewees	Interview dates
China Automotive Technology and Research Centre (CATARC)	4	Jul 2012; Jan 2014; Sep 2014
China Electric Power Research Institute	1	Jul 2012
China Electricity Council	1	Jul 2012
State Grid corporation of China	1	Aug 2012
China Association of Automobile Manufactures (CAAM)	1	Sep 2014
China Society of Automotive Engineering	1	Sep 2014

(SAE-China)		
GIZ China	1	Aug 2012
Changan auto Company	1	Sep 2014
BYD Company Limited	2	Jul 2012; Sep 2014
Qingyuan Electric Vehicle Co., Ltd	1	Jul 2012
Tsinghua University	1	Sep 2014
Beijing Institute of Technology	2	Jul 2012; Jan 2014; Sep 2014
Shanghai New Energy Vehicle Promotion Office	1	Sep 2014
Shanghai Anting Auto City, International Electric Vehicle Demonstration Zone	2	Sep 2014
National Development and Reform Commission (NDRC) in Shenzhen, Energy Efficiency and New Energy Vehicles Pilot City Leading Group Office	1	Sep 2014
Shenzhen Pengcheng EV taxi company	1	Sep 2014

3.8 Qualitative and Quantitative Methods

The main context of this dissertation is analysing EV promotion from various aspects that focus not only on technology and industry but also on market behaviour and policy aspects. Therefore, both qualitative and quantitative methods are used in this dissertation. Specific methods include: documentary research, interviews, life-cycle analysis, diffusion model, multi-criteria approach, scenario analysis, and case studies.

The relationships between the research methodology and research questions are shown in Table 3-3.

Table 3-3 Relationship between the research methodology and individual chapters

	Quantitative analysis	Qualitative analysis
Chapter 4		Documentary research; interviews
Chapter 5	GREET model; case studies; scenario analysis,	Documentary research, interviews
Chapter 6	Diffusion model; scenarios;	
Chapter 7	Multi-criteria approach; case studies	Documentary Research; interviews

Chapter 4 used qualitative methods to discuss the current status of EV development, including the industry, technology, policy and market conditions. The discussed information and evidence were mainly collected from two sources: documentary research and interviews. Through the documentary research, the history and current status of EV development in China are understood. The interviews provide more practical experience and timely data to supplement the information from the

documentary research give more specific comments based on the views of experts in EV-related fields.

Chapter 5 and Chapter 6 mainly focus on quantitative analysis using the GREET model and the diffusion model, respectively. In Chapter 5, the input data and information used in the model simulations were mainly collected from documentary research, including journals, the National Statistical Yearbooks, government ministry reports, state's grid reports and unpublished internal sources from research institutions. In addition, some timely data and non-public data were also collected from the interviews.

Chapter 7 combined both quantitative and qualitative analysis. In order to evaluate the EV demonstration program by considering more comprehensive aspects, Chapter 7 developed an evaluation framework by identifying various criteria. In the evaluation process, some indicators were quantitative, such as driving range, promoted EV numbers, infrastructure numbers, etc.; some were difficult quantify (such as R&D

ability, EV manufacture levels, and business mode effectiveness and non-financial incentives); and some indicators could not be quantified at all because of the lack of data (such as vehicle reliability and utilisation of charging facilities). For these indicators, qualitative analysis was required, and these indicators were identified through the expert interviews. In addition, the weights allocated to the criteria also required qualitative analysis based on the experts' opinions. The quantitative indicators were mainly collected from the documentary research and the interviews conducted during the fieldwork, and the qualitative indicators and the weights for each criterion were also based on the experts' (stakeholders') subjective judgments. The details of the criteria setting and measurement are introduced in Chapter 7.

Chapter 4: The promotion of Electric Vehicles (EV) in China: Lessons from the current EV demonstration

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4.1 Introduction

Electric vehicle (EV) technology has gained increased worldwide interest as an alternative solution to the conventional car so that road transport can effectively contribute to the reduction in oil dependence, GHG emissions and other forms of pollution (Sánchez-Braza et al., 2014; Yang et al., 2013). China considers the development of EVs as an essential strategy for the State to solve the serious issues faced in terms of energy security and air pollution (Zheng et al., 2012; He and Chen, 2013). The proportion of imported oil of the total oil consumption in China has increased from 7.5% in 1993 to 53.5% in 2009, and China has already become the highest CO_2 emitting country in the world (2008). According to the IEA (2013), the transport sector in China accounts for around 8% of the total energy related GHG emissions. Other forms of air pollution such as smog have also occurred with greater frequency in recent years; since the beginning of 2013, almost one fourth of the country's territory has been blanketed by smog and more than 600 million people have been affected (Zheng et al., 2014). All these issues will become more serious due to the rapid growth of vehicle ownership (Hao et al., 2011; Zhang et al., 2013).

The vehicle stock in China has increased from 0.8 million in 1990 to 137 million in 2013, which ranked just behind the vehicle stock in US in the world, and Hu et al. (2010) believe that if the current pattern continues, the private vehicle population in China may reach 400 million by 2030. The independent R&D capability on internal combustion engine vehicles (ICEV) in China is far behind the global competition. However, EVs (especially the battery electric vehicle (BEV)), which use a battery power system instead of traditional engines, could make up for the lack of engine technology in China. Therefore, the development of EVs has been seen as a good opportunity for the Chinese auto industry to catch up with the global competition (Yang, 2009). The Chinese government has therefore initiated a series of demonstration programs to develop and promote EVs (2009-2012).

In the early 1990s, China began to see EV development as a key component of the national strategy. Over the last 20 years, the Chinese government has continuously improved and enriched the electric vehicle development strategy and it has invested in not only EV related technology R&D but also in the EV market (Zheng et al., 2012).

At the beginning of 2009, the "Ten cities thousand vehicles" large scale demonstration project was jointly initiated by four Ministries of the Chinese Government (Zheng et al., 2012; CATARC et al., 2013). At first, 13 cities were designated as demonstration cities, which was then increased to 25 cities. Furthermore, the “Energy-saving and new energy vehicles development plan for 2012-2020” announced in 2012 by the State Council of China proposes that the accumulated sales of BEV and plug-in hybrid electric vehicles (PHEV) should reach 500,000 by 2015 and approach 5,000,000 in 2020 (State Council of China, 2012; Yang et al., 2013; Hao et al., 2014).

Although the Chinese government has invested a lot of resources in EV development and promotion, at present EVs still occupy an extremely limited part of the auto market in China; this is especially true in the private passenger vehicle market, where they have not been seriously considered by potential purchasers. By the end of 2012, the total ownership of Alternative Fuel Vehicle (AFV) (including BEV, HEV, PHEV and Fuel cell electric vehicles (FCEV)) was 27,432 and 23,032 of these AFVs are used for

public services, with only 4400 AFVs being found in the private passenger vehicle market. This means that only 10% of the primary promotion goal has been achieved. In comparison, the AFV population in the United States has already reached over 70,000 (2012), and in 2012 the annual sale of AFVs in the USA rose to 53,000 (CATARC et al., 2013).

This paper analyses the underlying issues in the process of EV development in China by considering the experience of the existing EV demonstrations. Following this, recommendations on how to improve the EV penetration process and solve the existing problems are made. The remainder of this paper comprises four main sections. The second section introduces the policy background and the existing EV demonstrations in China in terms of scope, rules and requirements, while the third section describes the results of the EV promotion status during the demonstration program. Based on the results introduced in Section 3, this study combines the views of the experts from various different EV related fields and considers the main issues found in the pilots cities; the root causes of these issues are discussed from several

different perspectives, such as the auto industry and policy aspects (Section 4). Finally, the last section provides some policy recommendations in order to improve the policy-oriented approach being developed for EVs in China.

4.2 Methodology

Data collection and Interview

To investigate the effectiveness of the current EV deployment process, the large-scale demonstration program (from 2009 to 2012) is chosen as the focus for discussion. Large amounts of data and information are required to present the results of the program and discuss the issues occurred. Primary data for this study is from 14 in-depth interviews during the author's fieldwork in July-August 2012 and January 2014. Each interview was based on open-ended communications and targeted high-level experts and managers came from various different EV related fields, including research institutions, universities, Grid Companies, Government departments, Auto manufactures, etc. In addition, some interviewees were part of the result assessment experts' team for the demonstration program (organised by the 4 ministries: Ministry

of Finance (MOF), Ministry of Science & Technology (MOST), Ministry of Industry and Information Technology (MIIT), National Development and Reform Commission (NDRC)). These experts have first-hand information and views regarding the promotion status of the pilot cities. Among the 14, 9 of the interviewees were from Beijing and Tianjin and prepared to be interviewed face to face. Phone and email interviews were used for the other 5 interviewees, and they live in other pilot cities such as Shanghai and Shenzhen. To comprehensive display the results of the demonstration program and minimize individual bias, author used the information that is either triangulated by multiple interviewees or confirmed by published sources. Other secondary resource such as some unpublished internal resource from the government and institutions are also collected from the fieldwork and used in this study.

4.3 EV demonstration in China

In China, the main targets and directions for the nation's economic development strategy are based on a five-year planning cycle ("Five-Year Plan"). The development

process for EV policy in China can be reflected through the national Five-Year Plan and can be traced back to 1990s. The EV demonstration programs that were instigated in 2009 can be seen as the cumulative product and realisation of China's EV development policies over the last 20 years (Zheng et al., 2012).

4.3.1 Policy background

The development of the EV first appeared as a National Key Scientific and Technological Project in the 8th Five-Year Plan period (1991–1995). Subsequently, EV development has been seen as one of the key elements in all the subsequent Five-Year Plan periods. In the 9th Five-Year Plan period (1996–2000), the ''National Clean Vehicle Action'' program led by 13 national Ministries pointed out that Compressed Natural Gas (CNG) and Liquefied Petroleum Gas (LPG) vehicles were considered as short-term technological alternatives, whereas EVs were considered as a mid to long-term technological measure. With the 10th Five-year plan (2001-2005), the development of EV received more attention and the "EV key project" was incorporated into the "863 project" of the Ministry of Science & Technology (MOST).

The new generation of EV technology has been considered as the major direction for auto technology innovation. Since then, the ‘‘Three verticals and Three horizontals’’ R&D strategy of EVs has been established (Figure 4-1).

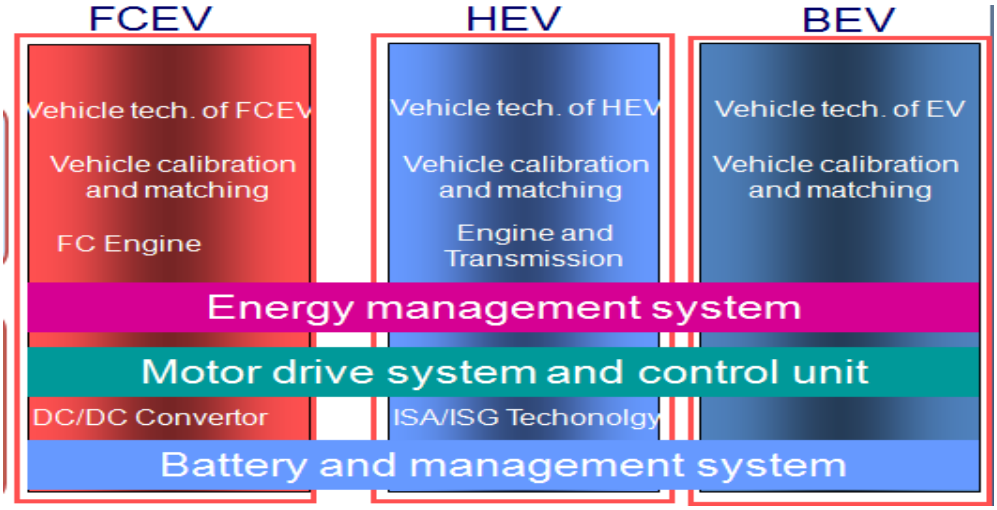

Figure 4-1 The ‘‘Three verticals and Three horizontals’’ R&D strategy in the 10th Five-year plan (Source from MOST, 2010)

The ‘‘Three verticals’’ refer to the three types of AFV, namely FCEV, hybrid electric vehicles (HEVs), and BEV; the ‘‘Three horizontals’’ refer to three key auto-related technologies (MOST, 2010; Zheng et al., 2012; Liu and Kokko, 2013). In the 11th Five-year plan (2006-2010), the National “The 11th Five-Year” Energy-Saving and New Energy Vehicle Key Project" was promoted and investment in this project was

increased to 1.2 billion CNY (125 million GBP)[1]. Of this 1.2 billion, 1.15 billion CNY was used to further reinforce the R&D activities of EVs and to promote the commercial market. In the current 12th Five-Year period (2011-2015), the National "The 12th Five-Year" EV key Technology Industrialization Project has been promoted and the Government is expected to invest 3 billion CNY (312.5 million GBP) to develop the key components of EVs, primarily focusing on batteries, including the development of next generation of battery and motors.

4.3.2 "10 cities 1000 vehicles" program

The "ten cities thousand vehicles" large-scale demonstration program was initiated on 17th February 2009 by four ministries: the Ministry of Finance (MOF), the Ministry of Science & Technology (MOST), the Ministry of Industry and Information Technology (MIIT) and the National Development and Reform Commission (NDRC). The roles and functions of each ministry are different (See Table 4-1). The demonstration program planned to promote AFVs (mainly EVs) in around ten medium or large cities in China and at least 1000 AFVs in each city over the next three

[1] Exchange rate used in this dissertation is 1GBP = 9.6 CNY

years. On 24th February 2009, the Notice on "Experimental Demonstration and Promotion of Energy Saving and New-energy Automobiles" (hereafter referred to as the ‘‘Notice’’) was issued by MOF and MOST to specify the details of the demonstration program (Zhang, 2011).

Table 4-1 The roles and functions of each ministry

Ministries	Roles and Functions
Ministry of Finance (MOF)	Subsidies to support EV demonstration and tax policies to support the development of energy-saving vehicles.
Ministry of Science & Technology (MOST)	Science and technology research related to EVs, primarily through the establishments of national science and technology projects such as the ‘‘863 program (State High-tech research development plan, referred to as 863 program)’’ and the establishment of the AFV industry innovation alliance.
Ministry of Industry and Information Technology (MIIT)	To form detailed rules and regulations for AFV access, investigate EV industry development strategy, and establish recommended models directory of energy-saving and AFV demonstration.
National Development and Reform Commission (NDRC)	To launch the "automobile industry restructuring and revitalization plan", study energy-saving and new energy vehicle "Technology Policy", and to incorporate EVs into "National Key Energy Saving Technology".

4.3.3 Pilot cities

After discussion, 13 pilot cities were selected (Feb, 2009): Beijing, Shanghai, Chongqing, Changchun, Dalian, Hangzhou, Jinan, Wuhan, Shenzhen, Hefei, Changsha, Kunming and Nanchang. In June (2009), Tianjin, Haikou, Zhengzhou, Xiamen, Suzhou, Tangshan, Guangzhou were awarded the same status for the second batch of demonstration cities. In addition, In August (2009), five more cities were chosen: Shenyang, Chengdu, Hohhot, Nantong and Xiangfan. Therefore, 25 cities constituted the demonstration program in 2009. Most of these pilot cities are either provincial capitals or large cities in China; the government only selected medium to large cities due to their strong economic capacity and the pollution caused by their continually expanding vehicle fleets (Zheng et al., 2012). These cities applied to the program for two main reasons: first, many cities (such as Zhengzhou, Tianjin, Changchun, Hefei, Beijing, Shenzhen, Wuhan, Shenyang, etc.) have an existing local auto industry, therefore they consider that it is a good opportunity to develop their local industry and in turn boost their local economy. However, other cities which do not have a local auto industry also think it's an opportunity for them to attract auto or auto

related companies by enjoying the benefits of the subsidies policy. Second, some cities such as Xiamen, Dalian, Hangzhou, Suzhou, Haikou, Hangzhou, Beijing, Kunming, etc. have economies based on tourism; they believe that the demonstration program can help them to build a clean and green city environment and can also enhancing the city's image, which can in turn help them to improve the level of tourism activity.

In order to accelerate the promotion of electric vehicles in the local area, incentives are provided by the local government in addition to the resources provided from central government. These additional subsidies include extra financial inducements for EV buyers; for instance, the Shenzhen government will give a further 30,000 CNY for a PHEV purchase and provide another 60,000 CNY for BEVs based on the 60,000 CNY subsidy provided by central government. For example, the original sale price of a BYD e6 is about 320,000 CNY, however with both the national and local subsidies the actual purchase price is around 200,000 CNY in Shenzhen, which is significantly reduced but still higher than the price of a similar ICEV (For example, the Toyota

Corolla ranges from 100,000 to 150,000 CNY). In addition, in some metropolitan areas such as Beijing and Shanghai, EV buyers can gain exemptions from vehicle driving restrictions and car license restrictions.

4.3.4 Vehicle eligibility

The "Notice" is also directed by the program scope and vehicle eligibility. Three main kinds of AFV are promoted in the demonstration program and these are BEVs, HEVs and FCVs. The subsidies in the program depended on the vehicle types and the energy saving performance (for HEVs). The details of the subsidies in the demonstration are shown in Table 4-2. It should be noticed that the AFVs subsidies identified in the table are all focused on public service vehicles such as buses, taxis, postal service vehicles, clean vehicles and the government fleet; the private vehicle market was excluded. The subsidy is provided to consumers who buy EVs directly, and the purchaser can be a company or a department. There are two reasons given by MOF and MOST to explain why the initial focus is on public vehicles. First, there are still many constraints that will limit the early market introduction of EVs, for

instance battery performance, safety and maintenance, and the supporting infrastructure (Zhang et al., 2013). Therefore, it will be difficult for private consumers to accept EVs immediately and the promotion of EVs needs to proceed gradually. However, public service fleets have a unified operational management and this is considered to be easier to monitor and maintain than private vehicles. Second, public service fleets such as buses and taxis are the major transportation modes and they can account for a significant proportion of the total vehicle in the medium–large sized cities in China. Therefore, the development of public service vehicle electrification is expected to have significant demonstration effects (Zheng et al., 2012).

Table 4-2 Subsidy standards in the demonstration program

BEV	• **A pure electric bus: 500,000 CNY** • **A pure electric car: 60,000 CNY**
HEV	• A hybrid electric bus: from 50,000 to 420,000 CNY (depending on the energy saving performance) • A hybrid electric car: 3000 to 50,000 CNY
FCV	• A fuel cell bus: 600,000 CNY • A fuel cell car: 250,000 CNY
Subsidies directly provided to consumers who purchase electric vehicles	

Source from MOST (2010)

After one year's demonstration of public service EVs, the Chinese Government decided to include private passenger cars in the demonstration program and to providing subsidies for the private buyers of new energy vehicles in six cities (from 1st June 2010): Shanghai, Changchun, Shenzhen, Hangzhou, Hefei and Beijing. For private AFVs, only BEVs and PHEVs are considered as the subsidy funds focus on private EVs allocated to auto manufacturers; private users can purchase the EV at a preferential price (including subsidies). According to the different types of AFV, the goals of the promotion plan in each pilot city are shown in Table 4-3 and Table 4-4. The 25 pilot cities planned to promote a total of 51,707 AFVs in the public vehicle service field by the end of 2012, and the six cities chosen for private electric vehicle demonstration planned to sell 70,000 AFVs in total (CATARC et al., 2013).

Table 4-3 The AFV promotion plan in pilot cities in the public service sector (2009-2012)

	Shenzhen	Beijing	Shanghai	Changsha	Hangzhou	Wuhan	Dalian	Guangzho	Jinan	Tianjin	Zhengzho
BEV	1000	4130	2661	800	1130	500	200	600	960	430	900
HEV	8000	870	1300	3200	1870	2000	1012	1450	650	1070	600
FECV	0	0	196	0	0	0	4	0	0	0	0
Total	9000	5000	4157	4000	3000	2500	2400	2050	1610	1500	1500
	Tangshan	Hefei	Chongqing	Shenyang	Nantong	Xiangfan	Haikou	Chengdu	Xiamen	Changchu	Kunming
BEV	830	690	575	100	430	970	400	920	655	0	90
HEV	650	710	575	1000	670	100	650	110	355	1000	910
FECV	0	0	0	0	0	0	0	0	0	0	0
Total	1480	1400	1150	1100	1100	1070	1050	1030	1010	1000	1000
	Nanchan	Suzhou	Hohhot								
BEV	240	100	30								
HEV	760	900	570								
FECV	0	0	0								
Total	1000	1000	600								

Source from “Energy-saving and new energy vehicles Yearbook (2011)”

Table 4-4 The EV promotion plan in each pilot city in the private market (2009-2012)

	Beijing	Shenzhen	Hefei	Shanghai	Hangzhou	Changchun
BEV	23000	3000	13100	19000	10000	2000
PHEV	7000	22000	8000	1000	10000	14000
Total	30000	25000	21100	20000	20000	16000

Source from “Energy-saving and new energy vehicles Yearbook (2011)”

4.3.5 Charging infrastructure

The charging infrastructure is a necessary condition for the development of electric vehicles, especially the BEV. However, the program has not yet provided incentives for infrastructure construction, and the local government, the grid company and the EV manufacturers are the main bodies responsible for building charging facilities. Different local governments have provided different incentives; in some cities, the government has provided subsidies to cover a certain proportion of the charging station construction costs (for example, 30% the charging station equipment costs will be covered by subsides in Guangzhou), whereas other cities are prepared to eliminate the grid capacity expansion fees required as part of charging station construction and some cities provide the land used for charging station construction.

4.4 The Results of the demonstration program

By the end of the 2012, the three-year period demonstration program ended. In December 2012, the four Ministries (MOF, MOST, MIIT and NDRC) jointly arranged for experts to visit the pilot cities for fieldwork and to inspect the results of EV

promotion in the 25 pilot cities (including the six private vehicle pilot cities). This section will describe the development status of the different types of electric vehicles over the three years and the results of the growth in the charging infrastructure. In addition, various issues that occurred and were reflected in the demonstration will also be summarised.

4.4.1 The number of AFVs promoted in the demonstration

According to the reports from the expert group (2012), the total number of AFVs promoted in 25 cities is 27,432, of which public services vehicles accounted for 23,032 and private purchases accounted for only 4400 vehicles. It is clear that although the demonstration has significantly increased the number of AFVs, it is still far away from the primary desired target of the demonstration plan (see Table 4-3 and 4-4). According to the statistics, only 60% of the promotion goal in public service and less than 10% of the primary promotion target for private consumers has been achieved (CATARC, 2013). Table 4-5 shows details of the promotion of the different kinds of AFVs in the demonstration program. From the perspective of vehicle

classification, the HEV, due to its long driving range, relatively low price and lower infrastructure dependence, is the most effective vehicle type in the demonstration program (Zheng et al., 2012). More than 15,800 HEV vehicles were bought by the end of 2012, accounting for 58% of the total number of AFVs. From the perspective of pilot cities, the top three cities that promoted the largest number of AFVs are Hefei, Shenzhen and Beijing, and the numbers of AFVs (including both public sector and private sector) promoted in these three cities are 4973, 3422 and 3388 respectively. In contrast, Nantong, Tangshan and Xiamen had the lowest number of AFVs purchased at less than 200 vehicles in each city. From the perspective of marketing, the top three cities with the highest number of AFVs used in the public service sector are Beijing, Shenzhen and Changchun. In the private sector, Hefei, Shenzhen and Shanghai are the top three cities with the highest number of EVs. The details of the AFVs promoted in each city and each sector are shown in Figure 4-2.

Table 4-5 The promotion of different kinds of AFVs in the demonstration

SECTOR	**Category**	**Subtotal**
Public Area	Hybrid Bus	12156

	Pure Electric Bus	2526
	Hybrid Passenger Car	3703
	Electric Passenger Car (Including BEVs and PHEVs)	6853
	Other Electric Vehicles	2194
Private Sector	Electric Passenger Car(Including BEVs and PHEVs)	4400
SUM in total / At the end of 2012		27432

Source from Wu (2013)

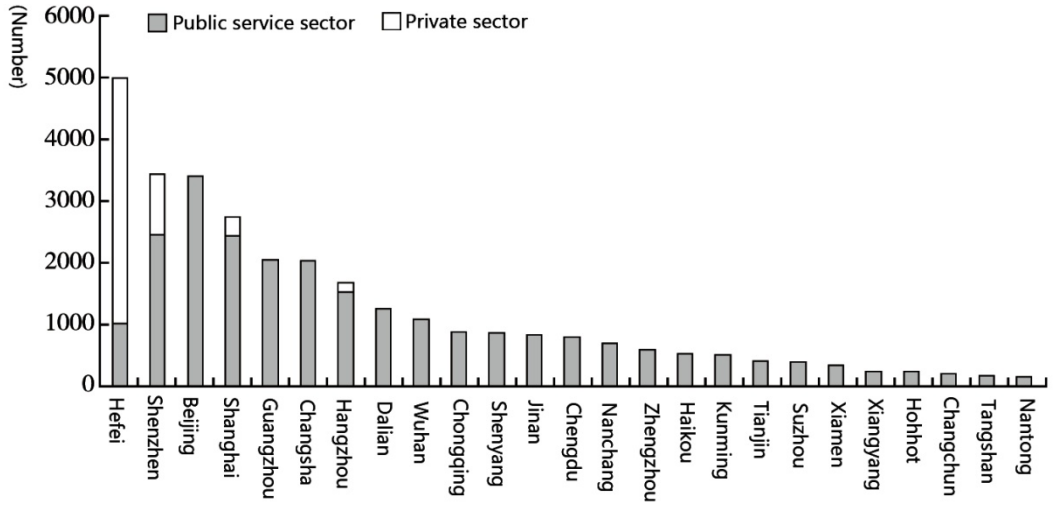

Figure 4-2 The numbers of AFVs promoted in each pilot city (Source from CATARC et al., 2013)

However, the promoted numbers do not reflect the extent to which the promotional goals have been reached. By considering their initial promotion plans, the actual completion rate of each pilot city by the end of 2012 has been shown in Figure 4-3. It can be seen from the diagram that the completion rate rankings are not consistent

with the EV promotion rankings (See Figures 4-2 and 4-3). For example, although Shenzhen has promoted 2440 AFVs and thus ranks 3rd in all 25 cities, its target completion rate is only 27%. In the public sector, only Guangzhou has completed its promotion plan (2000 AFVs). There are only seven cities that have completed more than 60% of their initial targets, and almost ten cities achieved less than 40% of their initial targets. In the private sector, Hefei promoted the most AFVs that achieved 19% of its targets, and Shenzhen, Shanghai and Hangzhou only achieved 4%, 2% and 1% respectively (See Figure 4-3). Beijing and Changchun did not make any progress within the private sector. The number of EVs purchased by the private consumer in these two cities is zero. It can be seen that almost all of the cities were overly optimistic in estimating the AFV promotion situation. In other words, these pilot cities did not seriously assess their development plans when they applied for the demonstration program.

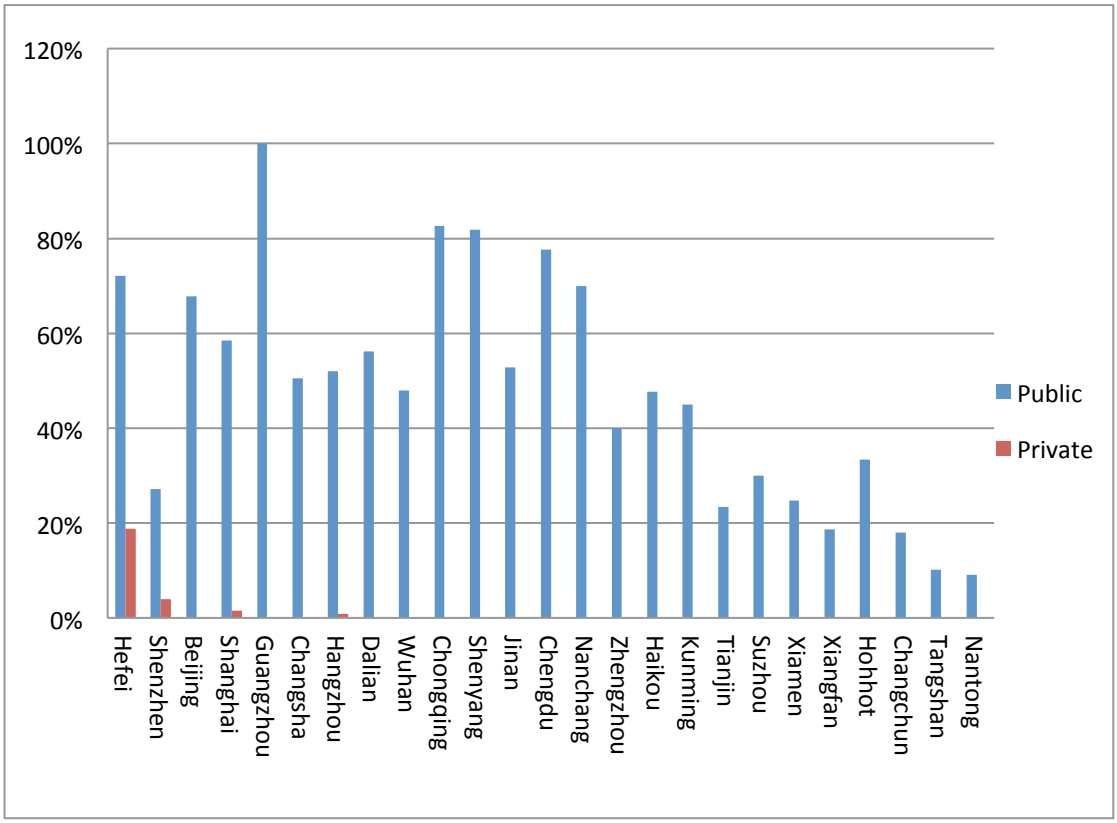

Figure 4-3 The target completion rate of AFVs in each pilot city (2009-2012)

4.4.2 Charging infrastructure in the demonstration

In order to create a good environment for electric vehicles, the charging infrastructures have also been developed over the three years. Besides hydrogen refuelling stations for FCVs, the charging infrastructures for BEV and PHEV in China are mainly focusing on three options: charging stations, battery swap stations and charging spots. Charging spots can be installed in public car parks, residential car parks and home garages; they use the slow charging method and are used mainly

during the night. The charging station is a professional charging facility, which allows fast charging, but it can have a significant impact on the grid, and this means that specialised distribution lines are required. Battery swap station can allow battery replacement in ten minutes, and the batteries will have a unified charged and be managed by the station; therefore, wait time is minimized. Currently, battery swap stations in Hangzhou can replace the battery in three minutes (CATARC, 2013). These three charging infrastructures are mainly constructed by three companies: the State Grid, the China Southern Power Grid and Putian New Energy. By the end of 2012, these three companies had built more than 383 charging stations (including 200 battery swap stations) and 18,000 charging spots nationwide. The details of the development status of these charging facilities in each pilot city are shown in Figures 4-4 and 4-5.

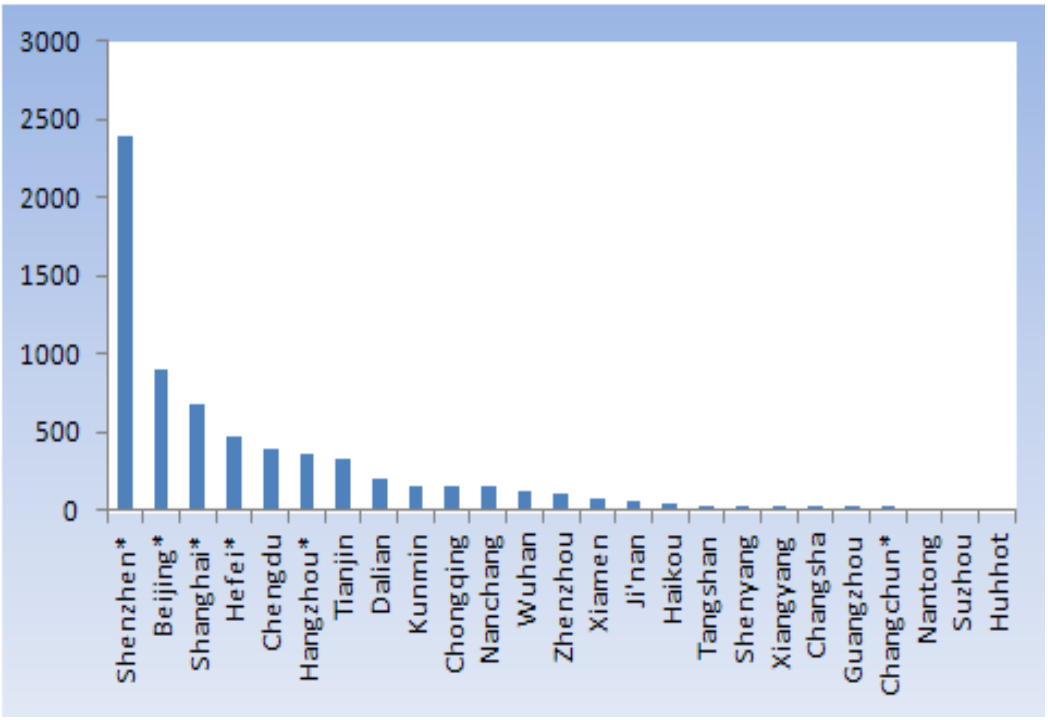

Figure 4-4 The number of charging spots in the 25 demonstration cities

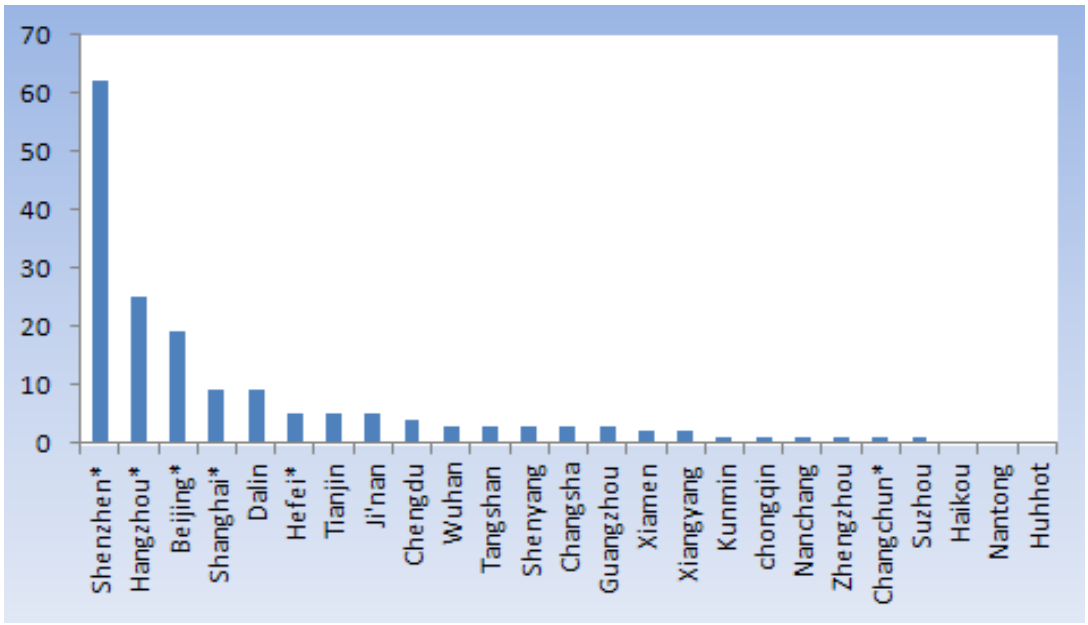

Figure 4-5 The number of charging stations (including battery swap stations) in the 25 demonstration cities

Source from Interview

4.5 Discussion

Based on the survey of the results of the demonstration program, the main conclusion is that although the development of EVs has made some progress in the three year demonstration period, it is still below expectations (See Tables 4-3, 4-4 and Figure 4-3). To highlight the issues that occurred in the demonstration process and to understand how these have hindered the development of electric vehicles, this study combines the views of various experts and scholars through interviews and fieldwork. Based on the views of expert interviews and the other information (Internal documents and non-public resources) collected from the fieldwork, the issues occurred in the demonstration process are discussed and commented on in this section. Their views can be divided into three aspects: vehicle issues and purchase behaviour, policy issues, and infrastructure issues.

4.5.1 Vehicle issues and purchase behaviour

Purchase cost

The purchase cost and the vehicle performance are considered to be two of the main barriers for AFV development (Lane and Potter, 2007; Kang and Park, 2011; Egbue and Long, 2012; Sierzchula et al., 2014). The experts from the interview also reached a consensus on this point. One expert from the China Automotive Technology Research Centre (CATARC) said:

> *"There is still a gap between the price of EV and ICEV even considering the government subsidies, which is a key issue which hinders people's willingness to purchase an EV in China if the EV do not show any significant advantage than ICEV."*

In simulations run by Zhang et al. (2013) on the acceptable purchase price of AFVs in China, the results show that 42% of respondents will accept an AFV purchase price between 60,000 CNY and 150,000 CNY and 20% of respondents would consider an AFV worth between 150,000 CNY to 250,000 CNY. Only 7% in total would be able to afford the high price AFV, which is between 250,000 CNY to 500,000 CNY. In addition, the survey by Tencent Auto (2014) on consumers' purchase behaviour shows that 40.48% of the respondents will not accept the price of the AFV being higher than the

traditional ICEV model, and 50.24% of the consumers will not accept a price gap between AFVs and ICEVs of more than 20%. However, the current price of AFVs (especially for the BEV) in the demonstration is still higher than the corresponding conventional cars even when considering financial subsidies. Compared to the similar traditional ICEV model, the current price gap of the three well developed EV models BYD E6, BYD F3DM (PHEV) and JAC Tongyue are 200%, 175% and 155% respectively (CATARC, 2013). It can be concluded that the high cost of BEVs is the one of the main reasons influencing BEV purchases in the demonstration program, especially in the private consumer sector. From another perspective, this cost issue also explains why the HEV plays a dominant role in the total number of AFVs developed in Table 5.

Vehicle performance

In addition to the cost issue, vehicle performance is also a particularly important consideration in the purchasing decision. Even if the subsidies can reduce the price gap, the consumers won't consider the EV if they are dissatisfied with the vehicle performance (Egbue and Long, 2012, Sierzchula et al., 2014). Some studies on public

acceptance of AFVs in China (Xu and Xu, 2012; Zhang et al., 2013) have shown that the vehicle range is the main factor considered by the Chinese AFV's buyers and this includes safety, reliability, comfort, speed, and practicality. Especially for the BEV, the range, charging time, safety and reliability are considered as the primary promotion challenges. Some studies have found that the average daily mileage of vehicles is not significant, for example the GM survey shows that more than 70% of the US daily car mileage is less than 64 km (Zhang, 2011). According to the statistics for EV users in the Shanghai International Electric Vehicle Demonstration Zone (SIEVDZ) (Cao, 2012), the average daily car mileage is 51 km (See Table 4-6). Most of the EVs developed in the program can provide driven with a range of around 100-180 km, thus meeting the normal demand. However, there is evidence that the expectation and requirements of consumers on the range of EVs is much larger than the average daily mileage. According to the survey conducted by Tencent Auto (2014), the range of the AFV is the second highest ranked factor (following price issues) that significantly affects the decision-making of consumers. A similar survey of EV test drives by SIEVDZ showed that 83.7% of the test drivers expressed concerns about the driving range and more

than 50% of the respondents preferred EVs with a driving range of 160-200 km or more (Cao, 2012). Based on the interviews, the views of experts are different. The manager from BYD considered that anxiety regarding driving range is the most important issue for consumers, therefore BYD chose the development of PHEVs (such as BYD "Qin") as the main direction for the private car market. However, some experts from Grid companies and other vehicle manufactures (such as BAIC) considered that the anxiety is a "false proposition"; the expected driving range is much more than their real daily demand. They argue that the charging infrastructure network and the high reliability of vehicles are more important than the driving range.

Table 4-6 The driven distance of EVs in the Shanghai International Electric Vehicle Demonstration Zone

Daily driven distance	The proportion of users
14km -22km	42.8%
42km -61km	28.6%
63km -72km	28.6%
The average daily car mileage is 51 km	

Source from Cao (2012)

Reliability of local brand auto manufacturers

The problems discussed above are common issues encountered in the electric vehicle industry around the world (such as the driving range, charging time, etc.) (Kang and Park, 2011; Zhang et al., 2013). However, some interviewees generally considered that the low reliability of EVs produced by China's local brand Auto companies is a specific issue which has increased the level of concern regarding the performance of EVs. One expert from the result assessment experts team mentioned:

> "*There are more than 600 AFV models that have been developed over this three year demonstration program, and most of them have been developed by local independent brand car companies with a relative short product development cycle time.*"

Apart from a few companies such as BYD and Chery, most of the local independent brands are relatively small in scale and their R&D level and production capacity are limited compared to large international companies or Joint Venture Auto companies. The interviewees from auto manufactures mentioned that as a result the small companies lack financial strength and industrial scale, their products and brand lack competitiveness, and they find it hard to be accepted and recognised by consumers. The expert interviewee from CATARC considered that the limited financial resources

cause the small companies to be too dependent on government subsidies. This will drive them to shorten the development cycle and launch the product as soon as possible. However, without enough testing and trial operations, the AFVs may cause some quality problems for the users during the operation process. According to the information provided by the interviewees from the result assessment expert team in the actual operation process, the actual availability of AFVs is low. One expert from the team said:

> "*In some cities, nearly half of the EVs (50%) were always in the repair status due to the reliability issues, and the maintenance time is always long, caused by issues of maintenance parts availability. Therefore, the EV buyers such as Bus Company need to be equipped with more EVs (twice the traditional bus) to make sure the normal service of bus lines is maintained. Such huge financial pressure will make these bus companies reluctant to continue to expand the number of electric vehicles in the demonstration program.*"

These interviewees mentioned that consumers are also concerned with the safety and reliability of local independent brands in the private sector, which will reduce people's acceptance of local brand AFVs. This concern has also affected the promotion process of electric vehicles more generally.

Choosing an EV as a first car

Due to the limited range and the inconvenience of charging, EVs are impractical for long distance driving. Therefore, in many countries EVs are widely considered to be suitable as a second car or as a city vehicle. According to a survey, 93% of EV buyers also have an ICEV (Holtsmark and Skonhoft, 2014). In China, there is a survey by SIEVDZ focusing on how the levels of car ownership could affect the consumer's plan to purchase EVs. The results of the survey demonstrate that most of the consumers who do not own any vehicles do not want to purchase an EV as their first car (Cao, 2012). However, car ownership in China is still relatively low and the 2010 level was 58 cars per 1000 people as compared with the global average of 141 cars per 1000 (2011) (JAMA, 2012) (Wu et al., 2012). This means that most of the consumers in China do not have one ICEV. Therefore, their concerns about electric vehicles and the difficulty involved in choosing EVs as their first cars will affect the promotion of electric vehicles in the private car market. In order to increase the advantages of buying EVs, some local governments have introduced a number of provisions such as exceptions from driving license limitations and waiving travel restrictions for those

with EVs. The interviewees from the result assessment expert team pointed out that these provisions can effectively solve the difficulties encountered by people travelling by traditional cars and increase people's awareness and acceptance of EVs. However, only a small number of local governments have launched this kind of policy, and there are still only direct subsidies from the national policy. The lack of diversification of non-financial incentives means that the advantages of buying an EV are not clear in many pilot cities, with the result that most of the consumers still prefer the traditional ICEVs.

4.5.2 Policy issues

Serious local protectionism

From Figure 2, it can be seen that the EV development status among the 25 cities has huge variations. In some cities such as Shenzhen and Beijing, there are over 3000 AFVs in operation, whereas in Tangshan and Nantong there are only 200 AFVs in operation. Most of the interviewees considered that the strong local protectionism is one of the main reasons for this situation; in the demonstration program, each pilot

city wanted to boost the region's industrial development and so demonstration vehicles running in that region were required to be locally produced. Some cities even required motors, batteries and other key components to be locally sourced. In addition to the central government's subsidies, the local government also provided local enterprises with considerable financial subsidies for EV products and foreign vehicles could not get local subsidies, making the market difficult to enter (for example in Shenzhen, the local subsidies for local production of pure electric cars is 60,000 CNY/vehicle). In Beijing, a public transportation company first considers the alternative energy buses from Beijing Automotive Company (BAIC) (Liu and Kokko, 2013). It can be seen from the data in Figure 2 that most of the pilot cities which have good performance on AFV promotion always have a local automotive company or automotive manufacturers in their city or region. For example, Shenzhen has BYD, JAC is located in Hefei, and Beijing has BAIC. In addition, ROEWE belongs to Shanghai Automotive (SAIC) which is located in Shanghai, and Chery Auto was established in Anhui Provence (where Hefei is located). These five Auto companies (BYD, JAC, BAIC, Chery and SAIC) are the main producers for China's own brand EVs manufacturers,

and their AFVs have the best sales in the demonstration program (See Figure 4-6). The interviewees from institutions and government entities expressed strong opposition to this local protectionism. They argued that in many pilot cities where the auto industry is not well developed, local protectionism means that strongly performing EVs cannot enter the local market and the local production of EVs will reduce consumer acceptance and trust regarding electric vehicles due to their imperfect performance and reliability. The promotion of electric vehicles is therefore especially difficult in these pilot cities. The expert from the China Association of Automobile Manufacturers (CAAM) stated that:

> *"Only focusing on the development of local Auto industry caused the local government to ignore the importance of energy saving performance, operations, and infrastructure construction, which depart from the original intention of the demonstration program."*

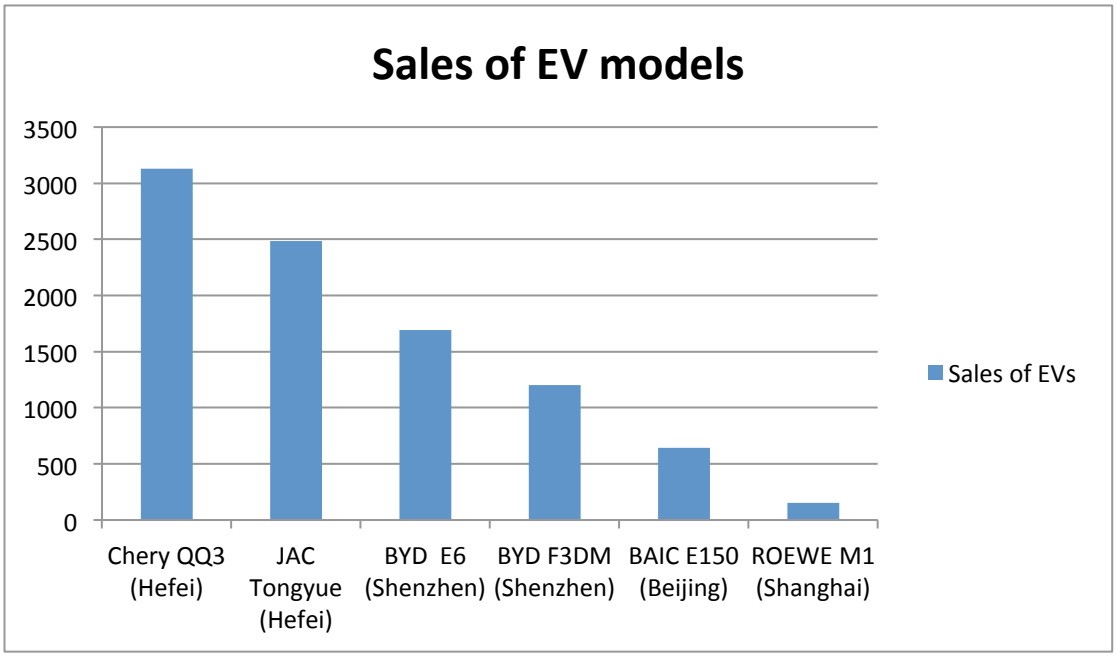

Figure 4-6 Domestic brands of electric car sales in 2012 (Source from CATARC et al., 2013)

Monitoring and evaluation

The interviewees from the research institutions pointed out that the pilot cities only committed themselves to increasing the number of electric vehicles as much as possible; there are no detailed plans about monitoring and evaluating EV promotion either at the national level or the local level. The interviewees from the government department indicated that according to the provisions introduced by MIIT, there should be 100% monitoring of BEV operation and 30% of HEV operation. The monitoring system should be based on an on-board data system, which can collect

virtually all of the control parameters of the vehicle, for instance the state of each battery cell, the vehicle travelling speed, and GPS positioning information. An expert from the result assessment expert team introduced such a system in the practical demonstration process. However, He pointed out that:

> *"Most of the pilot cities have established this monitoring system, and a lot of data has been collected in the last three years. However, almost all of these pilot cities did not carry out in-depth comprehensive analysis of that data, and many cities even did not do any analysis of the data."*

According to a survey by the World Bank (Zheng et al., 2012) during the demonstration program, only four cities (Kunming, Wuhan, Nanchang and Dalian) had plans to establish or hire institutions to monitor and evaluate the performance of their demonstration program. However, the survey also showed that these four pilot cities were more focused on the operating performance of the demonstration program (e.g., EV numbers and reliability) rather than the efficiency of the energy saving or the GHG emission reduction (Zheng et al., 2012). The expert from CATARC considered that this has two main causes: one is that the EV manufactures or battery companies are the weakness in the data analysis capabilities, while the other is that most of the pilot cities only took the numbers of EVs into account and they did not

care about value of vehicle technical analysis, demonstration mode analysis, policy implementation analysis and energy consumption and GHG emission analysis. Some cities only focus on the results and do not want to summarise the problems. However, the energy savings and GHG emission reductions are the two main intentions of the EV development in China. For China's coal based energy mix in particular there is continuing debate on the performance of the EVs in terms of CO_2 reduction through the entire life cycle process (Ou et al., 2010; Huo et al., 2010; Wu et al., 2012). Many studies have suggested that the penetration of BEVs could actually lead to higher CO_2 emissions based on the current power generation structure (Wu et al., 2012; Zhou et al., 2013). It is necessary to understand the actual effect of the different kinds of EV penetration on energy consumption and CO_2 emission and to find a more effective way to save energy and reduce CO_2 rather than simply considering the numbers of EVs sold. Therefore, over 70% of the interviewees mentioned that detailed guidance and standards for the monitoring and evaluation of the demonstration program should be launched by the government. Some of them suggested that the four government ministries (MIIT, MOF, MOST, NDRC) should

jointly organise a specific expert group with responsibility for developing the regular inspection and assessment system, introducing the content and workflow of monitoring and assessment, monitoring and evaluating the project, and directly reporting to the national government.

4.5.3 Infrastructure issues

Inadequate regulations and monopolisation by Grid companies

The demonstration program attempts to develop a variety of charging models (such as battery swapping, fast charging, and charging spots), and a variety of business models (such as vehicle sales, vehicle leasing, and leasing batteries). However, from the policy and regulation perspective, there is a lack of clear action to provide a unified planning approach and consistent standards for infrastructure construction. No policy incentive or support for infrastructure construction has been clearly stated at the state level in the demonstration program. Therefore, grid companies have monopolised the construction of infrastructure. The State Grid and the China Southern Power Grid are the two largest grid enterprises in China, with the State Grid

accounting for more than 80% of the power grid market. In order to control the EV charging infrastructure and also the battery market, the State Grid and the China Southern Power Grid were forced to promote the battery swap mode; this has caused some pilot cities to place too much emphasis on the “battery swap mode” during the three-year demonstration program. In total, 200 battery swap stations have been established and these account for 60% of all charging stations.

Based on the interviews, it has been found that the promotion of the battery swap mode is highly controversial with the experts and researchers. The interviewees from the Grid Company have introduced the reasons why the Grid Company prefers developing the battery swap mode; there are some significant advantages which can reduce consumer concerns regarding EVs. For example, the fast swap time can solve the issues of charging time and driving range, and the unified management of batteries and the battery leasing mode can significant reduce the initial purchase cost of the EV and consumer concerns over the battery life cycle and reliability. However, the “battery swap mode” advocated by Grid companies is strongly opposed by the car

companies. First, if the “battery swap mode” is widely promoted due to the unified battery specifications and performance then the differences in competitiveness among EV enterprises cannot be reflected, which will hinder the development of brand and company. Second, almost all of the auto companies demonstrated their concern that the Grid companies (State Grid and China Southern Power Grid) will not only monopolise the electricity supply industry but will also resist future expansion that could challenge their monopoly of the battery industry and the EV industry. Interviewees from research institutions expressed a more neutral view, arguing that the “battery swap model” is more suitable for public transport such as buses and taxis. First, the fast swap time can ensure the buses and taxis achieve their lengthy and high frequency operational requirements. Second, the unified model of buses and taxis means the battery specification and performance issues can be ignored. These interviewees also explained that the “battery swap model” is not suitable for large scale promotion in private vehicles. First, battery swap stations have the highest investment costs as this includes the cost of equipment, the maintenance costs, and the high costs and storage requirements of the batteries in the station. The total cost

of one battery swap station in China is about 900 million CNY (93.75 million GBP)[1], which is more than twice the cost of a fast charging station (about 400 million CNY). The interviewees mentioned that the battery swap stations in the demonstration program were all losing money and still did not show any profit potential. Second, due to the frequent removal and replacement of the batteries, the connection (swap) area for batteries and EVs can cause failures and safety problems. The swap mechanism requires high level professional maintenance, but there are still concerns about safety within the station. Third, as the batteries are not being charged by the consumer, payment should depend on the recharging time and the cost of the electricity; however, this may cause problems for the battery swap station as the advantages of flexibility in replacement options are reduced. For example, EV consumers may not replace completely (or almost completely) depleted batteries as some users may run them lower than others, and this may result in more variable use patterns and levels of recharging required. In the demonstration program, battery swap stations were only used for the public transport, for example buses and taxis. The station operators do not charge EVs by time, instead charging the bus companies

[1] Exchange rate used in this dissertation is 1GBP = 9.6 CNY

and taxi companies by month depending on the total amount of electricity used. Therefore, most of the interviewees reached a consensus that large-scale construction of battery swap stations without rational regulations and planning by the government may have little effect on accelerating the promotion of EVs in the private vehicle market and may also result in a misallocation of resources.

Limitations of charging spots in China

Compared to the battery swap model and fast charging stations, charging spots seem to have more advantages for large scale application. For example, compared with the other two charging options, charging spots have the lowest cost at about 10,000 CNY per spot. A charging spot uses the slow charging method and this has lower impacts on the grid system; there is also the potential for the charging spots to be completely dependent on the existing power supply network provided that the system uses management optimisation approaches. In addition, the charging spot approach can use available space in existing public car parks, residential car parks and home garages, and there is no need to allocate new land. The payment method of charging

spots can be based on time use or electricity consumption. If smart grid technology is applied, the payment can also be automatically adjusted for different electricity prices at different times. However, interviewees from the result assessment expert team commented that in the demonstration program, charging spots still showed some limitations for development. Many interviewees considered that these limitations are mainly caused by China's specific situation. Unlike Europe or America, China has very high population density, especially in the medium and large cities; most of the citizens do not have their own private garage. Most existing public car parks and residential car parks do not have a specific grid system installed for charging and the necessary retrofitting of the electricity supply to car parking spaces is expensive, especially for private consumers. At present, there is no policy support to promote this installation process, and this means that with low levels of market penetration the costs of recharging are high. In addition, there is no clear policy or regulations to guide improvement in the electricity supply system in existing parking areas and the installation of EV charging systems as part of the construction of new car parking.

4.6 Summary of the current issues

Based on the analysis above, there are 7 main issues that can be summarised as the main barriers for the EV demonstration program in China.

1. Limitations of EV performance

The limitation of the battery technology is one of the main challenges for EV development. The cost and specific energy of the battery causes disadvantages such as the high cost, low driving range and long charging time. These issues are not only faced by China but also the entire global EV industry.

2. The lack of the auto industry level in China causes reliability issues with China's local brand EVs.

Due to the lack of technology and quality control in the traditional auto industry, the performance and reliability of China's local brand EVs is still behind the global level; this has caused a lack of recognition and acceptance among Chinese consumers.

3. Specific market conditions & consumer behavior

The specific situations in China (such as limited parking space and low car ownership) mean that the consumers have higher requirements in terms of the driving range and the layout of the charging facilities.

4. Limitation of the Policy

The local protectionism in the demonstration program means that the local government only focused on promoting the EVs produced by local manufactures and ignored the real performance and technology level of the EVs. This severely hampered the development of electric vehicle technology.

5. Lack of evaluation and standards

Currently, the “numbers of the EVs” are the only targets and indicators for the EV demonstration program. However, a more comprehensive evaluation could become a driving force encouraging local governments to pay more attention to a comprehensive range of variable instead of only the numbers of EVs, which could help to solve vehicle reliability and charging facility issues.

6. Lack of charging infrastructure

Based on the experience from the Phase 1 demonstration program, the charging infrastructure can't meet the requirements of the consumers due to the lack of clear and effective policies and practices.

7. Uncertainty regarding the effectiveness of EV development on energy saving and GHG reduction

Due to the coal-based energy mix in China and the lack of evaluation and monitoring, the current performance of EVs in energy and environmental aspects is still under debate. Whether the current EV demonstration program has contributed to energy saving and pollution reduction is still uncertain.

4.7 Latest Policy and Recommendations

Based on the lessons from the first round of demonstration projects, the four Ministries (MOF, MOST, MIIT and NDRC) jointly issued a notice entitled the "Notice to continue to promote the application of new energy vehicles" on 17th September 2013.

The Notice mentions that the next round of demonstration projects will run from 2013 to 2015 and will attempt to avoid the issues that occurred in the previous round of demonstration projects. This time, the demonstration cities or regions must meet the following conditions:

1. In 2013-2015, the cumulative number of AFVs (BEV, PHEV and FCV) in the main metropolitan areas and key areas should be at least 10,000. The numbers of new energy vehicles in other cities or regions should be at least 5,000.

2. Foreign brands (Chinese brand) of EVs should account for at least 30% of the total local number of new EVs. The local government cannot set restrictions on purchasing foreign brand vehicles.

3. Public fields such as government agencies and public institutions should give priority to the use of new energy vehicles. New energy vehicles should account for more than 30% of the total new or updated vehicles in public transportation, public affairs, logistics and sanitation vehicles.

4. The relevant cities are subject to annual examination and evaluation, and they will be excluded if they fail to meet the annual promotion goals (Not implemented so far).

5. For the subsidies, the Notice has clearly defined that the subsidy targets are directed at Electric Vehicles (electric battery powered vehicles) and this includes BEVs (excluded lead–acid battery vehicles), PHEVs and FCVs. HEVs are no longer included (See Table 4-7).

In addition, on 9th July 2014, Premier Li Keqiang chaired a State Council executive meeting where it was decided that from 1st September 2014 to the end of 2017, three kinds of EVs (BEVs, PHEVs and FCVs) that obtain licenses sold in China (including import) will be exempt from vehicle purchase tax.

Table 4-7 Subsidies for EVs in the demonstration project (Phase 2) (Unit: 10000 CNY / vehicle)

Vehicle types	**Pure electric driving range R (Km)**			
	80≤R＜150	150≤R ＜ 250	R≥250	R≥50
BEV (Car)	3.5	5	6	／
PHEV (Car)	／	／	／	3.5
	Length of the Bus L (m)			
	6≤L＜8	8≤L＜10	L≥10	
BEV (Bus)	30	40	50	
PHEV (Bus)	/	/	25	

FCV (Car)	20
FCV (Bus)	50

Source from MOST, MIIT, MOF and NDRC (2013)

From these new policies, it can be seen that the government has begun to appreciate the hazards caused by the local protectionism created in the early (Phase 1) demonstration process, and it has also started to emphasise the role of tax policy in promoting EVs. It can be expected that these new policies will have a positive effect on the penetration of EVs. However, in relation to the main issues summarised above, there are still some issues discussed here that have not been clearly mentioned and solved in these new polices.

First, the technology level of the batteries is hard to breakthrough in a very short space of time, and the new policies do not enhance the importance of technology research and industrial development. It seems that there are no clear incentives and regulations provided to the EV R&D and manufacturing process. The interviewees in this study generally reflected that the lack of R&D strength and production

technology is a key issue for local EVs manufactures. Improving the performance and reliability of the local EVs has been considered as a necessary prerequisite for the large-scale promotion of EVs; therefore, the government should consider providing a range of incentives (e.g. subsidies, loans, and tax credits) to the EVs manufacturers and related battery manufacturers to help them improve their manufacturing and R&D capability. Clear regulations and standards are also necessary to control the technical level and quality of EVs. In addition, the expert from CATARC also pointed out that State financial support should be established for several specific research projects (such as vehicle models and batteries), and the manufactures should concentrate on tackling some of the common difficulties. He argues that a wide range of the subsidies paid to each manufacture would result in some waste because some of their R&D projects are the same. In addition, the average subsidies for every car will become lower, which is not enough for a separate vehicle manufacturer to achieve technological breakthroughs in research alone.

Second, the new Notice mentions that the pilot cities are subject to annual examination and evaluation. However, the interviewees from CATARC, CAAM and Society of Automotive Engineers of China (SAEC) pointed out that the examination of pilot cities has not been implemented so far, and assessment methods and assessment indicators are still being discussed. There is still a lack of monitoring and evaluation. More comprehensive mechanisms should be established for monitoring and evaluating the EV demonstration at both the national and local levels. Instead of only considering the operation performance of the EVs, demonstration mode analysis, policy implementation analysis and energy consumption and GHG emissions analysis of the EVs in the promotion process should be given more attention. As the interviewees have suggested, the government should introduce some provisions to regulate the establishment of mechanisms such as data analysis, evaluation method and monitoring agencies. It's better to have a specific organisation responsible for monitoring and evaluating. It could be jointly organised by the four Ministries (MOF, MIIT, MOST and NDRC) and be given absolute authority to work independently. The result of the monitoring and assessment should be directly reported to the national

government. Meanwhile, the organisation should release regular assessment reports to each pilot city and ensure that lessons learnt are shared between these cities.

Third, as the issues reflected in the demonstration program, there is a lack of regulations, planning and policy support for the charging infrastructure construction. However, the new policy for the next round of demonstrations still does not contain regulations, planning and policy support for the charging infrastructure construction. The interviewees from research institutions have given some suggestions. First, the government should launch a series of clear standards and regulations for the development of different charging models to break the monopoly held by the grid companies and encourage all kinds of investors to support charging infrastructure in accordance with the standards and regulations. Second, there should be policy incentives at both the national level and municipal level to encourage the construction of charging infrastructure. For example, there should be direct subsidies and grants to develop the charging facilities. The government policies should consider charging infrastructure construction sites as public infrastructure land, thus giving

preferential land prices. In addition, in order to solve the issues of charging spot installation mentioned in this study, an interviewee from China Electricity Council (CEC) suggests that the government should release regulations to guide the installation process of charging spots in community parking and public parking locations, also introducing provisions for grid companies and residential properties that help private EV users to install charging facilities. An expert from the result assessment team also gave his opinion:

"As same as the lighting power requirements, the residential standards and residential renovation requirements should include the electric car charging grid and charging spot set construction."

In addition, the construction and renovation of public facilities such as commercial areas, transportation hubs (coach stations, railway stations, airports, etc.), public parking and enterprise parking should consider the EV grid and charging facilities.

Fourth, in the demonstration period, directly subsidies were only provided to the consumers at the national level. The new policies still does not give any other clearly policy support in addition to the purchasing subsidies. From 1st September 2014, the

new policy on "EVs are exempt from vehicle purchase tax" will start to be carried out, which means the Chinese government will begin to pay attention to the role of tax incentives. However, compared to the support policies launched in some other countries, the current incentives policy in China still seems too monotonous. For example, Denmark has introduced certain tax exemption for EVs as well as free parking in Copenhagen. In addition, Norway provides comprehensive incentives which not only include tax exemption from vehicle purchase and sales but also include the "lower annual motor vehicle tax/road tax", "free public parking fees", " EVs are allowed to use bus and collective traffic lanes", " EVs can use most toll roads and several ferry connections free of charge", and "battery charging free in public funded charging stations" (Holtsmark and Skonhoft, 2014). In the interviews, several experts said that the EV exemption from car license limitation in Shanghai and Beijing has shown a strong impact in terms of increasing people's attention and interest in EVs. In Beijing and Shanghai, car licenses are limited to private consumers as the result of serious traffic congestion. In Beijing, the private car license requires a waive number just like a lottery, while the EV licenses can be waived individually which

greatly increases the chances of getting the license. In Shanghai, the private ICEV licenses take the auction approach, and the average auction price of a license was around 90,000 CNY to 100,000 CNY in 2013. However, EVs in Shanghai can get the license directly without any fees, which means a further 100,000 CNY can be saved compared to the ICEV besides the government EV subsidies. In addition to the case in Shanghai and Beijing, some experience in other countries can also be promoted in China. For example, private vehicle travel is restricted by date in many large cities in China due to the increasingly serious traffic congestion. If the EVs are exempt from vehicle travel restriction or if EVs can use bus and collective traffic lanes during peak hours, the advantages of buying EVs will become more significant and more attractive. Therefore, In order to increase the competitiveness of EVs compared to ICEVs, diversification incentives should be further developed in China to increase people's awareness and recognition of EVs.

4.8 Conclusions

The Chinese Government has started phase 2 of the demonstration project from 2013 to 2015. In addition, some new regulations and notices have been set out to further support the raising of the EV penetration rate in this new round of demonstration projects. Based on some opinions from the interviewees and also the existing experience gained from the "phase 1" program, there are some strong policy recommendations made in this study. Instead of only focusing on increasing the EVs promotion number, a comprehensive evaluation framework should be developed to pay more attention to the environmental impacts, technology development, consumer behaviour and charging infrastructure in the EV promotion process. In the phase 2 demonstration project, there is still a lack of incentive policies on EV operational processes and charging infrastructure. In order to increase the advantages of EVs compared to the traditional ICEV, the government should diversify the support and incentive policies to build a positive promotion environment for EVs instead of only providing lump-sum subsidies. The experience and recommendations introduced in this study should help the government in understanding the current

issues facing current EV promotion strategies and help in developing future longer term strategies. In addition, the lessons from China could also be relevant to other countries thinking about introducing EVs in the future.

Chapter 5: Electric vehicles in China: "Well to Wheel" energy consumption and CO_2 emissions for the different vehicle types, regions and periods in China.

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5.1 Introduction

5.1.1 Energy security issues in the transport sector

As a result of the rapid economic growth in the last two decades, China has become the second largest energy producing and consuming country in the world (Yan and Crookes, 2007; and NSBC, 2008). Oil consumption in China has increased by nearly 4 times over the past 20 years (114.9 Mt in 1990 to 408.3 Mt in 2009) (Leung, 2011). China was still an oil-exporting country until 1993, but since then the proportion of import crude oil has increased from 7.5% (1993) to 53.5% (2009) (Tien, 2010; and Wei, 2010). According to the IEA (2008), unless demand management measures are introduced, China's oil demand in 2030 will reach 808 million tons (Mt), and the oil import dependency in China will increase to 74%. Energy security has become a serious issue in China, and the transport sector is seen as the dominant factor contributing to this high level of imported oil consumption. Oil consumption from the transport sector currently accounts for almost 61% of total world oil consumption (IEA, 2009). In China, the use of gasoline and diesel by vehicles in China was responsible for more than 1/3 of the total oil consumption (Zhang, 2010).

5.1.2 CO_2 emissions from the transport sector

China's CO_2 emissions reached 7,050 million tons (Mt) in 2008 and this now makes China the largest CO_2emitting country in the World (Yan and Crookes, 2010). According to the IEA (2010), 22% of the total global CO_2 emissions in 2008 can be attributed to the transport sector. In China, the CO_2 emissions from transport had already increased from 136.29 million tons (Mt) in1990 to 524.85Mt in 2008, and the share of transport sector in the total CO_2 emissions has also grown from 6% to 8% (International Transport Forum, 2011; and IEA, 2010). This figure is expected to increase in China due to the sustained and rapid growth in energy demand from transportation (Ou et al., 2010a). Therefore, given the coal-based energy structure and the growth of travel demand, reducing CO_2 emissions from the transport sector is a real challenge for China (Loo and Li, 2012).

5.1.3 China's road transport sector

China became the world's largest car manufacturer in 2009. However, China's current vehicle ownership is still very low compared to that in developed countries and the world average, and this means that China is also the world's largest potential vehicle market. According to Wu et al. (2012), vehicle ownership per 1000 population in China was 58 in 2010, and this compares to a figure of 833 per 1000 population in the USA (2007), and the global average was 141 per 1000 population (2011) (JAMA, 2012). This means that there is a huge potential for growth of the vehicle stock in China, even to catch up with the global average level (about a 2.5 times increase). Wu et al. (2012) forecast that the car ownership per 1000 population in China will reach about 120 by 2020 and will further increase to 300 by 2030. And there is no doubt that if there is no alternative fuel source orany new advanced vehicle technology, this rapid growth in car ownership will continue to exacerbate the challenges of energy security and the carbon dioxide emissions in the transport sector.

5.1.4 EVs and Coal based energy mix in China

To reduce oil demand and CO_2 emissions from the transport sector, the Chinese government is now making great efforts to introduce alternative vehicle fuels and advanced vehicle technology such as electric vehicles (Ou et al., 2010b). The Chinese government has introduced many policies and financial subsidies to support the development and promotion of electric vehicles. Starting from 2008, the Ministry of Finance (MOF), the Ministry of Science and Technology (MOST), the National Development and Reform Commission (NDRC), the Ministry of Industry and Information Technology (MIIT) have each introduced some new energy vehicle development plans. These include the "Automotive Industry Policy" and the "Automobile Industry Promotion Plan" to jointly promote the commercialization of EVs, and they have started the "10 cities 1000 vehicles" demonstration project to support the EV development in China (12^{th} 5-year Strategic Plan, 2010). In addition, MIIT also introduced a development plan of "Energy-saving and New-energy Vehicle" (2010), and the overall target of this plan is that the numbers of EVs and PHEVs in China will increase to 500,000 in 2015 and 5,000,000 in 2020 (MIIT, 2010).

However, even when vehicle electrification is used to reduce energy consumption and CO_2 emissions in China, there is still a substantial carbon content as China's energy mix is coal-based, and coal-fired thermal power has accounted for 80-83% of the total electricity generating capacity since 1990 (State Grid Energy Research Institute, 2011; Chen and Xu, 2010). Power generation accounted for 89.98% of the total primary fossil energy consumption, and 87.80% of the total GHG emissions (Ou et al., 2011). China's resource structure is characterized by "lack of oil, less gas, relatively rich in coal", and the proportion of coal in China's entire energy consumption system is about 70%, meaning that the coal-dominated energy consumption structure is difficult to change in the short term (Song *et al*., 2008).

5.1.5 Research motivation of this study

As the introduction above, fast growth of vehicle stock made China facing increasing pressure from energy security and CO_2 emissions. The advanced vehicle technologies such as HEV, BEV and PHEV are considered as potential pathways to solve these

issues due to their high fuel economy and less CO_2 emissions during the vehicle operation process. However, as the coal based energy mix in China, it is necessary to consider the full life cycle of the EVs' fuel pathway in order to understand the real contribution of EVs development to reducing energy consumption and CO_2 emissions (Ou et al., 2010a; 2010b; and Wang and Huo, 2009). In addition, for the existing demonstration program (2009-2012) in China, there is lack of a comprehensive evaluation system which focusing on the real performance of EVs penetration in each pilot city. However, the performance of EV development on energy saving and CO_2 reduction in different cities in China are considered to be different due to the uneven distribution of power resources. Therefore, This study uses the GREET model to simulate the energy consumption and CO_2 emissions of three main types of electric vehicles (BEV, PHEV and HEV) with different hypotheses for the power mix in China in different EV pilot cities and different periods from 2012 to 2030. In order to make better comparison, this study only chose the light-duty passenger vehicles. The different scenarios of energy mix and technical improvements in the future will be discussed and assessed. Finally, based on the result of the model simulation, the real

performance of different types of EVs will be compared and discussed, and further recommendations are given to improve the EVs development strategy in China.

5.2 Methodology

5.2.1 GREET model

This study uses the GREET model as a platform to simulate the energy consumption and CO_2 emissions from three main types of EVs. The conventional ICEV is also considered as a benchmark against which these three types of EVs can be compared. The GREET model is chosen by this study because that it is a comprehensive, well-known and widely used model which specific designed for vehicle fuel pathway simulation. For example, It has been several times used by US Department of Energy (DoE) and General Motors (GM) to evaluate the WTW energy consumption and emissions of different vehicle types and advanced vehicle technologies in North America (Zhang et al., 2008; Brinkman et al., 2005). In addition, more and more studies used GREET model to evaluate the different powertrains and emissions of different fuel and vehicles not only in North America but also EU and Asia (Choudhury

et al., 2002; Li, 2006; Wang, 2002; Torchio and Santarelli, 2010; Hekkert et al., 2005). The GREET uses a spreadsheet based approach, and it has been developed by theDoE and the America National Lab (ANL). It can be used to assess the energy efficiency and emissions of the entire fuel cycle for a range of alternative fuels and different types of advanced vehicle technology (Wang, 1999; and Li, 2006). It evaluates the greenhouse gas emissions and the energy efficiency for a variety of different vehicle fuels from the well to wheel (WTW). The WTW can be further divided into two stages: the Well-to-Tank (WTT) and the Tank-to-Wheels (TTW). WTT includes extraction, refining, processing, distribution and storage of raw materials, fuel production, transport, storage and distributing the fuel to consumers, etc.; TTW is related to the use of the fuel in the vehicle, which mainly consists of the engine operation and power transmission (Zhou et al., 2010; Torchio and Santarelli, 2010; Song *et al*., 2008; and Wang, 2002). However, the original GREET model is developed and calibrated on the US situation. In order to use it to analyze the China situation, changes are required in many of the key parameters in the model. Section 5.3 has introduced the key parameters used in this study based on China's own situations. Due to the

limitations of data acquisition and the variable data of model itself, only the key parameters that are considered can significant affect the results are changed, such as the levels of coal mining and coal transport, the different energy efficiency of the different power sources, and the transmission loss rate. Therefore, there are still limitations in this study to replace all of the parameters in the model based on China's situation.

5.2.2 System boundaries

The main objective of this study is a comparison between the life cycle of energy consumption and CO_2 emissions for the three types of EVs, and it focuses on two fuel pathways in China (electricity and petrol). The assessments in this study focus on the both national level and regional level. From national level, it includes the different power mixes currently used in China and the forecast of the different possible energy mixs in China in the future (2020 and 2030). From regional level, according to Huo et al. (2010), there are six inter-provincial power grids in China that are divided by geographical area: Northeast grid, North grid, Central grid, East grid, Northwest grid,

and South grid (see Figure 2). By considering the pilot cities in the "10 cities 1000 vehicles" plan (12th 5-year Strategic Plan, 2010), this study chooses 5 pilot cities from 5 different grids to evaluate the performance of EVs development in their different energy mix, and these 5 cities are: Changchun, Beijing, Shanghai, Chongqing, and Shenzhen (See figure 5-1).

Figure 5-1 Six inter-provincial power grids in China

In addition, the light-duty passenger vehicles (LDPV) have played a dominant role in China's vehicle market. According to the China Automobile Industry Yearbook (CATARC and CAAM, 2011), China's passenger vehicle production and sales volume reached 13,897,100 and 13,757,800 in 2010, respectively, accounting for 76.09% and

76.17% of the total vehicle production and sales in China. With the continuous growth of the LDPVs, Huo and Wang (2012) forecast that the share of LDPV will reach 93%-94% of the total vehicle stock in China (2030), and the new energy vehicles such as EVs and HEVs are expected to become a major part of the total vehicle stock. Therefore, this study has chosen the passenger vehicle (curb mass less than 1320kg) as the basic vehicle type, and it is particularly concerned with the different performance of the three different technologies of new energy passenger vehicles (BEV, HEV and PHEV). The HEV considered in this study is Grid-independent and only use the petroleum as vehicle fuel. And the PHEV in this study is the model that both using Grid electricity and petroleum. The conventional petrol ICEV is used in the study as the baseline for comparison. In addition, the potential technology improvements and their effect on the fuel economy of each vehicle technology are considered and discussed.

5.3 Input data and the key parameters in the model

As the WTW analysis has a significant regional dimension to it, and in order to calculate the real energy consumption and CO_2 emissions in the China WTW situation, the data and other parameters in the model need to be made specific to the local situation. In this study, the data needed for the calculation of the WTW aspects is mainly based on the existing data available from a documentary research, including the Statistical Yearbook, public information of national and regional statistical offices, the publications of various industry associations, and research reports published by authoritative research institutes. In addition, some of the key parameters in the electricity fuel pathway have been collected from the relevant government departments (such as China Electricity Council, State Grid, etc.) directly through interviews. Table 5-1 has shown the key input data and parameters for material extraction, processing and transportation in this study. The data in this table is mainly from the China Energy Yearbook and China Transportation Statistical Yearbook that published by the National Bureau of Statistics, which has a very high quality and

reliability, but some data was not statistics by the Yearbook and will be set based on some existing similar studies.

Table 5-1 The input data for material extraction, processing and transportation

Coal	
Coal mining	Open-cast mining 6%, underground mining 94%
Coal mining process	Energy consumption of unit coal mining (tonne)：Electricity: 36 kWh, Raw coal: 25 kg.
Coal transportation	Railway: 56% (595 km); waterway: 17% (1900 km) and road: 27% (80 km).
Nature Gas	
NG Extraction	Extraction efficiency: 96.00%; the process fuel mix for NG extraction: electricity (40%), NG (23%), residual oil (20%), diesel (8%), coal (7%) and gasoline (2%);
NG processing	NG processing efficiency: 94.00%; the process fuel mix for NG processing: residual oil (40%), NG (28%), coal (20%), electricity (10%), diesel (1%) and gasoline (1%).
NG Transportation	Pipeline: 100% (1500 km)
Oil	
Oil extraction	Extraction efficiency: 93.0% Process fuel mix: electricity (37%), crude oil (20%), NG (23%), coal (10%), diesel (8%), residual oil (1%) and gasoline (1%).
Oil processing	Petroleum refinery efficiency: 97.0%, Process fuel mix: crude oil (50%), coal (20%), electricity (12%), refinery still gas (10%), residual oil (4%), diesel (1%) and gasoline (1%).
Oil transportation	Sea tanker: 50% (11,000 km); rail: 45% (950 km);

	pipeline: 80% (500 km) and waterway: 10% (250 km).

Data obtained from Ou et al., 2012; Energy Statistics Division of the National Bureau of Statistics, 2013; Zhang et al., 2008; CATARC and GM, 2007; China Transportation Statistical Yearbook, 2011.

5.3.1 Electricity generation

Electricity generation mix is a key parameter that can affect the energy consumption as well as CO_2 emissions of PHEV and EV in the WTW calculations. From national level, the thermal power still contribute to more than 78%, and this figure do not change a lot during the last 30 years (See Table 5-2). The proportion of thermal power is always around 80%, and the figures are in constant fluctuation, and declining trend by year is not significant. Among these, coal-fired power continues to play a dominant role in thermal power, and it contributes 98.2% of the total thermal power production. Compared to the date of 2000, the proportion of thermal power has about average 2%-3% reduction in last 10 years.

Table 5-2 The proportion of thermal power in last 30 years

1980	1990	1995	2000	2005	2007	2009	2010	2011	2012
80.6%	79.6%	79.8%	82.2%	81.9%	83%	80.3%	79.2%	81.3%	78.1%

Data obtained from Energy Statistics Division of the National Bureau of Statistics (2013)

Considering the total power demand will growth and the thermal power will continually decrease in the future, this study assumed the proportion of thermal power would reduce 3%-4% in each 10 years. From studies focusing on the forecast of China's electricity generation mix (Wu, 2007; Wu et al., 2012; and Energy Research Institute of NDRC, 2003), the proportion from the coal-fired power will further reduce in the future (2020 and 2030), but still remain the highest proportion in the power mix and it is likely to account for 70%-78% of all electricity production. Based on the information above, the detailed data for the electricity generation mix (National level) used in this study has been summarized in Figure 5-2. The data assumed in this study is mainly based on the forecasting of China’s energy mix by the existing studies from institutions and government.

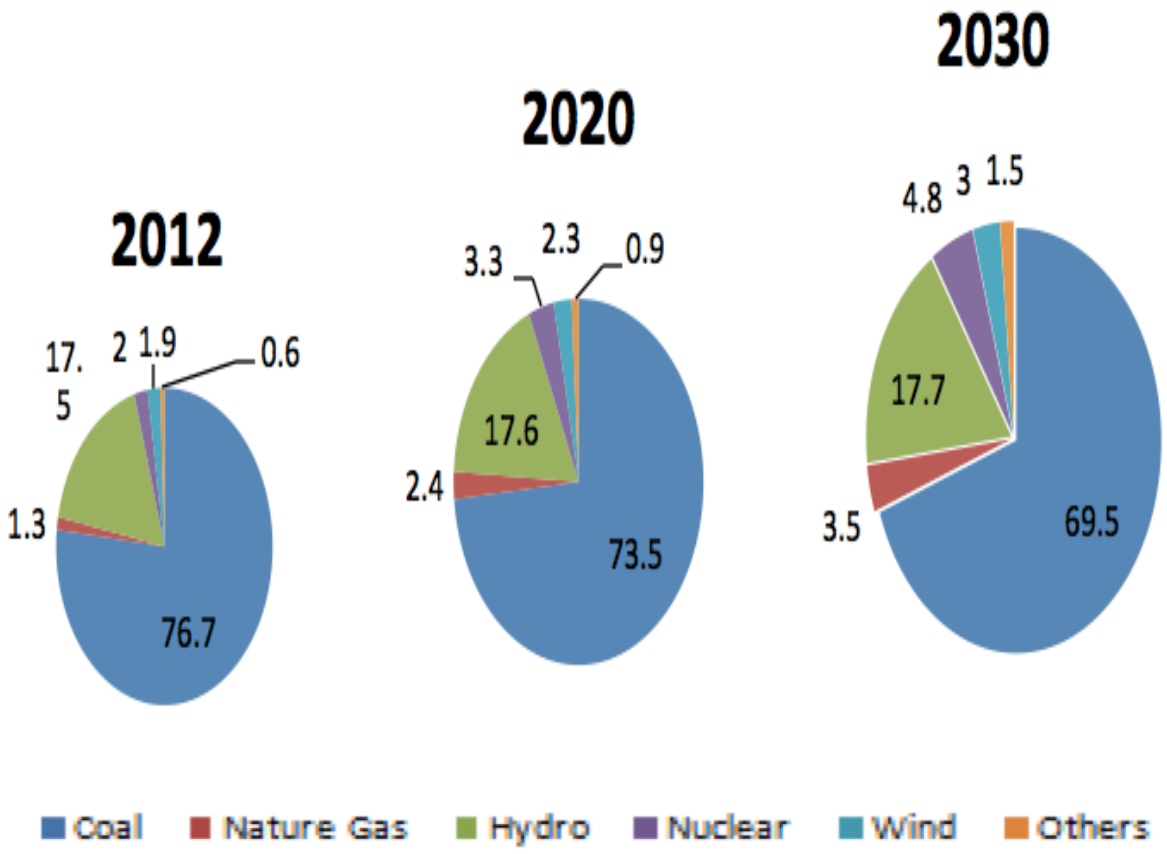


Figure 5-2 The electricity generation mix in this study

Data obtained from Wu (2007); Wu *et al.,* (2012); Energy Research Institute of NDRC (2003); and Energy Statistics Division of the National Bureau of Statistics (2013)

From regional level, according to Zhang (2004), the distribution of China's energy is uneven, 82.2% of the existing coal reserves concentrated in the north and northwest of China, and hydropower resources are mainly distributed in the west and southwest. Therefore, mainly affected by the regional energy constraints, generating energy mix is significantly different in various regions of China. In the Northeast and North grid, the coal is dominant in the energy mix that can account for 95-98% of the

total electricity generation. However, in the South grid, Central grid and Northwest grid, the hydropower can account for 22%-30% of the total power mix (Huo et al., 2010). Therefore, the 5 pilot cities considered in this study have covered the five main grids in China (except the Northwest Power Grid). Based on the authoritative statistics in China's Energy Yearbook, the power mix of each city in 2012 has been set and displayed in Table 5-3 (Energy Statistics Division of the National Bureau of Statistics, 2013).

Table 5-3 The power mix of five cities (2012)

	Changchun (CC)	Beijing (BJ)	Shanghai (SH)	Chongqing (CQ)	Shenzhen (SZ)
Coal	82.9%	96.5%	96.2%	56.1%	73.2%
Natural Gas	0.6%	0.8%	2.2%	0.6%	3.3%
Hydro	9.5%	1.5%	0%	41%	9.8%
Nuclear	0%	0%	1%	0%	5%
Others	7%	1.2%	0.6%	2.3%	8.7%

Data obtained from Energy Statistics Division of the National Bureau of Statistics (2013)

In 2010, the coal consumption for power generation was 335g/kWh and this figure is 39g/kWh lower than the corresponding figure for 2005. The transmission line loss

rate in 2010 was 6.49% and this is 0.69% lower than the rate in 2005 (see Table 5-4) (Liu, 2011). According to the forecast by State Grid (2012a, 2012b), the line loss rate assumed in this study has been shown in Table 5-4. In addition, Table 5-5 has shown the energy efficiency of different power in the electricity generation process in current period and the potential situations in the future. The data used in Table 5-4 and Table 5-5 is mainly from author's interview from State Grid and China Electricity council.

Table 5-4 Line loss rate in China from 2000 to 2030

Year	2000	2005	2010	2020	2030
Line loss rate (%)	7.70	7.18	6.49	5.70	5.00

Source from: data obtained from State Grid (2012a), State Grid (2012b) and Zhang *et al.* (2008)

Table 5-5 The energy efficiency of different power in electricity generation

	2012	2020	2030
Coal	36.4%	38.8%	40%
Oil	40%	40%	40%
Natural Gas	52.1%	55%	57%

Hydro	100%	100%	100%
Nuclear	33%	33%	33%
Others	78.5%	89.5%	90%

Source from: data obtained from the China Electricity Council (Liu, 2012) and existing studies (Ou et al., 2011; Wu et al., 2012; CATARC and GM, 2005)

5.3.2 Vehicle types and fuel economy

In order to reduce the energy consumption by LDPV, China has started to implement the passenger car fuel economy standards in two phases (since 2005 - Wagner et al., 2009). The Phase 3 standard was set up in 2011 (started in 2012), and it requires the vehicle manufactures to start consider the target from 2012, to reduce the fuel consumption gradually, and to achieve the average fuel consumption (average of all car fleet at that time) target in 2015 (See Table 5-6)

Table 5-6 The Passenger vehicle fuel economy standards in three phases (L/km)

Curb weight (CW) Kg	Phase 1 (2005) Upper limit (no more than)	Phase 2 (2008) Upper limit (no more than)	Phase 3 (2012) Target (achieve by 2015)

CW≤ 750	7.6	6.6	5.6
750<CW≤ 865	7.6	6.9	5.9
865<CW≤ 980	8.2	7.4	6.2
980<CW≤ 1096	8.8	8.0	6.5
1096<CW≤ 1205	9.4	8.6	6.8
1205<CW≤ 1320	10.1	9.1	7.2

Source from Wu, et al., (2012)

The new standards are expected to reduce the average fuel consumption rate of the new LDPV in China to 7L/100km in 2015 and around 5 L/100 km in 2020 (Wang et al., 2010). The average fuel-consumption rate of new vehicles in 2011 is about 7.8L/100km for passenger cars (Huo et al., 2011a). If an improvement scenario is based on Japanese and European standards, then targets of about 5.9L/100km(the current levels in Japan and European countries) can be achieved (Huo et al., 2011b), and these levels will be improved to 5.5L/100km by 2015 and 4L/100km by 2020. Wang et al. (2010) and Wu et al. (2011) carried out research to calculate the real-world fuel consumption rates for new LDPV during the period 2010 to 2030, and they estimate the average fuel consumption rate for light duty ICEV can achieve 7.3 L/100km in 2020 and 6.4L/100km in 2030. In this study, by considering the forecasts from a range of studies (Huo et al., 2011a, b; Ou et al., 2010; and Wu et al., 2012) and

the targets set by the new Japanese and European standards, the fuel economy of conventional ICEV for LDPV is assumed to be 8.6L/100km in 2010, reducing to 7.5L/100km in 2020 and 6.4L/100km in 2030. The parameters of fuel economy of each vehicle model in this study have been shown in the Table 5-7. The parameters are set by considering the default values in the GREET model and those based on China's situation collected through the fieldwork.

According to Elgowainy (2010), this value can be defended as the ratio of the equivalent petrol fuel economy compared to the baseline that is the fuel economy of the ICEV. For example, the fuel economy ratio of the HEV is 148% relative to the fuel economy of the ICEV (Elgowainy, 2010). As the PHEV is a car with the two power systems (the engine and the electric motor), it should be divided into two models for evaluation, one that is a charge-depleting (CD) model and another is a charge-sustaining (CS) model. Due to the different designs of the PHEV, such as power-split PHEV and the series PHEV, the share of vehicle miles traveled on CD model will also

be different (Elgowainy et al., 2010). In this study, using the data from You (2012), the shares of PHEV powered by Grid electricity and On-broad Engines are 33% and 67%.

Table 5-7 The parameters of fuel economy of each vehicle model

Vehicles	2012	2020	2030
ICEV (Baseline)	8.6L/100km (100%)	7.5L/100km (100%)	6.4L/100km (100%)
HEV	148%	168%	188%
BEV	350%	400%	480%
PHEV	Grid electricity 33%; On-broad Engines 67%.		

5.4 Results and Analysis

5.4.1 Comparisons of different EV models in different periods

WTW fossil energy use

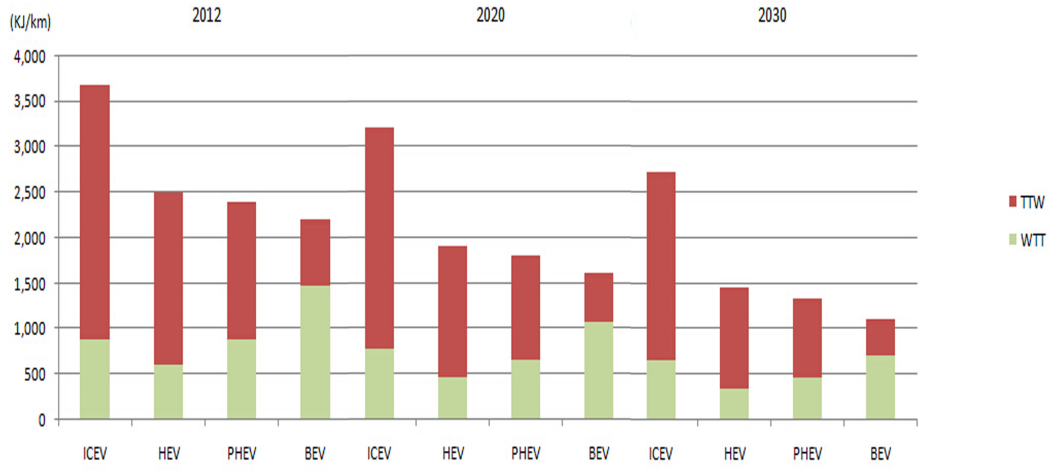


Figure 5-3 WTW total fossil use of 4 vehicle technologies in 2012, 2020 and 2030

The fossil energy use in the WTW process by each vehicle technology and for the different calendar years from 2012 to 2030 is shown in Figure 5-3 and the measurement unit for this is KJ per km travelled by each vehicle technology. For each bar of the chart, the bottom part (green colour) represents the energy consumption in the WTT process, and the top part of the bar (red colour) represents the energy consumption in the TTW process (both values are in KJ per km). From the results, it can be seen that the PHEV and BEV have more significant reductions on fossil use in the TTW process, however, the BEV has the highest fossil use in the WTT process, which even higher than the one of the ICEV in WTT, and this may be explained by the coal power plants having the potential to improve their refining efficiency compared to that of oil refineries in China. In total life cycle, the BEV has the best performance from among all these vehicle technologies. In addition, this WTW fossil consumption reduction benefits from BEV will become more significant in next two decades compared with the reduction expected for the HEV and PHEV (See Figure 5-4).

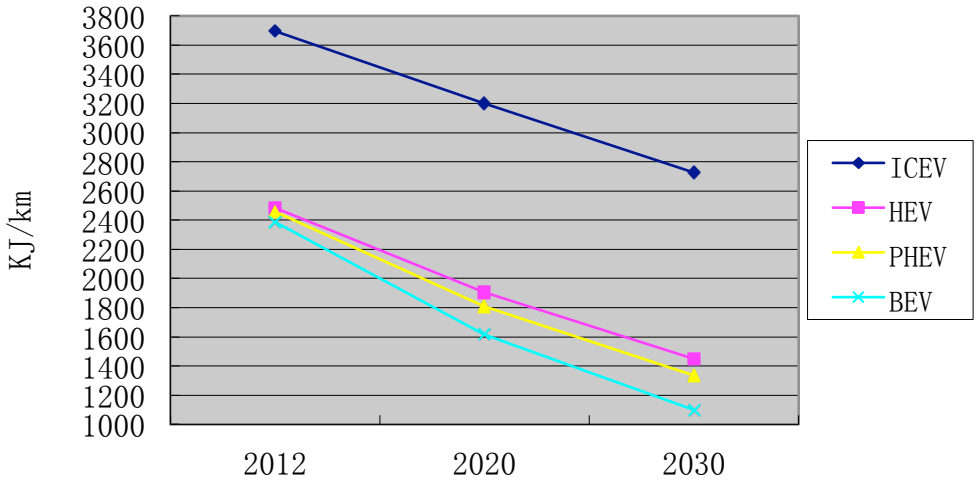


Figure 5-4 The trend of total fossil consumption change from 2012 to 2030

The Figure 5-4 shows the trend of total fossil consumption changes by each vehicle technology from 2012 to 2030. It can be seen that the rate of change for the HEV and the PHEV are similar in each calendar year. Compared with the other vehicle technologies (ICEV, HEV and PHEV), the reduction rate curve for the BEV changes more sharply.

Petroleum consumption

Petroleum consumption is the major energy security issue for China as a result of the high dependence on imported oil. Therefore, in this study, the WTW petroleum

energy use for each of the vehicle technologies has been calculated separately for analysis, and the results are shown in Figure 5-5.

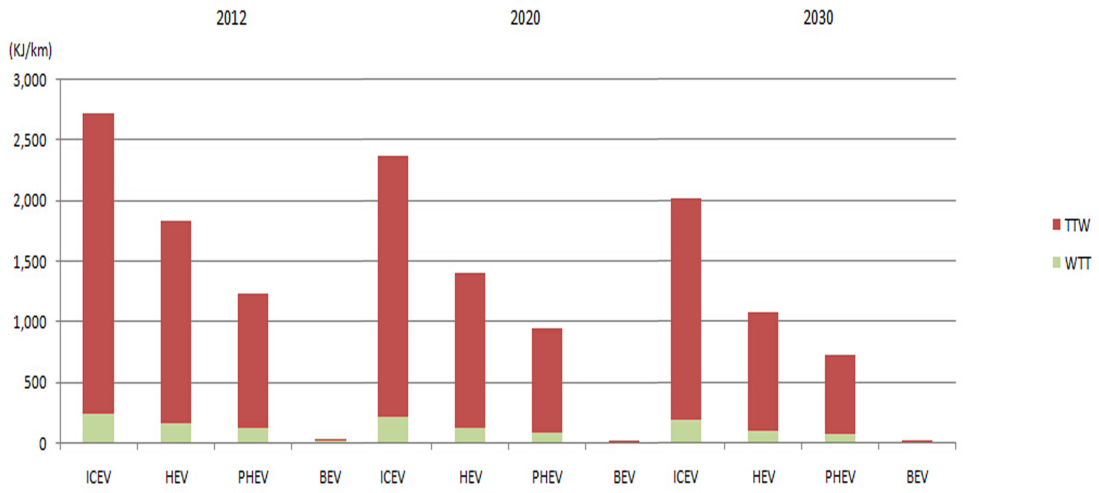


Figure 5-5 WTW total petroleum use of 4 vehicle technologies in 2012, 2020 and 2030

From the chart, it is clearly seen that most of the petrol is used during vehicle operation and only a low percentage of oil is used in fuel extraction, transport and power generation process, such as the oil loss in refining process and the oil cost during raw materials transport. The petroleum consumption is mainly concentrated in the TTW stage for the ICEV, the HEV and the PHEV. However, in contrast, for the BEV, because the vehicle is fully powered by electricity during the vehicle operation

process, only a very small amount of petroleum consumption is used in the TTW stage. Because of the low percentage of petrol use in China's recent power mix (less than 1%); the petroleum consumption for the BEV in the WTT process is also very low. For example, in 2012, the petroleum consumption of the BEV in the WTT stage is 29KJ/km, while the petroleum consumption for the TTW is only 14KJ/km. There is no doubt that the outstanding performance of the BEV on saving petroleum consumption cannot be matched by any other vehicles (HEV and PHEV).

However, it should be noted that the PHEV could also achieve a huge reduction in total petroleum consumption through the use of electricity. For example, the WTW petroleum consumption for the PHEV in 2012 is 1243KJ/km, which is 591 KJ/km saving compared to the 1834KJ/km for the HEV. In addition, the reduction percentage of the WTW petroleum consumption for the PHEV is about 54.2% (2012), which means more than half of the total petroleum consumption of the traditional ICEV. Wu et al. (2012) has pointed out that this figure is mainly affected by the battery performance and battery size. A similar conclusion was made by Elgowainy, et.al

(2010) in their study where it was suggested that for the PHEV, if the all-electric range (AER) of the PHEV increases, the performance of the petroleum energy saving in the WTW would also be improved.

WTW CO_2 ***emissions***

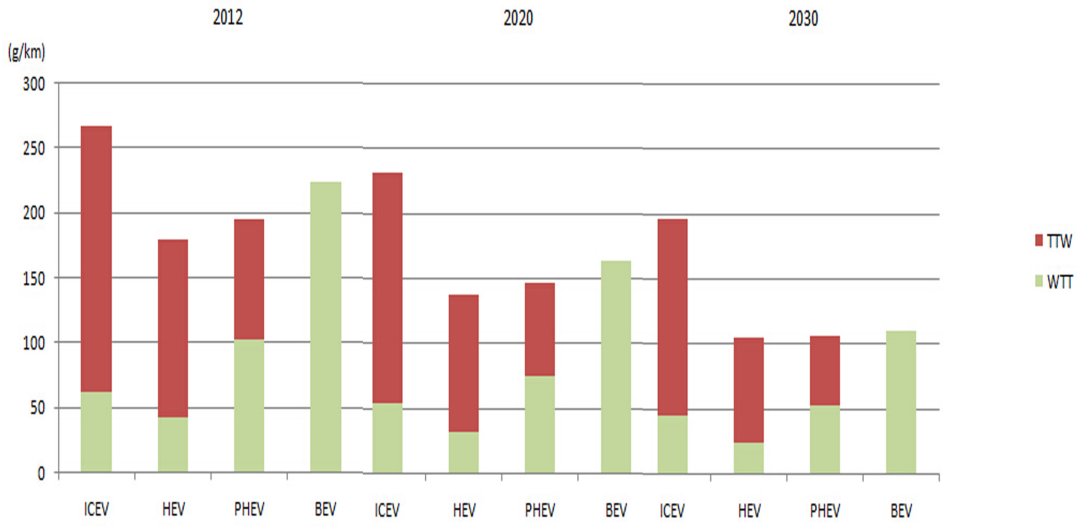


Figure 5-6 WTW total CO_2 emissions of 4 vehicle technologies in 2010, 2020 and 2030

Figure 5-6 presents the results of the WTW CO_2 emissions for each vehicle technology from 2012 to 2030. The measurement unit for this is grams of CO_2 per kilometre travelled by each vehicle technology. It can be seen that due to the changes in the

power mix in the future and the improvement of fuel economy of the vehicle, the WTW CO_2 emissions for each of these four vehicle technologies (including the ICEV) are continually decreasing over the next two decades. Unlike the energy consumption, the BEV has the worst performance in terms of reduction of CO_2 emissions among these three advanced vehicle technologies, and this conclusion is attributed to China's coal-based power generation structure. The total WTW CO_2 emissions for the BEV are all from the WTT stage and the CO_2 emission from the TTW is zero (See Figure 5-6).

By considering the changes in the power mix in the future and the advanced power generation technology such as advanced coal technology, the WTW CO_2 emissions for the BEV has decreased from 224g/km in 2012 to 111g/km in 2030. However, the carbon content per unit of coal is much higher than petroleum, and even considering the increasing use of nuclear power and other clean energy, coal will still remain as the main contributor to China's energy structure over the next decades. Therefore,

the WTW CO_2 emissions reduction for the PHEV and the BEV are always worse than the performance for the HEV even in 2030.

However, even the BEV still contribute more CO_2 emissions than the HEV before 2030, it has shown the most potential in CO_2 reduction among all these vehicle types (See Figure 5-7). Figure 5-7 shows the curves for total CO_2 emissions by each vehicle technology. The curve of BEV has the sharpest decrease, and the WTW CO_2 emissions for the BEV and PHEV is getting closer and closer to the one for the HEV by 2030. It can be expected that the BEV will achieve better performance on CO_2 reduction than one of HEV in the future with the continuously improvement of upstream power generation efficiency and the increasing proportion of clean electricity.

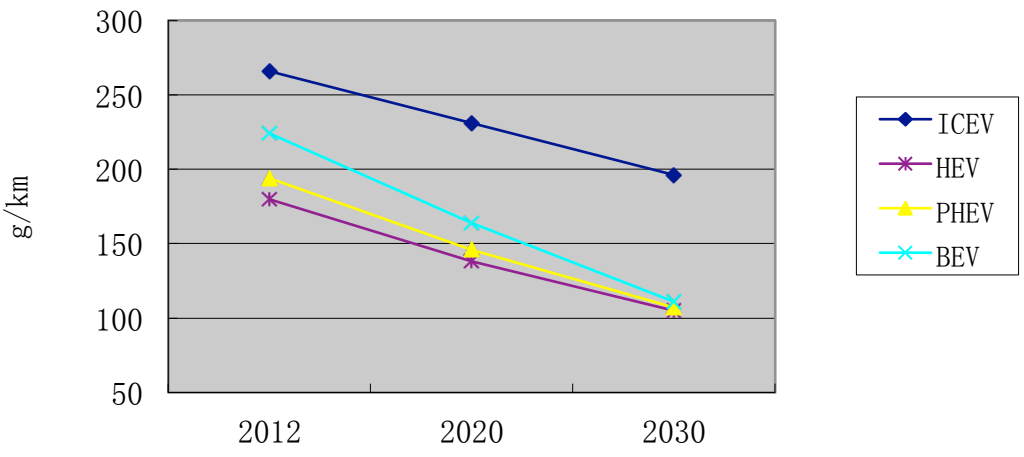
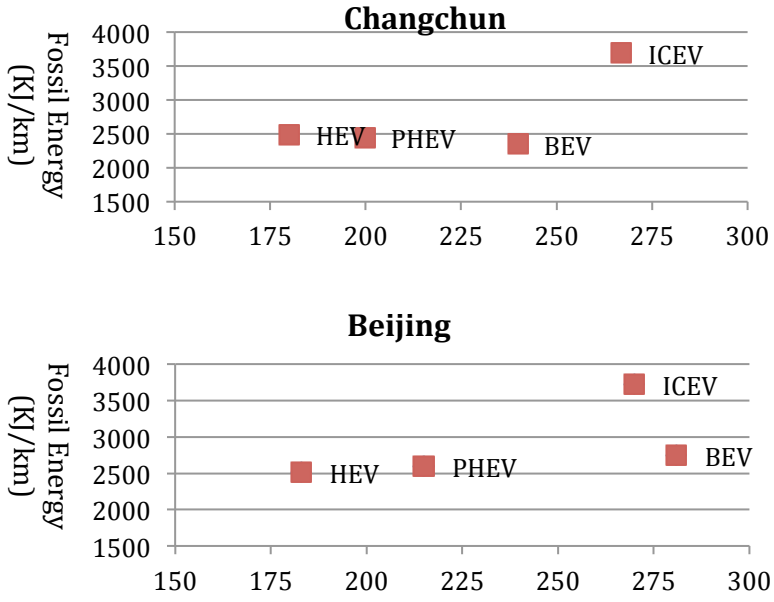


Figure 5-7 WTW CO_2 emissions curves of two scenarios and each vehicle technology

5.4.2 Comparisons of different EV models in different regions

Due to the uneven energy distribution in China, the generating energy mix is significantly different in various regions of China. Based on the currently situations (2012 data), this study calculated the fossil energy consumption and CO_2 emissions of four vehicle technologies in 5 New energy Vehicle pilot cities, which include Changchun, Beijing, Shanghai, Chongqing and Shenzhen (See Figure 5-8). From the result it can be observed that the BEV only has higher life cycle fossil use than the PHEV and HEV in Beijing and Shanghai, due to the high proportion use of coal fired power generation in these two cities (96.5% and 96.2%). In addition, the high proportion use of coal power also caused the CO_2 emission of the BEVs in these two cities have the worst performance among all the cities, and the CO_2 emission of the BEVs in Beijing and Shanghai are even higher than the emission from ICEV, which can result in an increase of 4.1%(Beijing) and 4.4%(Shanghai) of CO_2 emissions relative to ICEV counterpart. In contrast, the performance of the BEV on fossil energy saving and CO_2 reduction in Chongqing is the best compared with the performance in all other

cities, due to the 41% hydro power in its power generation mix. It should be note that the CO_2 emission of the BEV in Chongqing first time becomes lower than the one of the HEV. In addition, because of the electricity use in the WTT process, such as the electricity used in Petroleum refining process, the local power generation mixes among different cities also have a slightly different impact on the WTT CO_2 emissions and energy consumption of ICEV and HEV, even if these two kind of vehicle do not use electricity as operation power. For example, the CO_2 emission of the ICEV and HEV in Chongqing (276g/km and 176g/km) is slightly lower than the one in in Beijing (270g/km and 183g/km).



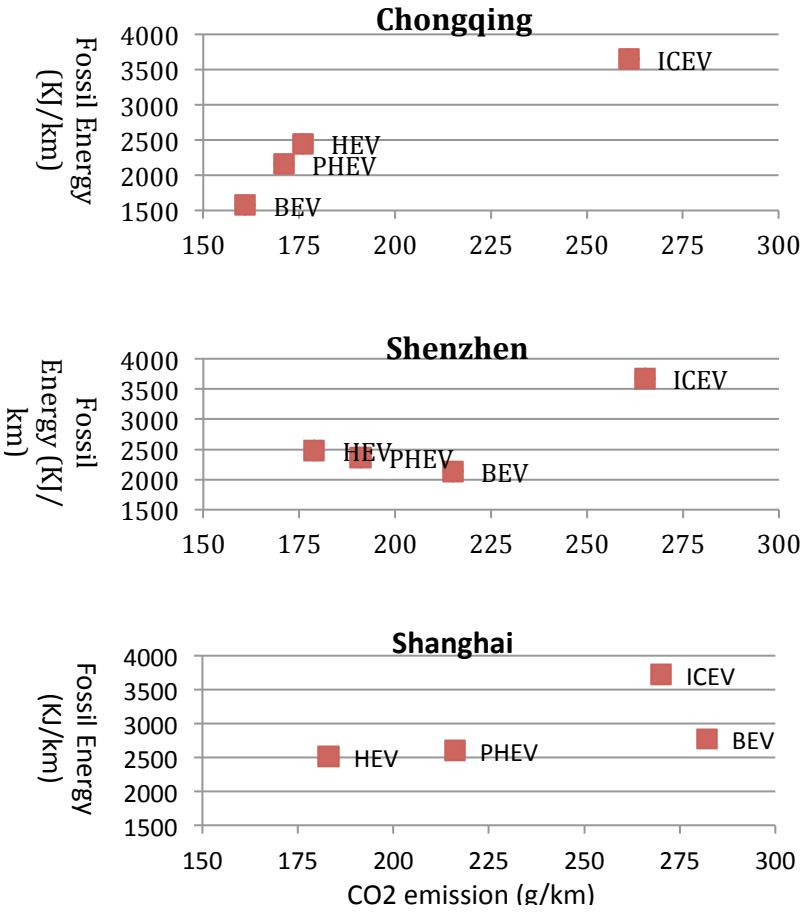


Figure 5-8 The total CO_2 emissions and fossil energy consumption of each vehicle technology in five cities

5.4.3 Breakpoint analysis

As the results shown in both national level and regional level, the performance of BEV is significantly affected by the different electricity generation mix, especially the proportion of coal fired power and clean power. China's strategy is most focusing on the development of BEV, therefore, it is important to understand how will the performances of BEV on CO_2 reduction can be affected by the change of the coal fired

power. Based on the situation in 2012 (using the parameters of 2012), this study assumed that the proportion of Nature Gas in the generation mixes is 2%, and the share of coal-fired power will continually decrease and be replaced by the clean power (wind, hydro, nuclear and others). As a result, this study find out the break point of the proportion of coal fired power when the CO_2 emission of the BEV can be lower than the ICEV and when the CO_2 emission of the BEV can be lower than the HEV (See Figure 5-9).

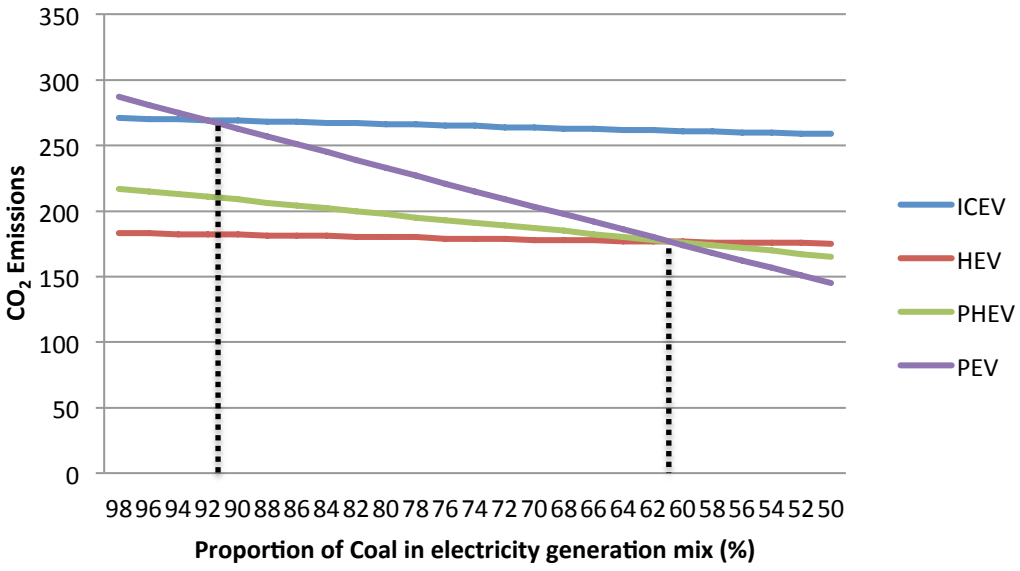


Figure 5-9 The Break point analysis of different vehicle models

From Figure 5-9, it can be known that the CO_2 emission of BEV and PHEV shows a clear linear relationship with the proportion of the coal-fired power. In fact, not only

the BEV and PHEV, the CO_2 emissions of ICEV and HEV are also slightly reduced through the decrease of the coal-fired power, which may caused by the using of electricity during the oil exploration and processing. As the Figure shown, the breakpoint between BEV and ICEV arise when the proportion of coal in electricity generation mix reduced to 92%. It means that when the coal-fired power occupied more than 92% of the total power mix, the CO_2 emissions of BEV is even higher than the one of ICEV, such as the situation of Beijing and Shanghai. And the BEV will show a better performance than the ICEV once the coal-fired power share below the 92%. In addition, the breakpoint between BEV and PHEV and the one between BEV and HEV will almost appear at the same time when the proportion of coal-fired power reduces to 61%. Once the proportion of coal reduces below the 61%, BEV will start to show a better performance on CO_2 emissions than the HEV and PHEV, such as the situation of Chongqing in this study. And it also can be clearly known from Figure 5-9 that the slope of CO_2 reduction of BEV is much sharper than the one of HEV and PHEV, which means that the BEV can contribute to more and more CO_2 reduction than HEV through the continually decrease of coal-fired power after 61%. For

example, when the proportion of coal-fired power reduces to 50%, the WTW CO_2 emission of BEV is 145g/km, which is 17% lower than the one of HEV (175g/km). However, as the Table 5-2 shown in this study, currently, the thermal power still contribute to more than 78%, and this figure do not change a lot during the last 30 years. There was only 3% reduction in last 10-12 years. If considering more significant declining trend of thermal power in the future and assumed the proportion of thermal power would reduce 5%-6% in each 10 years, the proportion of coal-fired power can reduce to 61% around 2040, which means the CO_2 reduction of BEV in China cannot show better performance than the one of HEV until 2040. However, if considering the fuel economic improvement of the EVs, this breakpoint may be achieved earlier than 2040.

5.5 Discussion and recommendation

5.5.1 Accelerate the restructuring of energy power

The government and auto industry in China have considered the BEV as the best vehicle option for development. As Figure 5-3 and Figure 5-5 both show, the BEV

plays the dominant role in the reduction of fossil energy consumption and petroleum consumption among all these vehicle technologies (BEV, HEV, PHEV). However, due to the high proportion of coal-based power generation in the national level, the BEV has the worst performance in the reduction of CO_2 emissions among all three EV technologies until 2030 (see Figure 5-6). Based on the result from break point analysis, the BEV will not produce lower CO_2 emissions than the HEV until the coal-fired power proportion reduce to 61%, and based on the change trend of thermal power in last 30 years, this figure (61%) will not be achieved before 2030.

Therefore, the transformation of the automotive industry should reflect the power generation mix. This means that the transformation speed of the automotive industry needs to be synchronized with the de-carbonization of power generation in China. The optimization of the energy structure needs to be seen as part of the rapid auto industrial transformation, otherwise separate pathways may result in the overall levels of carbon emissions increasing as motorization takes place. It might be considered that changing the existing generating energy structure in China (reducing

the dependence on coal and increasing the use of clean power) is the most direct and effective means to optimize the performance of the electric vehicle for both energy consumption and CO_2 emissions.

5.5.2 Emphasis on the development of the HEV and the PHEV as a transition for long-term EV development

From the results reported here, the BEV and the PHEV have the potential to achieve greater reductions for both fossil energy consumption and petroleum consumption as compared with the HEV, and this advantage also continues to increase over the next decades as a result of the changes in the power generation mix. However, the HEV has shown an outstanding performance on reducing CO_2 emissions, which cannot be exceeded by other vehicle technologies over the next two decades.

Therefore, combined with the performance and feature of each kind of EV on fossil consumption, petroleum consumption and CO_2 emissions, the EV development strategy in China should not only focus on one kind of electric vehicle. Especially in the short term, China should achieve comprehensive development of all three EV

technologies, using the better performance of the HEV and the PHEV on CO_2 emissions reduction to achieve the emission reduction target in next 20 years. The HEV and the PHEV can be developed as a short-term strategy in China, and they would be seen as the transition technology to achieve the ultimate goal of a high level of BEV penetration. Then, as time goes on, with the changes in the structure of the energy generating mix, China can start to transfer the focus of the EV development strategy to the BEV technology. For example, as the results of this study have shown, the BEV has the large potential to show good performance on CO_2 emission reduction after 2030, resulting from the energy mix changes and the power generation efficiency improvement. By considering the technological improvements in batteries in the future, the BEV will have a sufficient period to develop and become dominant after 2030.

5.5.3 Different EV development strategy depend on the different regions

In China, the development of EVs has already been considered as an industry revolution for future sustainable transport (Wu, et. al, 2012). The HEV, the PHEV and

the BEV are now being demonstrated widely in many large cities in China, as there are 25 cities in China which have joined the program of "10 cities 1000 vehicles" to promote EV development (2009-2012). However, the generating energy mix is significantly different in various regions of China, and this has affected their relative performances. As the results shown in this study (Figure 5-8), only the Southwest of China (Chongqing) can achieve the gratifying performance both on energy consumption and CO_2 emission for the BEV development, due to its abundant hydro resources. In other regions (Northeast, North, East and Southeast), the BEV performance on CO_2 emissions reduction is worse than the one of the HEV and PHEV. Especially in Beijing and Shanghai, The BEV showed the worst performance both on energy consumption and CO_2 emissions among the three advanced vehicle technologies, and the CO_2 emissions of the BEV are even higher than the one of the ICEV. Despite the majority of electricity in Beijing (68%) and Shanghai (35%) are imported from other provinces (Energy Statistics Division of the National Bureau of Statistics, 2013), based on the power mix in national level, the large-scale electric vehicle applications in these regions still may result in more CO_2 emissions than for

the conventional vehicles. Therefore, promoting alternative development strategies in different regions based on the different performance of EVs in these areas are also very important and necessary considerations. For example, the BEV and the PHEV could be vigorously promoted in the South and Southwest in China where a high proportion of hydropower is being used in the power mix. In contrast, Beijing and Shanghai should develop the HEV and the PHEV instead of developing the BEV in short period.

5.6 Conclusions and Policy Implications

Based on the discussion and analysis above, it can be shown that by only focusing on the development of EVs does not completely solve the problem of energy consumption and carbon dioxide emissions in China. The current policy in China is very much focused on the development of the BEV in order to achieve the ultimate objective of clean mobility in one step. The latest policy which has been proposed by four Ministries (17th September 2013) clearly stated that for the next round of EV demonstration projects, the subsidy targets are for all electric battery powered

vehicles (BEV, PHEV and FCV), but the HEV is no longer included. In addition, for the PHEV, the subsidies only provided to the PHEV when the electric driving range can achieve 50km or more (MOF, MOST, MIIT and NDRC, 2013). The Government is still only focusing on BEV, and even though the PHEV is included in the subsidies objectives, the requirements of the battery driving range means that most types of PHEV are excluded.

However, based on the results of this study, it can be seen that the development of HEV and PHEV will have very good results in terms of energy saving and CO_2 emission reduction (to 2030), and they have a better performance on reducing CO_2 emissions than BEVs given the current power mix. In addition, PHEVs can be more easily accepted by the consumers due to their lower price and longer driving range compared with BEVs. Therefore, the promotion of PHEVs in the short-term and mid-term future will be very helpful in promoting the construction of the charging infrastructure, and in the creation of a favourable market environment for BEV introduction. The Government needs to think about a specific strategy for different

periods, and for the introduction of more policies to support the R&D and the promotion of PHEV in the short-term future.

The development strategy for the EVs in China needs greater flexibility to reflect the regional variations that include the local power mix, the local auto industry and the local environment. For example, the weather of Northeast of China is very cold in winter, and according the experience from the existing EV demonstration program, the batteries of the BEV do not work very well in the cold weather such as -30 to -40 degrees. In addition, more energy consumption of heating in the cars will lead to shorter driving range. The promotion of HEV may be more suitable for the Northeast cities in China such as Changchun and Harbin. In addition, the South and Southeast regions in China such as Chongqing and Shenzhen will be good choice to be selected as the pilot city for the promotion of BEV due to its high proportion of hydropower and also the developed economy and leading electric car company such as BYD. In addition, a clearly developed strategic roadmap would consider the EV transition and promote speed in terms of decarbonizing the energy mix, so that the ultimate goal of

BEV penetration would take place as soon as possible. Low carbon futures in China need to consider both the power generation structure (nationally and regionally), together with the particular transport requirements in the rapidly growing cities and regions. It is not just a transport problem, but also one that relates to national energy and carbon strategy.

Chapter 6: A diffusion model to forecast the market penetration of the Battery Electric passenger Vehicle in China to 2040

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6.1 Introduction

As a result of the concerns over climate change and energy security, Electric Vehicles have been widely considered by many countries (such as US, China and EU countries) as having a major contribution to make to GHG emission reduction and energy saving in the transport sector (Baran et al., 2013 and OECD, 2010). Electric vehicle (EV) technology would be vigorously developed in all vehicle markets, to take advantage of their lower greenhouse gas (GHG) emissions, less dependence on petroleum resources, and positive effect on technological competitiveness and economic growth (Yang et al., 2013). According to the different technologies, the EVs contain many different vehicle types; this study considered the EVs mainly contain four kinds of vehicles which include the battery electric vehicle (BEV), the hybrid electric vehicle (HEV), the plug-in hybrid electric vehicle (PHEV) and the fuel-cell electric vehicle (FCEV).

China has been at the forefront of this thinking, and since the early 1990s the Government has been aware of the potential for EV development as part of the more

general desire to improve environmental quality, reduce the dependence on imported oil, and to promote economic growth and the domestic car industry (Yang et al., 2013; and Zheng et al., 2012). The overriding objective of the EV strategy in China is to promote battery electric vehicles (BEV) to replace the conventional vehicle, and to combine the BEV with other forms of advanced technologies (HEV and PHEV) as transition technologies. China has just entered the 12th Five-Year Plan period (2011-2015), and in 2011, the Ministry of Science and Technology (MOST) carried out the "12th five year" national plan for EVs. The plan clearly pointed out that the main focus is on "the development of light pure electric vehicles over the next five years" (Zhou et al., 2013). In June 2012, the latest report "Energy-saving and new energy vehicles development plan for 2012-2020" was published by the State Council of China. The report stated the new target for the EV industry in China, namely that the total production of BEV and PHEV together should reach 500,000 by 2015 and approach 5,000,000 in 2020 (the State Council of China, 2012; and Yang et al., 2013).

China has become the largest automotive manufacture and the petroleum consumer in the world (since 2009). According to Wang et al. (2011), the annual sales of vehicles in China dramatically increased from 1.4 million in 1994 to 18 million in 2010. However, the vehicle ownership in China is still very low compared to that in developed countries such as the US. For example, the vehicle ownership in China is 57.6 per thousand persons in 2010, which is only 1/14 of the levels in US (833 per thousand persons in USA in 2007) (Wang et al., 2011 and JAMA, 2012). If China wishes to catch up and reach the global average level, there still needs to be significant growth in the vehicle stock in China. According to Wu et al. (2012), the car ownership per thousand persons in China will approach 120 by 2020 and will reach 300 by 2030. As the Chinese government attaches considerable importance to the development of electric vehicles, it can be expected that the EVs (HEV, PHEV and BEV) will account for a significant proportion of the growth of total vehicle stock in China. Forecasting the diffusion trend of EVs in China will not only contribute to help the decision-makers to formulate development strategies of EVs, but also help to calculate the energy savings and GHG reductions in the future.

This study forecasts the potential diffusion trends of BEV in China's light duty passenger car market through considering a range of different scenarios. A diffusion model based on Generalized BASS model is used in this study for a comparative analysis of the different scenarios. Several scenarios have been set to determine the different potential situations in the future, to cover the different alternative products for the model simulation such as for the conventional vehicle and for the HEV, and to represent the different variables such as driving range, vehicle prices, the necessary supporting infrastructures and fuel prices. The potential future for pure battery electric passenger vehicles (BEPV) penetration in China until 2040 will be analysed through the comparison and discussion of the different results from the different scenarios. In addition, sensitivity analyses of the different variables have been carried out to find out the relationships between the BEV penetration and each variable. Recommendations are developed to improve the utility of this forecasting approach for the promotion of the BEV in China.

6.2 Literature review

BASS model, as one of the most widely used diffusion rate and time series model, is proposed by Bass in 1969 (Lee et al., 2013 and Park et al., 2011). The Bass diffusion model can describe the probability of adoption of a new product or technology at a particular time as the summation of the probability of adoption by an innovator group and the probability of adoption by an imitator group (Bass, 1969) (Nigel and Towhidul, 2006; Lee et al., 2013 and Park et al., 2011). The impacts of variables on the innovator group and the imitator group have been presented as innovation factor p and imitation factor q in the BASS model. However, for the original Bass diffusion model, the coefficients of innovation and imitation remain constant over time. This may not be true if, for example, the new product innovation is itself changed by the products updates or technology improvement, or if the market environment is changed by some factors, such as policy effects and cost reduction effects. Therefore, a Generalized Bass diffusion model was developed to consider a range of variables that can affect diffusion such as marketing and cost reduction effects. This model can

also consider how the innovation factor and the imitation factors might vary over time, as a result of the influence of variables. (Bass et al. 1994) (Park et al., 2011).

Both the BASS model and extended Bass diffusion model are widely used in the forecasting of electric vehicles, such as HEV, PHEV and Fuel-cell electric vehicle (FCEV). McManus and Senter (2010) developed four market models for predicting PHEV adoption, namely the BASS, Generalized Bass, Logistic, and Gompertz models. In their study, they developed a scenario prediction for each model, and the Generalized Bass model was specified differently to the Bass model by considering an expression, which is a function of the PHEV price premium and the difference in fuel costs per mile between the PHEV and the conventional vehicle. Cao (2004) carried out a similar study to forecast the future demands of alternative fuel passenger vehicles including light-duty automobiles and light-duty trucks by using an extended BASS model. The study established different scenarios by considering different impact factors such as petroleum price change and market potential of HEV. Furthermore, Cao's study also considered the situation when the coefficients of the Bass model

were kept unchanged over time, meaning that there will be no interaction effects from the impact factors. For example, this might occur when the vehicle technology does not have significant breakthrough and does not affect the coefficients in the mode. In addition, the diffusion rate of the products will also not be affected by government policies or marketing strategies. The diffusion of EVs in US to 2030 was modeled by Becker (2009), when the BASS model was used with two scenarios based on different petroleum prices. In the baseline scenario, the maximum market penetration of EVs is estimated to be 70 percent.

However, Park et al. (2011) described in their study that the lack of data to set model parameters has already become the greatest challenge for applying the diffusion model to a real problem. For a new product or technology such as EVs, there is no available historical market data for estimating model parameters, as the new product has not yet been introduced into the market or it has just been introduced into the market for a very short period. Therefore, in order to forecast the diffusion of new technology without enough sales data, many existing studies have considered the

possibility of using an alternative product that has enough past diffusion data and similar diffusion characteristics as the targeted product (Bose et al., 1996) (Park et al., 2011). This thinking has also been applied to forecast the diffusion of EVs. For example, Won et al. (2009) used a Bass diffusion model to simulate the diffusion rate of PHEV in Korea, but due to the lack of historical sales data of PHEV in Korea, they used HEV sales data in US as the alternative product data for the model. In addition, Park et al. (2011) assumed that the penetration characteristics of Hydrogen Fuel Cell Vehicles (HFCVs) are the same as the penetration characteristics of the HEV, and their study used the sales data of HEV in Japan to forecast the diffusion of HFCV in Korea. Although there are some studies using the BASS model for the EV forecasting, there are only limited studies of the impact of BEV on China's vehicle market. In addition, most of the existing studies only consider one or two key variables such as fuel price and infrastructures. In order to achieve a more accurate prediction, a more comprehensive model has been developed to consider a wider range of variables that influence EVs penetration. In addition, it is necessary to analyse the sensitivity of each variable so that the impact of each can be assessed on the diffusion of EVs.

The aim of this paper is to determine the potential diffusion trend of the BEV in China over time. Due to the limited existing market data, this study chose to use the BASS model to assess the BEV diffusion curve from a broader perspective. In addition, a model based on Generalized BASS model will be developed to show the different situation when more variables are considered (such as driving range, charging infrastructure, cost reductions and oil price increases). Two other factors are included in this analysis. First, to capture China's passenger car market characteristics, this study assumes that conventional passenger cars in China are alternative products for forecasting the BEV diffusion trend. The reason for this is because they are all automotive products, and they all have the same market environment and the same customer base. However, those EVs (especially the BEV), are a kind of electrified products, which have a different structure and function compared with internal combustion engine vehicle (ICEV). Considering the penetration characteristics of the conventional vehicles is not enough to elaborate the development path of EVs. Secondly, by considering the characteristics of the product itself, this study assumes

that the penetration characteristics of BEVs are similar to the penetration characteristics of the HEVs which are all alternative electric vehicles (as in the Park et al. (2011) study). The development of HEVs in China is also at a very early stage, therefore this study use the sales data of the HEVs in US as the alternative products data for the model simulation. According to the results based on these two alternative products data, this study will discuss the diffusion possibility in reality of the BEV in China.

6.3 Methodology

6.3.1 Generalized BASS model

The BASS model was first proposed by Frank M. Bass (1969). Bass considered that after the introduction to the market takes place, the diffusion rate of the new product was not only affected by the factors such as the mass media coverage, but also the internal factors such as word-of-mouth between individuals (Laciana et al., 2013; Bass, 1969 and Cao, 2004). Therefore, the BASS model combined the external influences and internal influences together to describe an S-shape diffusion curve of

the new product by using the innovation factor and the imitation factor. The basic function of the Bass diffusion model can be given as the mathematical formula below: (Bass, 1969) (Mahajan et al., 1990) (Nigel and Towhidul, 2006).

$$\frac{f(t)}{1-F(t)} = p + qF(t) \quad (1)$$

Where:

f(t) is the rate of change of the installed base fraction (the fraction of the potential market that adopts the new product at time t);

F(t) is the installed base fraction (the fraction of the potential market that has adopted the new product up to time t)

Thus:

$$F(t) = \int_0^t f(t)dt$$

p is the coefficient of innovation, represents the innovation factor which is the probability of adoption by an innovator group, and this coefficient is directly dependent on the number of previous adopters

q is the coefficient of imitation, represents the imitation factor which means the probability of adoption by an imitator group.

The innovation coefficient p and the imitation coefficient q in the original Bass diffusion model are considered to be stable and unchanged over time. However, due to the effects from variables, the innovation factor and the imitation factor will not be stable and are likely to vary with time. For this reason, a Generalized Bass diffusion model was also developed in order to overcome the limitations of the Bass diffusion model. Compared to the original Bass model, there is an mapping function x(t) added into the Generalized Bass diffusion model. The mapping function x(t) describes the current effect of the decision variables on the conditional probability of adoption at time t, and it was added to the Bass diffusion model(Bass et al.,1994):

$$f(t)/(1-F(t)) = [p + qF(t)]\, x(t) \qquad (5)$$

$$f(t)/(1-F(t)) = x(t)p + x(t)qF(t) \qquad (6)$$

6.4 BEV diffusion model based on Generalized BASS

From function (6), it can be found that the Generalized BASS model assumed that the variables will have the same effects x(t) on both the innovation factor p and imitation factor q. However, to promote the BEV, the innovation consumers and imitation consumers will have different value systems, and the variables will also have different effects. For example, the vehicle performance and costs may impact more on the innovation customer's choice, and the imitation consumers may focus more on word of mouth, the supporting infrastructure and the cost of using the BEV. Therefore, this study uses a BEV diffusion model based on the Generalized BASS model in order to focus more on the impacts that decision variables have on the innovation factor p and the imitation factor q respectively. In the diffusion model, the innovation coefficient p and the imitation coefficient q is not a continuous function of time, but can be changed over time. The innovation coefficient and the imitation coefficient of BEV consider the coefficient of alternative products (such as ICEV and HEV) as a reference. By comparing the differences between the BEV and alternative products factors such as vehicle performance, cost, fuel cost and infrastructure, adjustment

factors can be defined to simulate the innovation coefficient and the imitation coefficient of BEV. The Elasticity is an indirect prediction method which can predict one variable through considering the relative response of one variable to changes in another variable. This study uses the Elasticity method to define the adjustment factor by considering the difference between the BEV and alternative vehicles (See Function 7 and 8). The main function of the diffusion model has been shown as Function 9:

$$p_{BEV} = p_{car} * [A_t^{\alpha} * B_t^{\beta} * C_t^{\gamma} * D_t^{\lambda}]; \alpha + \beta + \gamma + \lambda = 1; \quad (7)$$

(A,B,C,D are the adjustment factors of innovation between the BEV and alternative vehicles, such as vehicle performance, vehicle cost, fuel cost, and Infrastructure, α, β, γ, λ are the weights which present the impacts of each adjustment factor on innovation factor)

$$q_{BEV} = q_{car} * [W_t^{\omega} * X_t^{\rho} * Y_t^{\vartheta} * Z_t^{\eta}]; \omega + \rho + \theta + \eta = 1; \quad (8)$$

(W, X, Y, Z are the adjustment factors of imitation between the BEV and alternative vehicles (they can be the same ones as the A, B, C, D, or different, ω, ρ, θ, η are the weights which present the impacts of each adjustment factor on imitation factor)

$$f(t)/(1-F(t)) = p[A_t^{\alpha} * B_t^{\beta} * C_t^{\gamma} * D_t^{\lambda}] + q[W_t^{\omega} * X_t^{\rho} * Y_t^{\vartheta} * Z_t^{\eta}]F(t) \qquad (9)$$

Related to this study, there are many kinds of variables, such as the vehicle performance, operating costs, the petroleum price, the charging infrastructure, government policy and so on, that could be used. Based on the interviews with the Shanghai EV ZONE, a survey was carried out to analyze the awareness and experience of EV potential consumers. From 1st Jan 2013 to 31th Dec 2013, the survey elicited 6144 effective questionnaires from the EV test driving consumers in EV ZONE (Shanghai). The results of the survey showed that driving range, purchase cost, infrastructure and safety are the top issues which affect customers to buy EVs (Shanghai International Automobile City (Group), 2014) (See Figure 6-1).

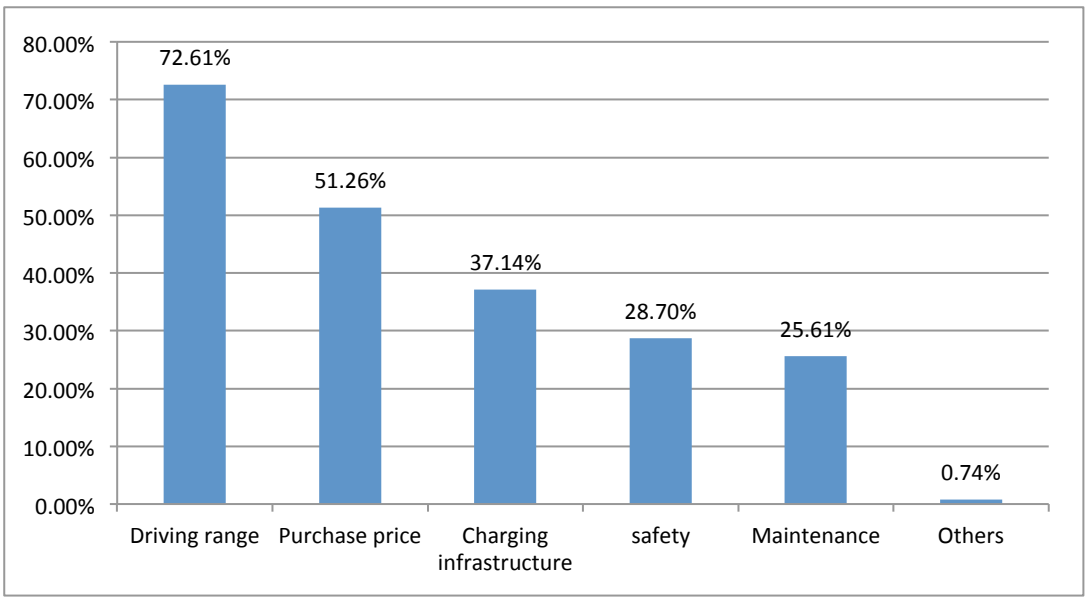

Figure 6-1 Main concerns from EV test driving consumers

Source from the new energy vehicle demonstration annual report (2013) in Shanghai International Electric Vehicle Demonstration Zone

However, because some variables are difficult to measure (such as safety and maintenance costs), this study focuses on the impacts of vehicle driving range, vehicle cost, fuel cost, and charging infrastructure on the innovation factors. The imitation group is also affected by these four variables, but there are more variables that will affect the imitation factor in reality, such as word of mouth and the awareness of EVs. In this study, due to the limitations of available data and the difficulties in quantifying some variables (such as the word of mouth), this study has assumed the adjustment factors for imitation between the BEV and alternative vehicles (W, X, Y, Z) to be the

same as the adjustment factors for innovation factors (A,B,C,D) (i.e. driving range, vehicle cost, fuel cost, and Infrastructure). These impact factors will be considered as the main variables in this study to affect the parameters p and q over time. And these adjustment factors are considered to have different impacts on the p and q, which means the innovation elasticities ($\alpha, \beta, \gamma, \lambda$) are different with the imitation elasticities ($\omega, \rho, \theta, \eta$).

6.5 Parameter setting

As stated above, there are three main parameters in the BASS model, namely the market potential M (see below – Section 4.1), the innovation coefficient p, and the imitation coefficient q. In addition, the elastic coefficients of the main variables on p and q are also important, which presented as $\alpha, \beta, \gamma, \lambda$ (innovation), and $\omega, \rho, \theta, \eta$ (imitation).

6.5.1 Maximum potential consumers function M

In this study, in order to simulate the potential market of BEPV, both the maximum potential market of China's total passenger vehicle and the competition among different kind of EVs such as HEV, PHEV, and BEV need to be considered. There are some researchers who believe that the EVs will finally replace ICEVs in the future (Yang et al., 2013). Therefore, it can be considered that in extreme cases, EVs (BEV, HEV and PHEV) can completely replace the traditional car, and this means that the total number of potential consumers of EVs is equivalent to all conventional car users in the future (i.e. a saturation level of 100%). In addition, EVs as new technologies are all still in the early stage of market introduction. The PHEVs were first introduced to limited production in 2004 and mass production started in 2011. Electric cars only began to be sold to the public in 2011 (Al-Alawi and Bradley, 2013). According to Zhen (2012), pure electric vehicles, plug-in hybrid vehicles, fuel cell vehicles, and hybrid cars will grow with little competition from each other in accordance with the early stage of market introduction (up to 2030). This means that the impacts from the competing market shares among different kind of EVs will be not significant. The

main factors influencing consumers' purchase decisions are mainly coming from the performance and cost of electric car itself compared to the conventional cars (Zhen, 2012). Therefore, due to this study only considering the diffusion trend of BEPVs until 2040, the penetration of BEVs in this study is assumed to be naturally growth without the competition among the other EVs. After 2040, with the rise of various forms of EVs ownership, the competition among these various EVs will become more intense. The natural growth environment no longer exists, and further study on the saturation point of the various vehicles is needed.

According to the development plan of the Electrification Coalition in US (2010), by 2040 the United States will have 250 million electric vehicles, and 3/4 of the light duty vehicles demand will be provided by electric vehicles. It can be seen that the electrification companies consider that the prospects for the dominance of the EV are very optimistic. In contrast, opinions of the oil and gas companies are not so optimistic. The reports from the ExxonMobil (2013) showed that the BEVs and PHEVs will account for 10% of the total vehicles in the world by 2040, and the HEV will account for 35% of the total passenger

cars. In addition, the report of “New Lens Scenarios” assumed that electricity and hydrogen begin to gradually take over the vehicle fuel market from 2030, and they will totally replace the fossil fuels around 2070 (Shell, 2013) . The report also showed the vehicle liquid fossil fuel use will reach a peak around 2035, and then begin to decline. The electricity and hydrogen will account for 22% of the total passenger road transport fuel use in 2040. In China, the State Council published the "Plan of Energy Saving and New Energy Vehicles 2012-2020", which established the development goals of EVs until 2020. The plan estimated that the total cumulative population of BEVs and PHEVs should reach 500,000 by 2015 and achieve 5,000,000 by 2020, a 10 times increase in 5 years. Therefore, this study has assumed that the BEV development status in China will be an “optimistic” future in light of China’s concerns over energy security and the substantial support from government. There is a program called “Prediction of long-term automotive market in China” (2012), which was completed in cooperation between CATARC, MOST (electric vehicle major project management office) and the National Information Centre (Zhen, 2012). According to the results of this program, the maximum market potential in the future for the light duty passenger cars in China will

reach 361.85 million. Based on these development plans and existing forecasting, this study has assumed that before 2040, the maximum market potential for EVs in China will be 70% of the maximum market potential of the total light duty passenger cars, and that the BEV can account for 60% of the total EVs. Therefore the maximum market potential of BEV in this study is assumed to be 150 million.

6.5.2 The innovation coefficient p, and the imitation coefficient q

Due to the lack of historical sales data, this study uses data on the conventional passenger cars in China and the PHEVs in US as two alternative products so that the parameters of the BEPVs in China can be set up. Therefore, the basic innovation coefficient p_{car} and the imitation coefficient q_{car} in the model will be equal to the innovation coefficients and imitation coefficient of the alternative vehicles (conventional passenger cars in China and the HEVs in US), respectively. The innovation coefficients and imitation coefficient of BEV in this study will be calculated by the comparison between BEV and alternative vehicles as Functions 7 and 8 demonstrate. For choosing conventional passenger cars in China as the alternative

product, the innovation coefficient p and the imitation coefficient q can be estimated by putting the historical data of China's private passenger cars growth from 1989 to 2012 into Bass model through the Nonlinear Regression method by using SPSS. Through the Nonlinear Regression method, the innovation coefficients and imitation coefficient can be calculated (Table 6-2). For choosing the HEVs in US as the alternative product, by considering the sales data of HEVs in US from 1999-2012 (Table 6-1), the innovation coefficients and imitation coefficient of HEV in US has been calculated and are shown in Table 6-2.

Table 6-1 The sales of HEV in US from 1999 to 2012

Years	1999	2000	2001	2002	2003	2004	2005
HEV Sales in US	17	9350	20282	36035	47600	84199	209711
Hybrids % of all vehicles sales	0.0001%	0.06%	0.14%	0.24%	0.32%	0.56%	1.77%
Years	2006	2007	2008	2009	2010	2011	2012
HEV Sales in US	252636	352274	312386	290271	274210	268752	322227

Hybrids % of all vehicles sales	2.55%	2.37%	2.79%	2.37%	2.11%	2.55%	2.97%

Data from Alternative Fuels and Advanced Vehicle Data Center (U.S. DoE) (2013)

Table 6-2 The innovation coefficient p_{car} and the imitation coefficient q_{car}

Alternative product	Innovation coefficient p	Imitation coefficient q
Conventional passenger cars in China[1]	0.0002	0.259
The HEVs in US[2]	0.0003	0.225

6.5.3 The elasticity parameters α, β, γ , λ and ω, ρ, θ, η

This study considered the vehicle driving range, vehicle cost, comprehensive cost (fuel cost), and charging infrastructure as the four main external variables, and the impacts of these four variables will have different impacts on the innovation factor p and the imitation factor q respectively. Based on the surveys done by the Shanghai EV ZONE, driving range, purchase cost and the infrastructure are seen as being the top three issues that affect customers' EV purchase decisions (See Figure 6-2). Because all of the questionnaire responses are from consumers who come to the EV test driving

[1] Data refer from "Prediction of long-term automotive market in China" (Zhen, 2012)
[2] Data calculated by the regression of the history sales of HEV in US

demonstration, and they have an interest in buying an EV, most of these EV test drivers can be considered as potential innovation consumers. Their concerns about the EV purchase decision can represent innovators' choice. In addition, according to the views of experts and EV consumers in China (Wu, 2013), they think that the vehicle performance and purchase price have more influence on the innovation consumer's purchase decision process than the use cost. In contrast, the fuel cost change (such as petrol price increase), the convenience of the infrastructure and the reliability of EVs will have more significant impacts on the imitation consumers' decision. Therefore, based on the survey result and the experts' views from the interview (See Figure 6-2), this study assumed that the driving range has the highest weight on the impacts of innovation factors, and this is then followed by purchase price, infrastructures and fuel cost. The elasticity coefficients of variables for innovation factors are: α= 0.4, β=0.3, γ=0.2, λ = 0.1; where $\alpha+\beta+\gamma+\lambda=1$; and for the imitation factors, this study assumed that the infrastructure and the fuel cost will have more weight compared with other two variables, therefore the elasticity

coefficients for imitation factors are: ω=0.2, ρ= 0.2, θ = 0.3, η= 0.3;

where $\omega+\rho+\gamma+\eta=1$;

6.6 Scenarios and results

This study will use two different alternative products to simulate the diffusion trend of the BEV in China. In order to compare the difference between each different situation, there are now three main scenarios have been established for simulation and analysis, which are introduced in detail below:

Table 6-3 The parameter settings for the three different scenarios

	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)
Driving range	ICEV: 500km HEV: 500km BEV: 160 km	BEV: increase 20% every 4 years	BEV: increase 50% every 4 years (2014-2026); increase 20% in every 4 years (2026-2040)
Purchase price	ICEV: 120k (CNY) HEV: 200k (CNY) BEV: 320k (CNY)	ICEV and HEV: decrease 5% every 4 years BEV: decrease 8% every 4 years	ICEV and HEV: decrease 5% every 4 years BEV: decrease 20% every 4 years (2014-2026); decrease 5% every 4 years (2026-2040) Subsides (CNY): 120k

			(2014-2018); 60k (2018-2022)
Charging infrastructures (percentage compared with petrol station)	ICEV and HEV: 100% BEV:5%	BEV: increase 80% every 4 years (2014-2026); increase 30% in each 4 years (2026-2040)	BEV: increase 150% every 4 years (2014-2026); increase 50% in each 4 years (2026-2040)
Fuel cost	Petroleum: 7 (CNY/L); Electricity: 0.8(CNY/kwh) Fuel consumption: ICEV: 10L/km; HEV: 4.5L/km; BEV: 15kwh/km	petroleum price: increase 10% every 4 years; electricity price: increase 10% every 4 years	petroleum price: increase 20% every 4 years; electricity price: increase 10% every 4 years

6.6.1 Scenario 1: variables do not change over time (Negative situation)

In this scenario, the development situation and technology of the EVs are considered not improved over time. The innovation coefficient and the imitation coefficient are considered to be constant. All of the variables are set based on their current performance in 2013 and will not be changed over time, including fuel prices, infrastructures and also the vehicle performance, and the vehicle prices for both the BEV and alternative vehicles. Therefore, this scenario can be seen as a negative situation of BEV development. This study uses the sale price and vehicle performance of the Prius (HEV) and the Corolla (ICEV) as the performance of alternative vehicles;

because they both have large sales volumes and they have similar size and performance. The sale price and the driving range of the E150 EV in BAIC (China) will be used as the performance of BEV. In addition, due to the different petroleum prices and electricity prices in different areas of China, this study uses the latest petroleum price and electricity price in Shanghai in 2013 as the input data for the calculation. The charging infrastructures data is based the current situation in Shanghai according to the interviews during the field work in China. The parameter setting in Scenario 1 has been shown in Table 6-2. The result of this scenario has been shown as below:

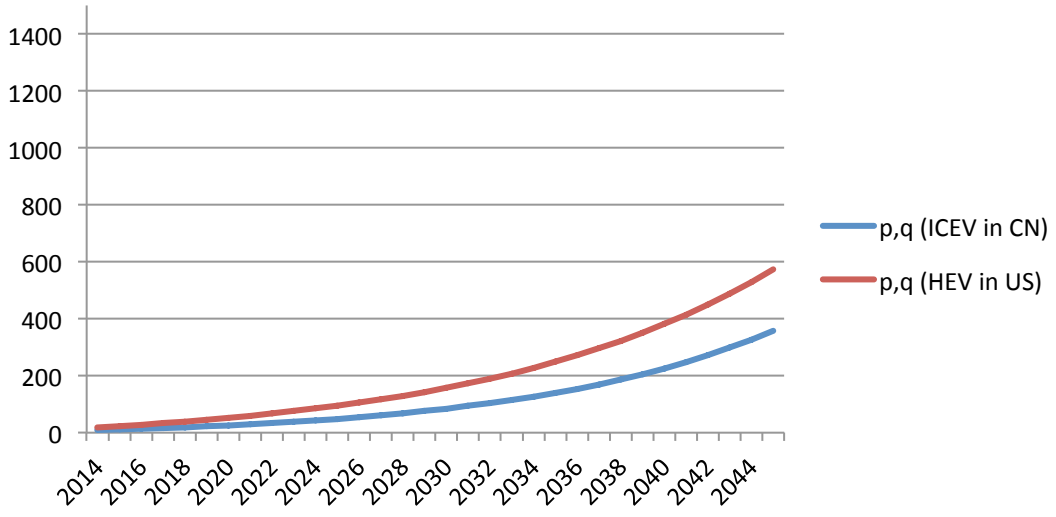

Figure 6-2 The diffusion trend of the BEV in Scenario 1

6.6.2 Scenarios 2: variables is changing over time (BAU situation)

In this scenario, the innovation coefficient and the imitation coefficient of BEV are considered to be affected by the variables and they change over time. This scenario considers the business as usual (BAU) situation which assumes that the external situation will be beneficial to the development of BEVs, but will not significantly change through impacts such as the technological breakthrough of BEV or large changes of oil price. Therefore, this scenario assumes that the average purchase cost of BEV will reduce quicker than the price of conventional car and HEV. The driving range of BEV and charging infrastructures will also be continuously improved in the next 30 years. The details of the parameter setting in this scenario have been shown in Table 6-3. Based on this scenario, the results of BEV diffusion trend have been shown in Figure 6- 3.

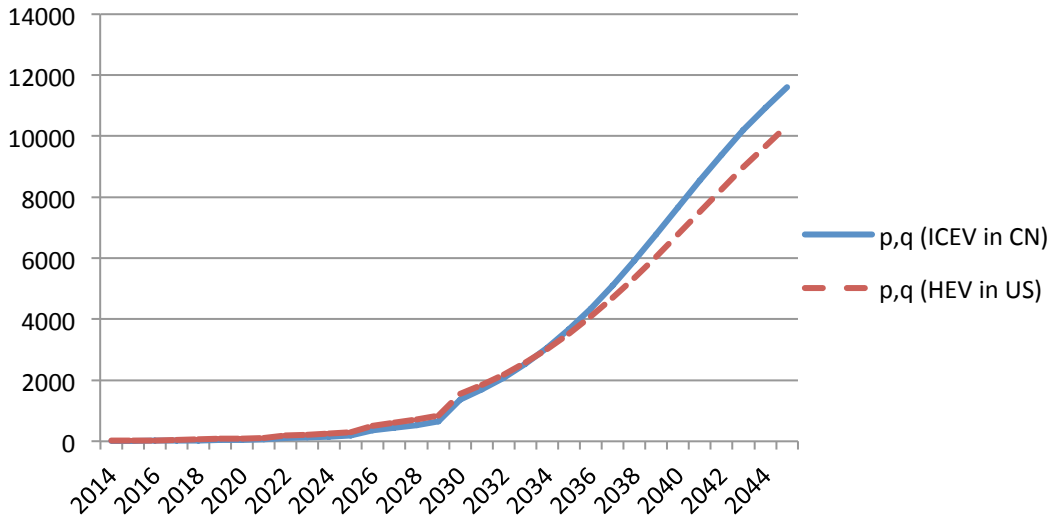

Figure 6-3 The diffusion trend of the BEV in Scenario 2

6.6.3 Scenario 3: positive development situation (policy support)

Similar to Scenario 2, Scenario 3 will also consider the coefficient of BEV in the model can be affected by the variables, and these coefficients will keep changing by time due to the variables changes over time. However, different from the general situation in Scenario 2, this scenario considers the extreme case which assumes that the variables will become very conducive to the development of electric vehicles in the future. For example, it has been assumed that some technological breakthrough of batteries will happen over the next 10 years, and this will result in the price of BEV being reduced by 20% every 4 years until 2026, and after 2026, the price of BEV being reduced by 5% every 4 years. The driving range for the BEV will also increase

dramatically before 2026 due to technological breakthrough. In addition, based on current policy incentives in China, this scenario has assumed that the governments (both state government and local government) will provide 120,000 CNY subsidies to the BEV buyers until 2018 and then reduce to 60,000 CNY until 2022. In addition, the oil price will increase dramatically in the future which will cause the petroleum price to increase 20% by every 4 years, and the growth ratio of electricity price every 4 years will remain in 10% that is as same as the figure in Scenario 2. Due to the improvement of the BEV and government support, the growth rate of charging infrastructures will achieve 150% in each 4 years until 2026, and then will be maintained at 50% (See Table 6-3). The result of BEV diffusion trend in this scenario has been shown in Figure 6-4.

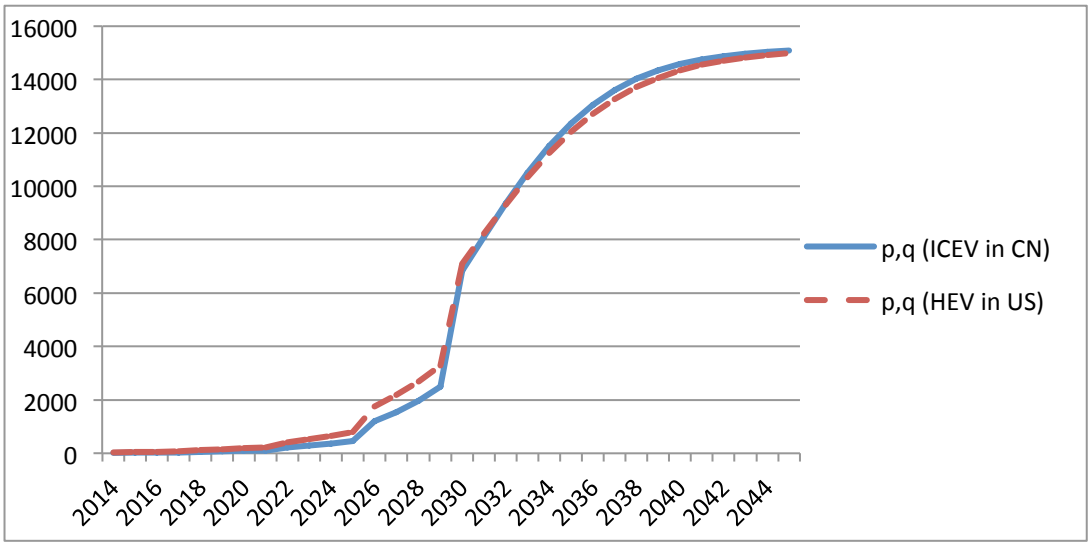

Figure 6-4 The diffusion trend of the BEV in Scenario 3

6.7 General discussion and Analysis

6.7.1 Combined analysis of scenarios

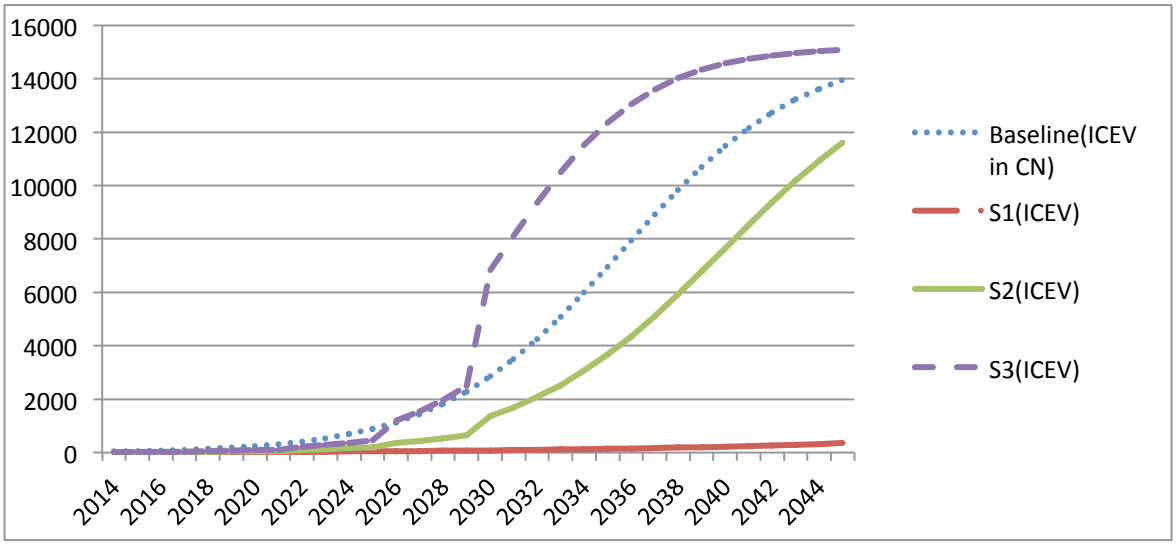

Figure 6-5 Combined analyses of scenarios in ICEV based situation

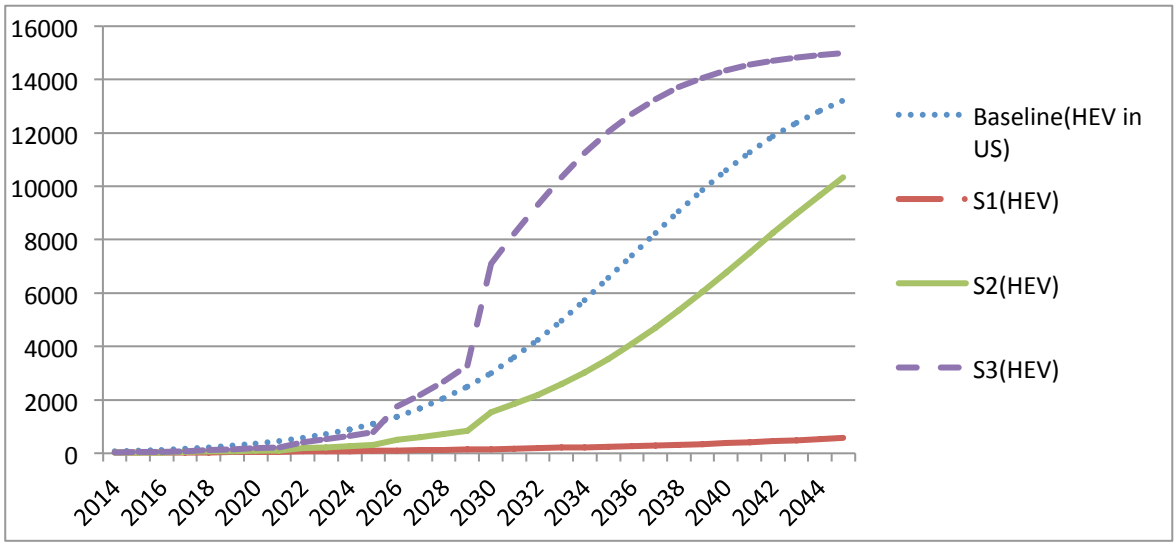

Figure 6-6 Combined analysis of scenarios in HEV based situation

Figure 6-5 and Figure 6-6 have combined the results of the three scenarios, and the diffusion trend of each alternative product (ICEV and HEV) has been shown as baseline for comparison. For the ICEV based situation (see Figure 6-5), the difference between Baseline (ICEV) and Scenario 1 (S1) demonstrate the big gap between the performance of the ICEV and BEV based on current situations. The BEV does not have any competitive advantage compared with the ICEV at the current stage. As Scenario 1 has shown, if there is no improvement on the performance and infrastructures of the BEV, the ownership of the BEV in China will only achieve 2.26 million by 2040. In the BAU scenario (S2), the variables will slowly be beneficial to the development of BEVs over time. The ownership of the BEV in China can achieve 76.6 million by 2040,

which is much higher than S1. However, the ownership of the BEV in 2020 can only reach 0.25 million, which is far away from the development goal set by the government. Because of the slow speed of the improvement, the BEV still shows worse performance than the ICEV on purchase price, infrastructure and driving range up to 2040. This situation has been changed in S3, where it has been assumed that there is a breakthrough in EV technology and strong policy support over the introduction period, and this means that the diffusion trend of the BEV will become much better than the ICEV. It should be noted that even when the fast changing variables are included, the BEV still shows a worse performance than the ICEV on purchase price, even in 2040, and the BEV will have a better driving range and infrastructure than the ICEV only after 2030. The innovation factor is affected by the purchase price and driving range, and in S3 it is still lower than the one for the ICEV up to 2030. However, the imitation factors of the BEV start to become larger than the ICEV after 2030, and this is mainly accounted for by the rapid development of the infrastructure and the BEV's significant advantages in lower fuel cost. From Figure 6-5, it can be seen that the diffusion of the S3 is lower than the baseline at the

beginning, and it only starts to increase strongly in 2030. The curve for S3 becomes much sharper than the baseline after 2030, and this is a result of the continuously increasing imitation factors. Finally, the EV ownership (S3) will achieve 140 million and come into Maturity period around 2038.

The diffusion curves for the HEV also show the same pattern (See Figure 6-6), due to the smaller gap between the HEV and BEV both on purchase price and fuel cost. Overall, the changes among the curves in the three scenarios are not as dramatic as ones in the ICEV based situation. In addition, due to the larger innovation factors, it can be seen that the diffusion of the BEV, when based on US figures (HEV) is much faster than the one using the ICEV situation in the early period in each scenarios. But the ICEV situations always show slightly faster growth than the HEV situation after the growth period (See Figure 6-3 and 6-4), which may be explained by the larger imitation factors. Based on the HEV situation, the ownership of the BEV will achieve over 10 million on 2021 (S2) and 2018 (S3), and also will final come into the Maturity period around 2040 (S3) when the number of EVs exceeds 140 million.

6.7.2 Difference between the ICEV based situation and HEV based situation.

The differences between the ICEV based situation and HEV based situation can be explained by the different situations of the consumers and automotive market in China and US. For the ICEV situation, the lower levels of economic growth and per capita income in 1989 (the beginning of the ICEV diffusion used in this study) have meant that the development of passenger vehicles in China was initially very slow. The auto industry and the vehicle stock volume are only now slowly increasing their growth levels. The innovation coefficient of ICEV is very small in this study, however, the rapid development of the auto market since 1998 makes the diffusion curve of the ICEV has more rapidly growth in the latest 15 years, which contributes to the relative high imitation factor. Due to the rapid popularization and development of passenger cars, as well as per capita income increases, the development of the BEV in reality may have a faster diffusion performance than the ICEV in the introduction period. Compared to the ICEV situation, the HEV (US) data is based on recent

situation (1999-2012); the HEV and the BEV have more in common for the consumers because they are all new products.

The penetration speed of the BEV in China is still considered to be slightly lower than the results of the HEV based situation in the early period. There are two main reasons. First, unlike the BEV, the HEV does not use the electricity power directly and does not need the charging infrastructure, and this means that it is more like a product which makes an improvement on conventional cars rather than a totally new product for consumers. Therefore, HEV are more likely to be quickly accepted by the consumers as a result of the existing mature auto market. Second, the market environment and consumer behavior are different between China and US. For example, In US, passenger cars have been popular, most of the families have their own cars. Buying a new HEV or BEV is considered to be the second or the third car for them. However, in China, car ownership levels are still very low, which means that buying a new car is the first car for most. There is little doubt that the consumers in China will be more cautious when they consider buying a BEV as their first car. This

study has considered that the development trend of the BEV in reality should be in the middle of the both the case of ICEV (CN) situation and HEV (US) situation. The results of the ICEV (CN) situation and HEV (US) situation can be seen as the lower and upper bounds for the BEV penetration. The diffusion potential of the BEV in reality is considered to be in the range between the lower and upper bounds.

6.7.3 Sensitivity analyses of the different impact factors

In order to understand how the variables affect the diffusion curve of the products, this study set that the impact factor as fixed value based on the parameters in Scenario 2 (HEV), and observed the variation curve by changing only one of the four impact factors. The results of each impact factor have been shown in Figure 6-7, Figure 6-8, Figure 6-9 and Figure 6-10.

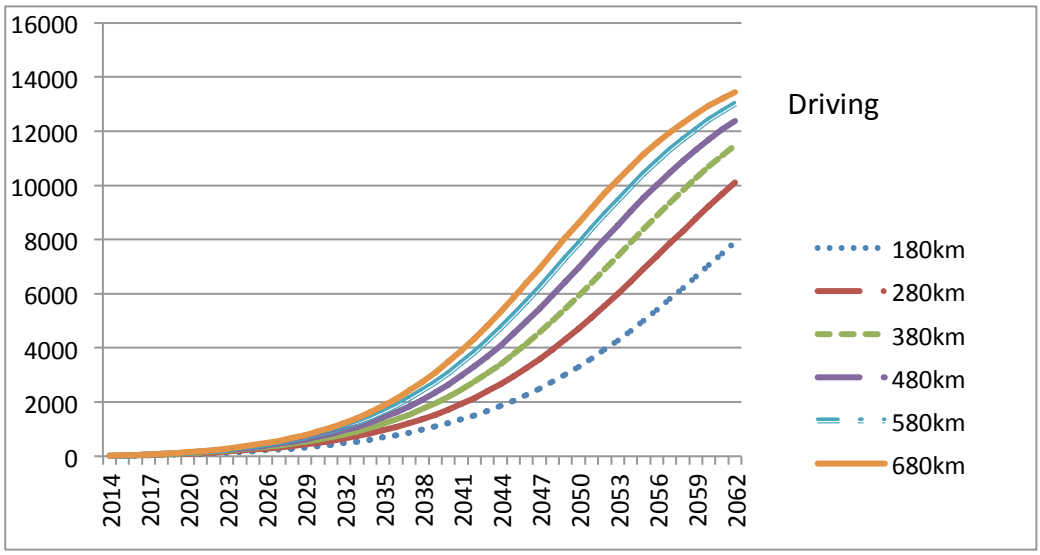

Figure 6-7 Sensitivity analyses of driving range

The improvement of driving range can improve the diffusion trend of the BEV, especially in the early stage. It can be seen from Figure 6-7 that the diffusion speed of the BEV can be significantly improved when the driving range is increased to 280km compared to the current situation of 180km. However, the improvement of the diffusion speed caused by the driving range increase will become less and less when the driving range increase over 380km. It means that improving the driving range in the current stage will be an effective way to improve the BEV penetration. However, the sustained growth of the driving range does not lead to continued improvement, and the improvement of the BEV diffusion will gradually become less and less after the driving range increasing over 380km. In addition, the curve (280km) has reached

the 20 million around 2042, which is 3 years earlier than the curve (180km). However, the growth period of the curve (280km) is not much different compared to the one of curve (180km). For example, the curve (280km) has spent 16 years to grow from 20 million (2042) to 80 million (2058), which is almost the same with the curve (180km) growth from 20 million (2045) to 80 million (2062). Therefore, it seems that the increasing of driving range has much more impact on the initial introduction period than on the overall growth. This may be explained by the weight elasticity of the driving range on innovation factors is much higher than the one on imitation factors.

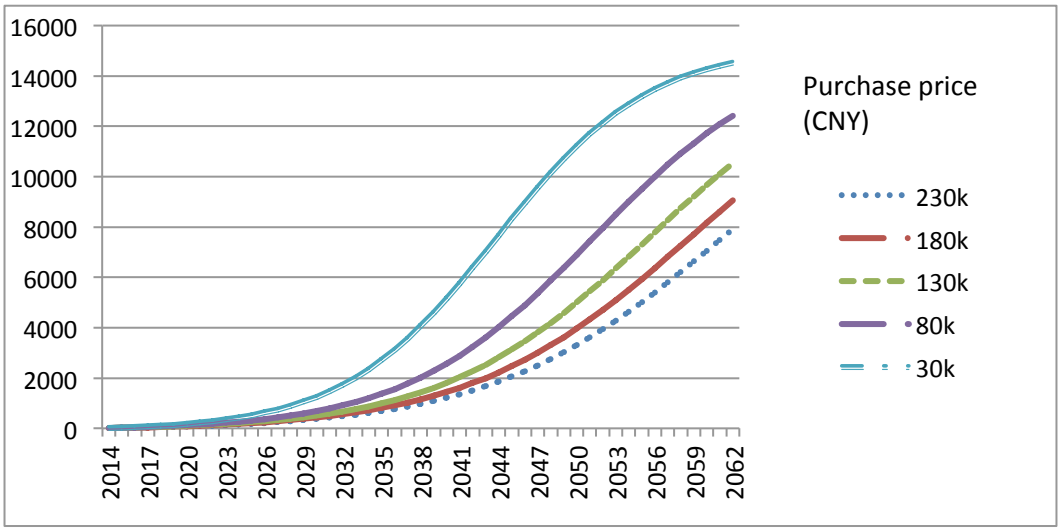

Figure 6-8 Sensitivity analyses of the BEV purchase price

Figure 6-8 shows the diffusion trend affected by the purchase price of the BEV. The reduction of the purchase price does not affect the diffusion trend very much at the

beginning, and the improvement of diffusion speed will become more and more significant once the price of the BEV reduce to a certain level. The price unit used in the study is CNY in China. As figure 9 shown, the diffusion curves do not change a lot when the purchase price reducing from 230k to 130k. However, when the purchase price reduces from 130k to 30k, the diffusion curve (30k) can achieve the 20 million level in 2033 which is 8 years earlier than the curve (130k). The growth period between the curve (130k) and curve (30k) are still not much different which is similar with the situation of driving range growth.

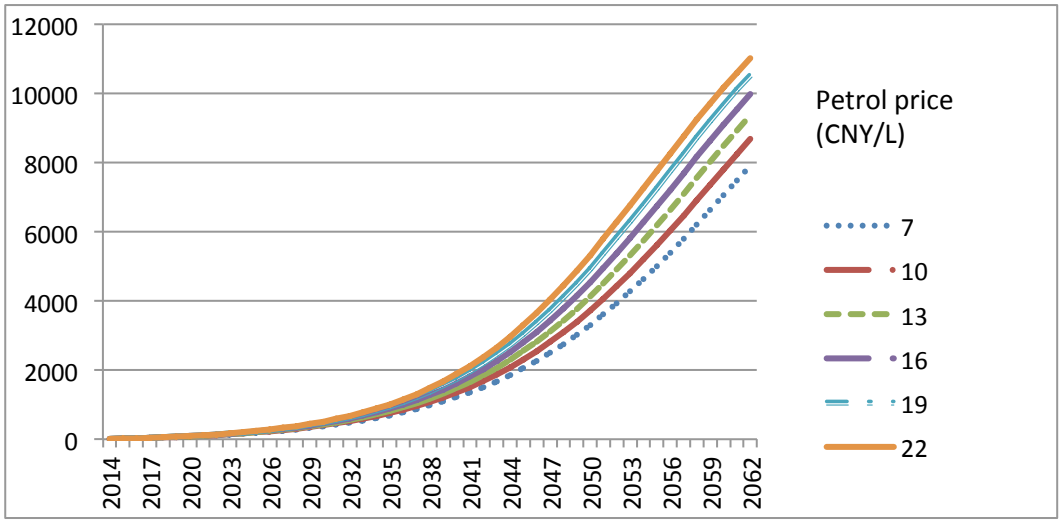

Figure 6-9 Sensitivity analyses of the petroleum price

For the fuel price increase, although the BEV would become more popular as the petrol price increases, and the changes in the total fuel cost are still less than

balanced by the influence of the vehicle price, when considering the total comprehensive cost. Therefore, as Figure 6-9 shown, the increase of the petrol price can improve the diffusion speed of the BEV, but not that significantly compared to the reduction of the vehicle purchase price. The fuel cost has less weight on the influence of the innovation factor because that the survey showed the potential innovation consumers do not always calculate the total life cycle fuel cost of the vehicle before they purchase the vehicle. The imitation consumers may pay more attention on the acceptance of electric vehicles fuel efficiency. Reflected in Figure 6-9, the increase of petrol price has a little more impacts on the improving the slope of the diffusion curve than its impacts on shortening the introduction period of the BEV.

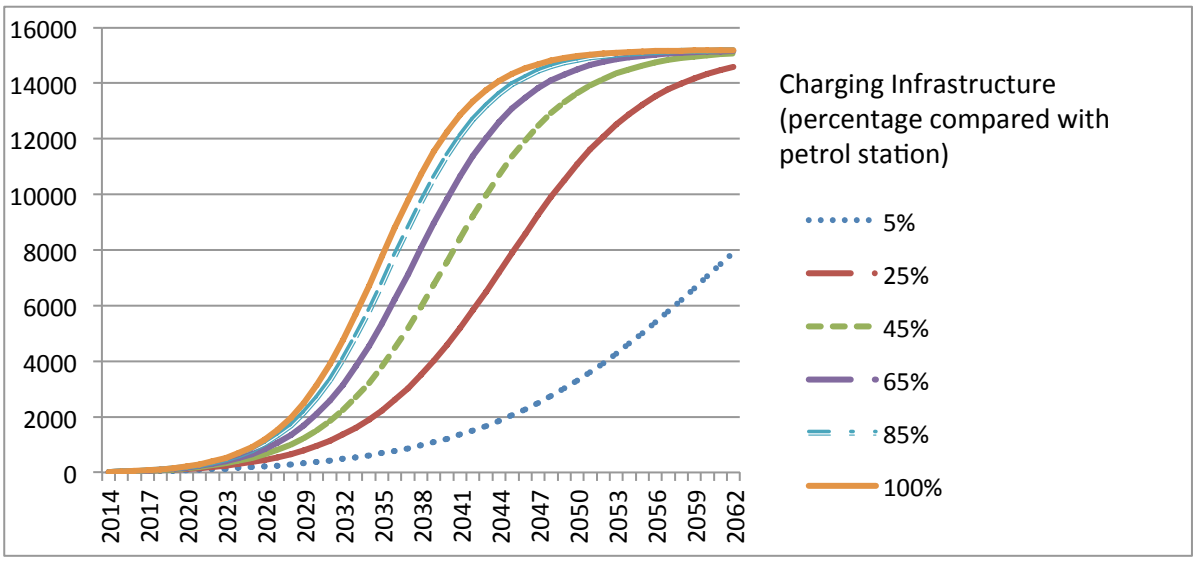

Figure 6-10 Sensitivity analyses of charging infrastructure

Compared with other three variables, increasing the charging infrastructures has the most significant effects on improving the diffusion trend of the BEV. Especially on current stage when the construction of the charging infrastructure is still in an initial low level, the penetration speed of the BEV will be a greatly improved if the proportion of the charging infrastructure (compared with petrol stations) has been increased from 5% to 25% (See Figure 6-10). Although the rate of the improvement will gradually become smaller and smaller as the infrastructure becomes more comprehensive, the promotion effect caused by the increasing infrastructures is still the best option among the other three variables. In addition, it should be noted that the increasing of the charging infrastructures is the only variable which can make the

diffusion curve of the BEV achieve the maturity period (around 150 million) before 2060, even if the other impact factors are not changed. The other three factors (driving range, purchase price and fuel price) cannot achieve this, even if their performance has been improved equal to the one of the HEV or ICEV.

By compared the sensitivity analyses of the different factors, it can be concluded that the charging infrastructure and the purchase price are the top two factors which have a clear impact on improving the diffusion of BEVs. However, the purchase price reduction is not very effective at the early stages, and it starts to show more and more contribution as the price continuously reduces over time. This means that if the other situations not changed, there are still large gaps between the BEV and ICEV on their vehicle performance and infrastructures, and this means that consumers are only likely to buy a BEV when its price is much cheaper compared with the ICEV or HEV. In the current stage, the BEV performance and the charging infrastructure is still at a very low level, and the purchase price of the BEV is still much higher than the

ICEV and HEV, and it is hardly likely to reduce to a substantially lower level over the very short term.

Combined the sensitivity analyses of all these factors; it can be found there are two main types of factors. For some factors, such as charging infrastructure and driving range, their changes will be more effective in the beginning, but the impacts caused by these changes will become smaller and smaller with the change increase. This study defined this kind of factor as “Early effect factor”; In contrast, some factor such as vehicle price, will only become more effective once their value increase or reduce to a certain level. This study called this kind of factors as “Delayed effect factor”. Based on the sensitivity analysis above, the promotion of the “Early effect factors” (charging infrastructures and the driving range) seem to be the most effective means to improve the BEV penetration rates.

6.8 Recommendation and Conclusion

This study developed a diffusion model for BEV forecasting based on Generalized BASS model. The ICEV development in China and the HEV sales data in US are used to provide the historical data on the alternative products for the BEV diffusion and three scenarios are used to forecast possible future situations for BEV penetration in China. According to the results, based on the current status of the BEV without considering the important technology breakthrough and a significant policy support, it seems that the BEV in China will take at least 20 years to reach the mass market scale and this is a much longer gestation period than that proposed by the Government.

According to the latest "Energy-saving and new energy vehicles development plan for 2012-2020" published by the State Council of China, the stock volume of EV (the BEV and PHEV) should achieve 5 million in 2020. According to the setting of this study, the BEV can account for 60% of the total EVs. The numbers of the BEV should achieve at least 3 million in 2020 to achieve the Government goals. Even though this stock volume of EV includes more vehicles than just passenger cars, they still remain the

largest part in the total vehicle stock. However, the results of this study have shown that the stock volumes of the BEV (both the ICEV based and the HEV based) are far behind the goal proposed by the Government. Even if the situation in S3 happened, the total stock volume for the BEV (HEV Based) and BEV (ICEV Based) will amount to 1.86 million and 0.9 million in 2020, respectively, and this means that there are still gaps in the requirements proposed by the Government. Therefore, based on the current situation, the levels of Government policy support are insufficient to establish the appropriate environment for the development of BEVs to achieve its stated goals. More effective policy support is important and necessary condition to achieve the fast diffusion of BEVs in China, especially in the early introduction and development stages. According to the sensitivity analyses of the different impact factors, improving the “Early effect factors” (such as infrastructure and driving range) instead of focusing on the “Delayed effect factor” (such as vehicle price), seems to be the most effective ways to accelerate the promotion of electric vehicles in the two early stages (introduction and development). Although reduction of the purchase price can also effectively improve the diffusion trend of the BEV, due to the low level of vehicle

performance and the infrastructures, the improvement of the BEV penetration will only become significant when the price reduce to a very low level compared to the ICEV, and this is hard to achieve in the short term. Therefore, investing more money and efforts on the charging infrastructure instead of only providing subsides for the BEV purchasing may be considered as a good option for the Government to develop the policy strategies and incentives for the BEV development.

This study only considered the impacts on the diffusion trends from modeling the purchase cost, fuel cost, driving range and the charging infrastructures assumptions. In reality, the penetration of the BEV can be affected by many other variables, such as the vehicle reliability, extra values (such as tax credit and exemption from driving limitation policy), word of mouth and the levels of support from Government through policy interventions and regulations. For example, Beijing and Shanghai have launched the policy that purchasing the EVs can be exempt from vehicle license restrictions in these two cities, and this has given additional value to the EVs compared to the traditional ICEV. According to the expert from the Electric Vehicle

Development Office in Shanghai, most of the EV buyers in these two cities have commented that the convenience of the BEV driving license created by this policy is the main reason for them buying an EV. In addition, some variables (such as word of mouth and vehicle reliability) will have a more significant impact on the imitation factors than the variables considered in this study. Due to the limitations of data, this study did not consider these variables in the model. This study has introduced a method that can consider a variety of factors for a more comprehensive analysis in the future. In addition, the sensitivity analyses of the different impact factors have proved that the changings of different variables will have different impacts on the diffusion trend, and their individual influences on the diffusion stage are also important. Therefore, the diffusion model, the comparative analysis and the sensitivity analyses used in this study should be further developed in other studies for examining the diffusion effects of EVs, and a wider range of policy relevant factors and imitation related variables would help improve the confidence attached to the results. These studies would also help governments in deciding which path to follow and what incentives might be most effective in realizing their stated objectives.

Chapter 7: Evaluation of the electric vehicle demonstration program in China using a multi-criteria approach

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7.1 Introduction

The development of electric vehicles (EVs) has already been seen as an essential state strategy in China. It not only helps to address oil security, air pollution and climate change issues (Zhang et al., 2013) (Hao et al., 2015), but it can also be seen as a good opportunity for the Chinese auto industry to become current with global technology (Yang, 2009). The development of EVs in China first appeared as a National Key Scientific and Technological Project, which established 'Research on the Key Technologies of EV' during the 8th Five-Year Plan period (1991–1995) (Zheng et al., 2011). Since then, EV development has been seen as a key component of national strategy in all subsequent five-year plan periods. In the 'Energy-Saving and New Energy Vehicles Development Plan for 2012–2020', which was announced in 2012 by the State Council of China, it was stated that the accumulated sales of pure battery EV (BEVs) and plug-in hybrid electric vehicles (PHEVs) should reach 500,000 by 2015 and approach 5,000,000 in 2020 (State Council of China, 2012).

In order to accelerate the penetration of EVs into the commercial market, a large-scale demonstration program called 'Ten Cities, A Thousand Vehicles' was jointly started by 4 Chinese ministries: the Ministry of Finance (MOF), the Ministry of Science & Technology (MOST), the Ministry of Industry and Information Technology (MIIT) and the National Development and Reform Commission (NDRC). The program began on 17th February 2009, and the government also launched the Electric Vehicle Subsidy Scheme at the same time. The first round of the demonstration program was four years and ended in December 2012 (Phase 1). The EV types considered in Phase 1 were hybrid electric vehicles (HEVs), PHEVs, BEVs and fuel-cell electric vehicles (FCVs). At first, 13 demonstration cities were designated: Beijing, Shanghai, Chongqing, Changchun, Dalian, Hangzhou, Jinan, Wuhan, Shenzhen, Hefei, Changsha, Kunming and Nanchang. Then, the number of cities increased to 25 in August 2009. In Phase 1, subsidies were provided to the public service vehicles in these 25 cities, for buses, taxis, postal service vehicles, clean vehicles and government fleets; the private vehicle market was excluded. Beginning on 1st June 2010, China began to provide

subsidies for private buyers of new energy vehicles in 6 pilot cities: Beijing, Shanghai, Changchun, Shenzhen, Hangzhou and Hefei.

There is no doubt that the EVs and the necessary charging infrastructures were rapidly developed during Phase 1 of the demonstration project. However, the project is still not considered successful because most of the demonstration cities did not achieve their ultimate goals in terms of market penetration of EVs, especially in the private vehicle market. According to the reports from the four ministries (2013), by the end of 2012, the total number of EVs promoted in the 25 cities was 27,432, of which public services vehicles accounted for 23,032; EVs accounted for only 4,400 vehicles. According to the statistics, only 60% of the public service promotion goal and less than 10% of the primary promotion target for private consumers were achieved (CATARC, 2013). Based on the results and lessons from Phase 1 of the demonstration program (2009–2012), the government updated the policy regulations and the subsidies for the second round of the program (Phase 2). Phase 2 began in 2013 and will end in December 2015. The government has invested substantial sums

to promote EV adoption, but EV promotion program in China has still not achieved its targets. This may be attributable to a number of reasons such as perceived vehicle performance, the effectiveness of the policy, Chinese consumers' behaviour and so on. One of the main issues is considered to be the lack of monitoring and evaluation of the EV promotion at either the national or the local levels. Even though the government has financed much of the demonstration program and collects some data and information from the program, it does not have a comprehensive and systematic evaluation to examine the demonstration program's performance. Therefore, it cannot effectively analyse the issues and lessons learned from the existing process, and the direction of development of EVs in many pilot cities will not receive impartial assessment. For example, in Phase 1 program, only 4 cities (Kunming, Wuhan, Nanchang and Dalian) commissioned organisations to monitor and evaluate the performance of their demonstration programs (Zheng et al., 2012). However, these cities only focused on the EV promotion numbers and EV industry development as the main evaluation criteria, and they ignored the progress made by the pilot cities in other areas, such as energy, the environment and social behaviour.

This means that there is a rather narrow interpretation of evaluation that focuses only on sales of electric vehicles while ignoring other factors that can affect the sustainable development of transport. However, other factors such as the convenience of the charging infrastructure, the performance and reliability of EVs and their environmental impact are all very important in their promotion. The main objective of this paper is to develop a comprehensive evaluation framework regarding the EV demonstration project that is expected to help to monitor and lead the pilot cities and EV manufacturers to promote EVs more comprehensively and effectively. This study develops an evaluation framework by using multi-criteria analysis (MCA) to examine the effectiveness of the EV promotion in China from a number of different aspects, including technology-industry, market conditions, policy and environmental factors. Then, based on the existing demonstration program, four pilot cities (Beijing, Shanghai, Hangzhou and Shenzhen) are selected as the case studies for evaluating the framework. Through the case studies, it is found that evaluating the program's effectiveness can help to identify specific issues and

individual performance in the EV promotion process. Furthermore, based on the comparative analysis of all of the case studies, this study further discusses and comments on the prerequisites for and useful experience regarding EV penetration at the national level, and it gives recommendations to help the government launch more effective policy support for EV penetration in the next round of the demonstration program in China.

7.2 Methodology: The Overall Approach

In contrast with the evaluation of other policy approaches, this study is mainly focused on evaluating the effectiveness of a complex program by using the Multi-criteria analysis (MCA) (Introduced in Chapter 3). According to the Department for Communities and Local Government (London) (2009), MCA techniques can be used to "identify single most preferred option, to rank options, to short-list a limited number of options, or simply to distinguish acceptable from acceptable possibilities". Based on the different approaches to EV promotion in the pilot cities (project level), this study evaluates the cities' comprehensive performance in the EV demonstration

program (program level) from multiple aspects (industry-technology, market conditions, policy and environmental). The objective is to develop a multi-criteria approach framework in order to rank the performances of the pilot cities in the demonstration program by combining both qualitative and quantitative criteria. This research includes detailed assessment of two base case scenarios, on based on the market and the other based on the environment. The analytic hierarchy process (AHP) was used to structure the decision problem and to attribute weights to the criteria. AHP is the most widely applied MCA tool for evaluating transport planning projects (Sharifi et al., 2006; Turcksin et al., 2011; Zubaryeva et al., 2012; Javid et al., 2014). In order to collect the views from the stakeholders, the Delphi method (Dalkey, 1969; Chen et al., 2014) was used to assign weights based on the views of experts in the EV industry, related institutions and government departments. First, the author individually interviewed each expert and asked each to score the weights of each criteria; second, based on the experts' views, two main views were summarised into the two base case scenarios to be assessed in detail. Then, this summary of the views was shared with each expert, and they were asked if they

wanted to modify their scoring for the two different scenarios. The details of the weights are discussed in the 'Weight and Scenarios' section of this paper.

To establish the MCA framework, the first step was to determine the options to be evaluated, and the author selected four pilot cities to study their effectiveness in the EV demonstration program (Step 1) (See Figure 7-1). The contexts for the different pilot cities included technological solutions, infrastructure construction, policy measures and so on. The next step was to identify the evaluation criteria (Step 2). The criteria and sub-criteria were identified by considering the opinions of China's EV experts, and they were mainly divided into four aspects: technology-industry, market conditions, policy and the environment. In addition, indicators and measurement methods were introduced to measure the cities' performance on the criteria, and the indicators were both quantitative and qualitative (Sun et al., 2015). Step 3 determined the relative weights of these criteria by considering the views from the stakeholders. Two different weighting systems were determined separately for the two different scenarios. An evaluation matrix (AHP method) was developed to

establish the comprehensive performance of each alternative with respect to the objectives of the EV demonstration program (Step 4). The 4 pilot cities were chosen as case studies for the evaluation and ranking. Discussion and analysis were given on the author's understanding of the current status of and issues with EV penetration in China (Step 5). Finally, policy suggestions were developed that could serve as potential pathways for decision makers to improve EV penetration in China (Step 6).

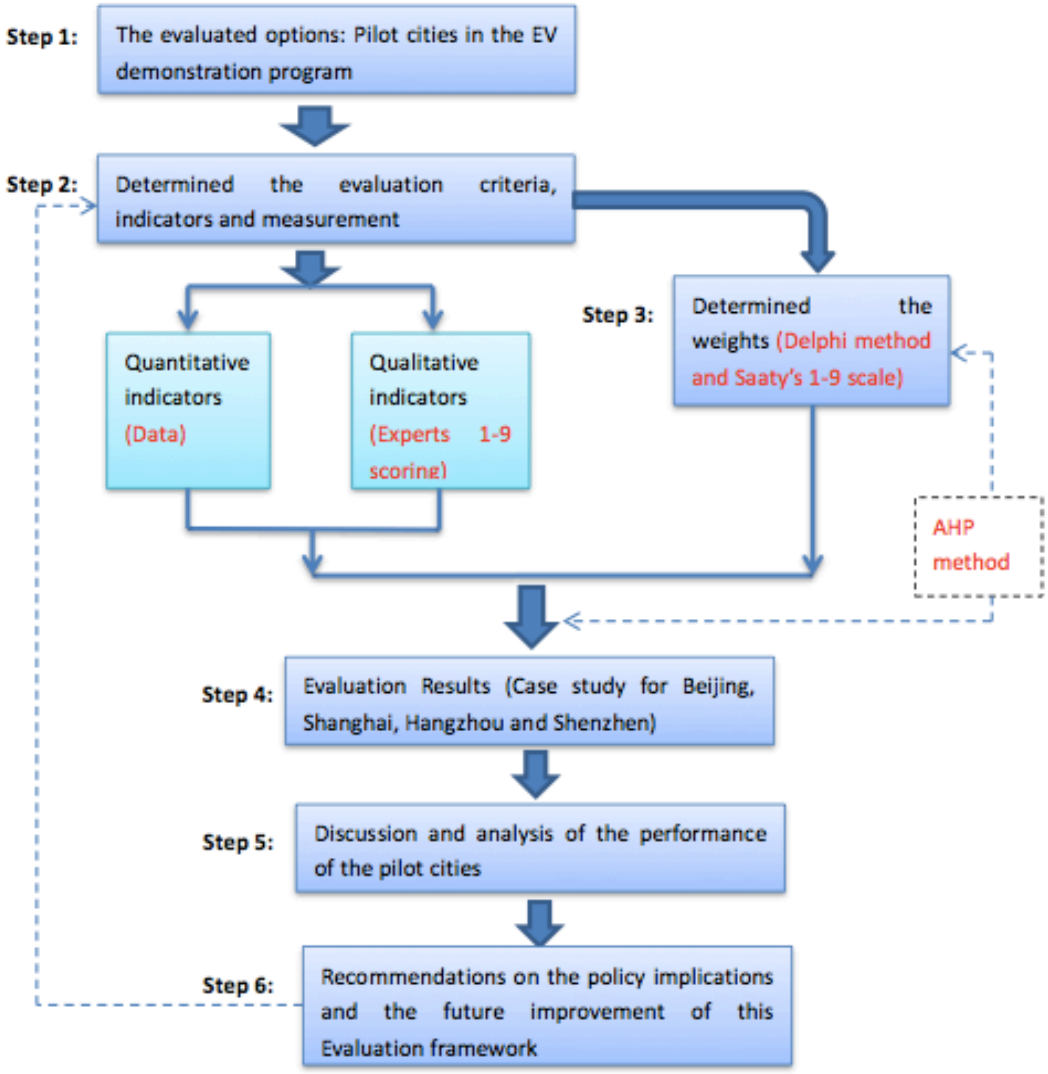

Figure 7-1 The Overall Approach Used in this Study

As noted in the description above, the indicators used in the evaluation framework were both quantitative and qualitative. The quantitative indicators were measured by numerical value and were mainly collected from the documentary research and interviews conducted during the fieldwork in China. The qualitative indicators and the weights for each criterion were both based on the subjective judgment of the experts

(stakeholders), from whom information was collected during the fieldwork in China (August to September in 2014). For the qualitative indicators, Saaty's 1–9 scale was used to determine the weights of each criterion, and each was measured by each expert; a total of 11 high-level experts from different stakeholder groups were interviewed. Three were members of the EV manufacturing industry (BAIC and BYD), 5 were members of EV research institutions (the China Automotive Technology and Research Centre (CATARC), the China Association of Automobile Manufacturers (CAAM), the Society of Automotive Engineers of China (SAE-China), and the Beijing Institute of Technology) and 3 were government policy makers from the experts group that was established jointly by the 4 ministries.

7.3 Methodology: Establishing the Evaluation Framework

7.3.1 Identify the criteria

This section mainly introduces the criteria for the evaluation in this study, which were divided into 4 aspects of the demonstration program: technology-industry, market conditions, policy and the environment (Table 7-1).

Technology-industry

The development of the EV industry in China was one of the main objectives for the government in launching the EV demonstration program. China's government considers EV industry development to be an important transition strategy for its auto industry, especially for domestic, regional vehicle manufacturers. However, EVs' technology limitations, such as the driving range and charging time, have been the main issues that hinder the promotion of electric vehicles. The chief engineer of the Shanghai International Automobile City (Group) Co., Ltd. (2014) stated that according to their survey of the existing EV test drivers, safety is a primary concern; drivers are worried about whether the EV batteries will catch fire or even explode in an accident. This fear can be explained by consumers' lack of knowledge about EVs because the technology is new and also by their distrust of domestic EV quality. However, according to the same survey, nearly 90% of EV problems were not caused by the battery system or the electric motor but by the traditional vehicle parts, such as the lights, air conditioning, electrical control systems, etc. These problems have mainly

been attributable to the backward vehicle production technology and poor quality control among China's domestic EV manufacturers. The institution and government experts also reported that the high failure rate of EVs was already considered as one of the main factors that has limited the effectiveness of the Phase 1 demonstration program. The reliability of EVs will significantly affect consumer acceptance, and it should be considered an important criterion in any evaluation of EV penetration performance in China. Table 7-1 summarises the main criteria and sub-criteria that were used in this study. The measurement methods are also shown in the table, including both qualitative and quantitative indicators.

Table 7-1 The criteria and related measures used in this study

	Criterion	Sub-criteria	Measure
Technology-industry	EV technology	Driving range	The driving range of the car battery (Km)
		Vehicle reliability	The operation failure rate (%)
		Advanced technology	Was advanced vehicle technology used in the manufacturing (experts' scores on a scale of 1–9)
	EV industry base	Manufacturers	The scale of the EV industry in each city (or region) (experts' scores from 1 to 9)
		Related	The scale of the battery and motor

		industries	industries in each location (experts' scores from 1 to 9)
		R&D ability	The EV research abilities (research institutions, universities) in each location (experts' scores from 1 to 9)
Market conditions	Market penetration		Actual completion rate of the promotion plan (%)
	Business conditions	Business model	Innovation and effectiveness of the business model (experts' scores from 1 to 9)
	Infrastructure	The scale of the EV infrastructure	Numbers of charging stations
		The rational distribution of the infrastructure	Utilisation of charging facilities (%)
Policy support	Purchase process		Total savings per vehicle including subsidies and the tax exception (Yuan)
	Operation process		Were there incentives for driving EVs and safeguards for their operation (y/n)
	Charging infrastructure	Incentives	Were there subsidies for infrastructure construction (y/n or percentage of the cost)
		Regulations and guidance for construction	Was there effective planning and guidance regarding the infrastructure construction (y/n)
Environment	CO_2 and air pollution	CO_2 reduction	Total CO_2 reduction per km compared with ICEVs (g/km)
		Air pollution reduction (PM2.5)	Total pollution reduction per km compared with ICEVs (g/km)

Market conditions

The main objective of the EV demonstration program was to aid in the early market introduction of EVs into China. As such, the marketing penetration, business conditions and infrastructure construction can be considered among the main criteria by which the EV penetration in the pilot cities can be evaluated. Currently, the sales numbers of the EVs in the demonstration program are counted. However, because of the different economic levels in the pilot cities, the promotion targets were different in the pilot cities, and the sales numbers does not fairly reflect the state of EV development in each city. Therefore, this study chooses the actual completion rate (actual sales/target sales) of the EV promotion numbers as the indicator for evaluation. In addition, the business model is very important in the early introduction of EV penetration. Currently, because of EVs' technology issues, the driving range, cost and charging convenience are still considered three main limitations in terms of purchasing EVs. Some new business models such as battery leasing, vehicle leasing

and car sharing are considered to have great potential to avoid some of these issues and help to promote more rapid acceptance of EVs by customers.

The construction of charging stations is also a key factor in consumers' purchase of EVs. CATARC (2014) conducted a study on consumer behaviour and EV purchasing, surveying 884 consumers from more than 10 pilot cities in China. Consumers cited inadequate infrastructure as the third most common reason for not purchasing an EV at the time, following the immature technology and the high cost. In Phase 1 of the demonstration program, there were 383 charging stations (including 200 battery swap stations) and 18,000 charging spots by the end of 2012. However, the experts who inspected the EV demonstration project observed that during Phase 1, although substantial infrastructure was established, it was not sufficient to meet consumers' requirements. In addition, more than half of the existing charging spots are not normally used, and some have never been used in many of the pilot cities because of the inconvenience of their distribution. Therefore, any evaluation of the infrastructure construction in pilot cities should consider not only the number of

charging stations but also the practicality and convenience of the infrastructure network. The utilisation rate of charging facilities in actual operation can be considered an indicator for evaluating the rational distribution of the facilities (Table 7-1).

Policy

In Phase 1 of the demonstration program, the national policy incentives mainly focused on financial subsidies, which were directly provided to consumers who purchased EVs, including BEVs, HEVs and FCVs; the subsidies differed by EV type and performance (see Table 7-2). The Electric Vehicle Subsidy Scheme was updated in September 2013 by the Chinese government for Phase 2 of the demonstration program (Hao et al., 2015). The new subsidies are more focused on electric (BEVs and PHEVs), and the traditional grid-independent HEVs no longer qualify (Table 7-2). In addition, a new policy incentive has been launched by the State Council. The new policy exempted BEVs, PHEVs and FCVs that have obtained a sales license in China (including imports) the vehicle purchase tax from September 2014 to the end of 2017.

However, some experts consider that the current incentive policy in China is still too focused on financial subsidies for EV purchases; there is lack of clear and effective policy on EVs' operation and infrastructure at the national level. In Phase 1 of the demonstration program, in order to accelerate the local promotion of electric vehicles, local governments offered their own policy incentives in addition to those provided by central government, including both financial and non-financial incentives. For example, in some metropolitan areas such as Beijing and Shanghai, EV buyers were exempt from vehicle driving and car license restrictions. As such, one of the objectives of the EV demonstration program has been to test the effectiveness of the diverse policy incentives in stimulating the development of electric vehicles. The comprehensiveness and effectiveness of policy support in the different pilot cities were the main criteria for evaluating the demonstration project in each city. In this study, policy support is further divided into three aspects: the purchase process, the operation process and the charging infrastructure (Table 7-1).

Table 7-2 The subsidies from central government in Phase 1 and Phase 2

Phase 1

BEV	1. A pure electric bus: 500,000 CNY 2. A pure electric car: 60,000 CNY	
HEV	1. A hybrid electric bus: from 50,000 to 420,000 CNY (depending on the energy savings) 2. A hybrid electric car: 3000 to 50,000 CNY	
FCV	1. A fuel cell bus: 600,000 CNY 2. A fuel cell car: 250,000 CNY	
Phase 2		
BEV	Car: Depending on the driving range (Km) 35,000 CNY (80<=R<150) 50,000 CNY (150<=R<250) 60,000 CNY (R=>250)	Bus: Depending on the length of the bus (m) 300,000 CNY (6<=L<8) 400,000 CNY (8<=L<10) 500,000 CNY (L=>10)
PHEV	Car: The pure driving range (more than 50 km) 35,000 CNY (R=>50)	Bus: The length of the bus 250,000(L=>10)

Environment

The main aim in developing of EVs in China was to solve the energy consumption and CO_2 emissions issues in the transport system, as well as the air pollution in the urban area. There is no doubt that using electricity can significantly reduce China's oil dependence in road transport. However, in China's current power generation mix, coal-fired thermal power still accounts for 80–83% of the total electricity-generating capacity (since 1990), and there are still concerns over whether promoting EVs can effectively reduce CO_2 emissions and other air pollutants such as NOx, SOx, PM2.5 and PM10 (State Grid Energy Research Institute, 2011; Chen and Xu, 2010).

In addition, the distribution of China's energy source is uneven; coal-based power generation is dominant, with 95–98% of the total electricity generation in north and northeast China coming from coal. In contrast, hydropower is abundant in southwest China, accounting for roughly 22–30% of the total power generation mix (Zhang, 2004; Huo et al., 2010). Therefore, based on the different EV types and regional energy mixs, the performances of EVs in environmental protection are completely different across the pilot cities. To achieve the ultimate goal of improving air quality and reducing CO_2 emissions, the effects of EV penetration on reducing CO_2 and other air pollutants in the different cities should be considered primary criteria in any evaluation of the demonstration program. In this study, the life-cycle CO_2 emissions and other pollutants ($PM_{2.5}$) of different types of EVs were considered by reviewing of existing related studies (Ou et al., 2012; Zhang, 2015). CO_2 emissions are considered an important global environmental issue, although other pollutants such as $PM_{2.5}$ are more concentrated locally. The CO_2 reduction in the pilot cities can be simulated by considering the life-cycle CO_2 emission reduction of each type of EV (compared with

traditional petroleum vehicles) multiplied by the numbers of each type of EV developed in each pilot city (Table 7-1).

7.3.2 Weights and Scenarios

The weights of each criterion were identified based on stakeholders' preferences. By weighing the criteria, the stakeholders assigned a controlled level of importance and emphasis for each criterion based on the main perspective of the demonstration program (Sun et al., 2015; Safaei Mohamadabadi et al., 2009). In this study, to accurately and carefully compare the criteria in terms of their importance, the Delphi method (Dalkey, 1969; Chen et al., 2014) and the analytic hierarchy process (AHP) (Saaty, 2008) method were combined and then used to determine the weights of each criterion. In order to reflect the varying importance of the different criteria, the study used Saaty's AHP scale of 1–9 to compare two random criteria (Saaty, 2008). This scale is used in matrices to determine the relative criteria's weights by comparison, and the ratio scale used in this study is shown in Table 7-3 (Javid et al., 2014; Saaty, 2008).

Table 7-3 Scale for Saaty AHP pairwise comparisons

Scores	Description
1	Equal importance
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Dominant importance
1/3, 1/5, 1/7, 1/9	Reciprocals

The Delphi method aimed at collecting information based on a number of independent experts' subjective assessments in order to obtain a relatively consistent set of information, advice and insights. In this study, the 11 experts were independently interviewed to collect their views and judgments on the criteria. Their opinions were then combined after the first round of interviews and then presented to each expert so that they would know the views of others. Based on the views of the experts from the first round review, there are two main different opinions being concluded, which are assumed as two different scenarios in this paper (market scenario and environmental scenario). Then, this conclusion of the total opinions and scenarios setting were restored to the experts, and asked them to modify their views and judgments in different scenarios, respectively. Finally, by collecting the views

from the second round, a more consistent and reliable conclusion was determined based on the experts' subsequent opinions.

Based on their different perspectives on the EV demonstration program, the views of experts were divided into two groups. The experts from the EV manufacturers and some experts from the government considered that the main aim of the EV demonstration program was to accelerate the market for early introduction and EV industry development in China, although the promotion of BEVs appears to have contributed little to the CO_2 emissions reduction owing to the current coal-based energy mix. The popularisation of electric vehicles will lead to diversity in the vehicle fuels, offering tremendous potential in the environment aspects through future energy mix improvement. These experts believed that in the early period of EV penetration, the focus should be on EV technology and industry development and also market promotion rather than on environmental performance.

In contrast, most of the experts from the EV research institutions and also some experts from government considered that the ultimate aim of EV development is to address issues of energy security, CO_2 emissions and air pollution in China. Therefore, according to these experts, environmental performance should be considered the most important criterion for the EV demonstration program's evaluation. To achieve sustainable road transportation, the promotion of EVs in China should consider their contribution to energy and the environment based on the country's own conditions. In addition, these experts also thought that industry development should not be considered as the main criteria for evaluating EV penetration at the local level.

During Phase 1 of the demonstration program, local protectionism was considered one of the main obstacles to the development of EVs; each pilot city wanted to develop its local vehicle industry to boost the region's industrial development. The demonstration vehicles that were being operated in a particular region were required to be locally produced, and foreign vehicles could not receive local subsidies, making the market difficult to enter. As a result, these experts believed that considering local

EV industry development as part of the local evaluation would encourage local governments to focus on manufacturing electric vehicles locally.

According to Safaei Mohamadabadi et al. (2009), different scenarios can help in studying the relative ranking of the criteria based on the stakeholders' different perspectives; based on the two different expert opinions, different weights were assigned to the criteria in the two different scenarios, the one based on the market and that based on the environment. In the market scenario, the pre-market introduction and EV technology development were considered the most important objectives for the current EV demonstration program. In this case, more weight was given to market and technology-industry criteria such as the business models, the charging infrastructure and the EV industry base (Table 7-4). In the environment-based scenario, the environmental protection offered by EV development was considered the most important aim of EV promotion in China. The EV technology and market introduction were still important for EV development, but the industry base was no longer considered a necessary objective for the EV demonstration program.

Therefore, more weight was given to the performance regarding reducing CO_2 emissions and air pollution, and less weight was given to EV industry development. Policy was given high weight in both scenarios because policy support is very important for pre-market introduction and future EV promotion. This study gave the same importance (weights) to the sub-criteria as that for the main criteria. The weights of each criterion for the two scenarios are all shown in Table 7-4, and the consistency of the weight matrix was also checked. This study allowed for calculating the consistency ratio (CR) as a measure of inconsistency between the experts; the ratio is computed as: CR= CI/RI (where CI is a consistency index and RI is a random index, the consistency index of a randomly generated pairwise comparison matrix). If CR < 0.1, it can be considered that the comparison has reasonable consistency (Zubaryena et al., 2012) (Saaty, 2008).

Table 7-4 The weights for each criterion in the different scenarios

Aspects	Criteria	Market Scenario Weight	Environmental Scenario Weight
Technology-industry	EV technology	0.2374	0.1089
	EV industry base	0.0473	0.0165
Market conditions	Market penetration	0.0473	0.0349
	Business conditions	0.1011	0.0490
	Infrastructure construction	0.2374	0.1724
Policy support	Purchase process	0.0567	0.0715
	Operation process	0.1011	0.1089
	Charging infrastructure	0.1558	0.1724
Environment	CO_2 and air pollution reduction	0.0160	0.2656
Consistency check CR= CI/RI		0.01784 < 0.1	0.01897 <0.1
The CR in each scenario is smaller than 0.1, which indicates the weight definition matrix has good consistency.			

7.4 Case Study Results

Based on the evaluation framework and criteria, this study selected Beijing, Shanghai, Hangzhou and Shenzhen as case studies. These are all large cities in China, and each has a strong economic base for developing EVs. These four cities are all among the 5

initial pilot cities for developing the private EV market (see Figure 7-5). Because the evaluation criteria are closely related to the private market, both the private EV market and public sectors are considered in this study. In addition, these four cities all have different local policies, including regarding the EV purchase process, operation process and charging infrastructure (see Table 7-5). The details of the differences among the four cities are introduced and analysed in this section below. For some criteria, such as driving range and purchase subsidies, the indicators were different for different types of vehicles. For convenient comparisons of these indicators, this study only considered the corresponding values of passenger cars in each city for comparison. The main data from the four cities were collected from the fieldwork and the interviews with the experts. For the qualitative indicators based on experts' judgment, this study used a 9-point scoring scale. This section first compares the performance of the different cities in each aspect and then evaluates each using the AHP method.

Table 7-5 The overview of the four cities

	Pilot city		Local subsidies	Other local policy incentives			EV industry
	Public sector	Private sector		Purchase process	Business model/operation	Infrastructure	
Beijing	Yes	Yes	Yes (BEV)	Vehicle license (BEV)	EV sharing rental/EV Taxi	Regulation/electricity price	yes
Shanghai	Yes	Yes	Yes (BEV and PHEV)	Vehicle license (BEV and PHEV)	EV sharing rental	Subsidies	yes
Hangzhou	Yes	Yes	Yes (BEV and PHEV)	Vehicle license (BEV)	Mini-EV rental model	n/a	Yes (small scale)
Shenzhen	Yes	Yes	Yes (BEV and PHEV)	Subsides (BEV and PHEV)	Battery lease model (Bus)/ EV Taxi	n/a	Yes

7.4.1 Technology-industry

For the technology-industry aspect, the results for the four cities in both scenarios (market-based and environment-based) are shown in Figure 7-2; the results of the performances of the 4 cities are represented as the relative performance histogram. The relative performance is expressed as a percentage, and adds up to 100% (1.0).

For the industry base, Beijing, Shanghai and Shenzhen all have local vehicle manufacturers (for example, the BAIC in Beijing, SAIC in Shanghai and BYD in Shenzhen). According to the data from the CAAM (2014), through March 2014, the cumulative sales of BYD's EVs (BEVs and PHEVs) reached 8,074, with the models being the e6 (BEV) and the Qin (PHEV). BAIC's cumulative EV sales numbered 2,231, mainly the BEV model E150, and SAIC's cumulative sales numbered 734, mainly the ROEWE E50 (BEV). It can be seen that BYD had the best performance in both sales and vehicle models, followed by BAIC and SAIC. Although Hangzhou does not have EV manufacturers in the city itself, there are local EV manufacturers (such as Zhejiang KanDi and ZOTYE Auto) in Zhejiang Providence (where Hangzhou is located). However, compared with BYD, BAIC and SAIC, the local manufacturers around Hangzhou appear not to have many competitive advantages in enterprise scale, visibility or electric car production levels.

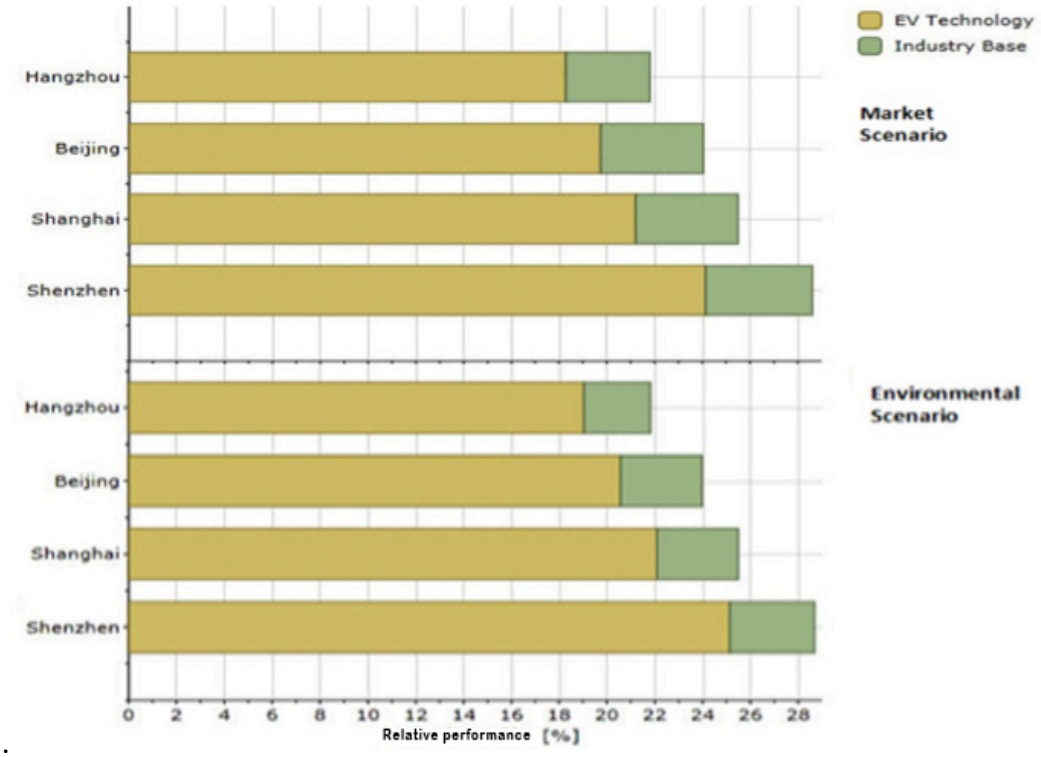

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Figure 7-2 The performance of the four cities in the technology-industry aspect

Regarding vehicle technology, the EVs in the four cities came from diverse EV manufacturers. However, because of the local protection phenomenon (the local subsidies and other incentives that are only provided to local manufacturers), the main types of EVs that were being operated in the pilot cities generally came from local EV manufacturers, and these large EV manufacturers are considered to have similar technology levels. When only the driving range of the BEV model is considered, the e6 from BYD has the longest range, 260 km, compared with the E150 (150 km) from BAIC and SAIC's ROEWE E50 (180 km); the reliability of these EVs is not

sufficient. In Phase 1 (2009–2012), the failure rate of the EVs approached 50%, meaning that only half of the total EVs could run normally at the same time. According to the interview with a manager from the Shenzhen Pengcheng EV Taxi Company based on their actual operating experience, the failure rate of the BYD e6 taxis was roughly 4 times that of the traditional petroleum taxis. Considering both the vehicle technology and the industry base, Shenzhen had the best the performance in the industry base, followed by Shanghai and Beijing. Adding the weights narrowed the gaps in the industry base (especially in the environment scenario), but the ranking did not change because of the performance of the EV technology (see Figure 7-2). It can be seen that the rankings in the EV technology and industry base are the same, which indicates that the technology of the EVs that were promoted in a given location were consistent with the level of local industry development. This can be explained by the local protection in the demonstration program: the local governments focused only on promoting EVs from their local manufacturers, and the local subsidies and other incentives were also only provided to locally produced EVs. Therefore, the EV

models that were promoted in each pilot city always depended on their local EV manufacturers rather than the EV technology level.

7.4.2 Market condition

The market performance of each city is shown in Figure 7-3. Based on the data collected from the CATARC and the local electric vehicle development offices in Shanghai and Shenzhen, the latest EV promotion numbers in each of the 4 cities through Phase 2 (from 2013 to the end of 2014) are shown in Table 7-5; the promotion rankings were: Shanghai, 1st; Zhejiang and surrounding cities, 2nd; Beijing, 3rd; and Shenzhen, 6th. It should be noted that Hangzhou was considered one city in the Zhejiang cities group (Hangzhou, Jinhua, Shaoxing, Huzhou) in Phase 2 of the demonstration program; if we considered their Phase 2 promotion plans, their ranks would change. The current actual completion rates of these 4 cities are shown in Table 7-6. Shanghai and Hangzhou have the best performance; they have already achieved their Phase 2 promotion targets (see Table 7-6).

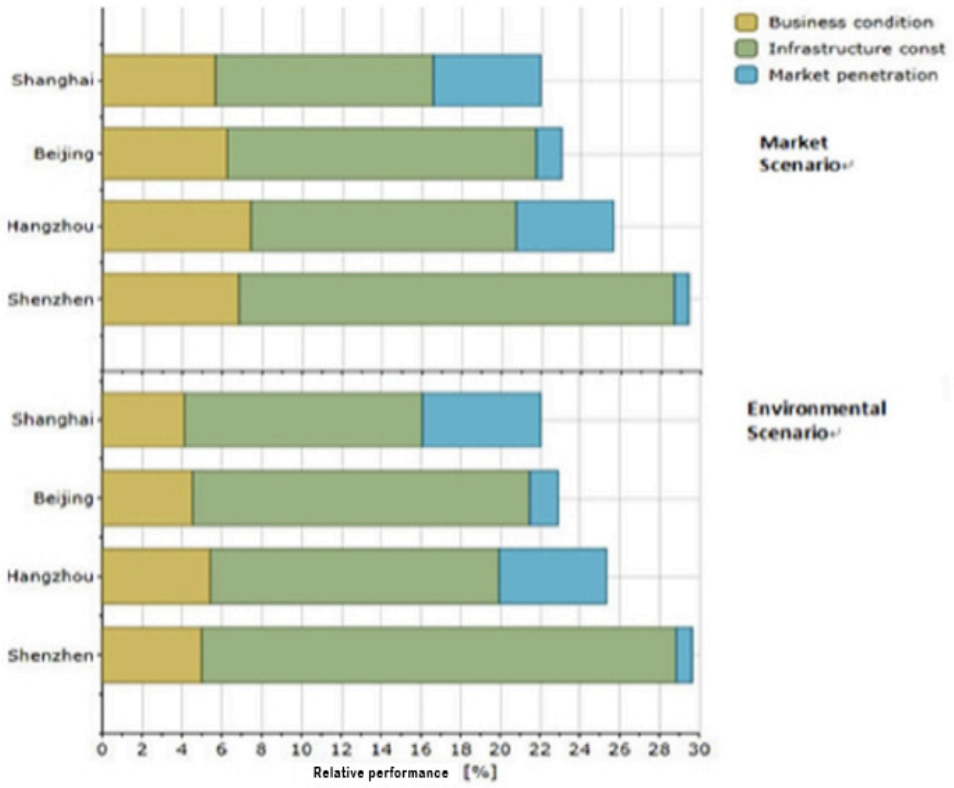

Figure 7-3 The performance of the four cities in market conditions

Table 7-6 The EV promotion in each city from 2013 to 2014

	Beijing	**Shanghai**	**Hangzhou (Zhejiang cities group)**	**Shenzhen**
Promotion numbers (2013-2014)	9,377	11,183	11,127	5,194
Plans for "Phase 2" (2013-2015)	35,020	10,000	11,000	35,000
Currently actual completion rate	26.78%	111.83%	101.15%	14.84%

For the business conditions, there is lack of specific survey for the consumer' attitude in each city. However, Beijing, Shanghai, Hangzhou and Shenzhen are all the large cities in China, which have similar income level per capital. According to the data released by the Ministry of Human Resources and Social Security (2014), the average wage levels (monthly wage) of Beijing, Shanghai, Hangzhou and Shenzhen are 5826, 5380, 4831 and 4744 (CNY), respectively. In this paper, the 4 cities were considered to have similar consumer attitudes, and their business models mainly determined the market conditions in each city. Given that these were the most advanced of all of the pilot cities, these cities all had their own business models (see Table 7-7). The experts considered that the battery lease (bus) model in Shenzhen and the car rental (mini public-transport) model in Hangzhou were the most innovative business models. For example, the car rental model in Hangzhou used not only used the battery swap method and battery charging unified management but also car sharing rental, which increased the use of EVs, making the model more suitable for private consumers. Initially, the Pengcheng EV Taxi Company in Shenzhen had lost 7 million CNY by the end of 2011; however, they achieved a profit of 12 million CNY by 2014. The BEV taxi

operation in Shenzhen is considered to be the most successful example. The car sharing rental model in Beijing and Shanghai have also accumulated useful experience, but the scale and scope of its application are still small. Based on the experts' scores, Hangzhou had the best performance in business conditions followed by Shenzhen, Beijing and Shanghai (see Figure 7-3).

Table 7-7 The business model in each cities

City	Vehicle type	Business model	Incentives and fees
Beijing	BEV passenger car (BAIC E150)	Car sharing rental model (car rental outlets at Tsinghua University and Beijing Institute of Technology)	159 CNY/day; 3,999CNY/month; 99 CNY/4 hours or 18:00-8:00 (next day); 3,000CNY rental deposit and 2,000CNY illegal deposit
	BEV taxi	BEV taxis operated in 8 suburban counties	0.81 CNY/kWh Charging fees; no fuel surcharges for the customers
Shanghai	BEV passenger car	Car sharing rental model by the hour (outlets at Tongji University and in the Jiading EV zone)	From 30 CNY/hour, 131 CNY/day (based on vehicle type); prices include insurance, maintenance and electricity costs
Hangzhou	BEV passenger car (Kangdi EV 2-person or 4-person)	Car rental model (mini public transport). Uses BEVs and recharging garages; car rental stations are located in airports, railway stations, business centres and residential areas. The EVs can swap batteries to quickly recharge	20 CNY/hour, 1,000CNY rental deposit. 24 hours operation

Shenzhen	BEV bus (BYD K9, Wuzhoulong pure electric bus)	Battery lease model: the bus company only purchases the 'naked bus' (without batteries); the batteries are purchased and operated by the Potevio New Energy Company. Potevio is responsible for the charging facilities, charging services, maintenance and operation	The bus company leases the battery from Potevio and rents the battery for 8 years. In addition, the bus company is supposed to pay Potevio for the operation fees for the charging service.
	BEV taxi (BYD e6)	Pengcheng EV Taxi Company: jointly established by the Shenzhen Bus Company (55%) and BYD Company (45%); more than 800 BEV taxis are in operation	Free taxi licenses for 5 years; 3,500kwh/month charging credits for the taxi driver, 1.18CNY/kwh for the electricity over the credits); no fuel surcharges for the customers. The driver is supposed to pay 720CNY/day to the company.

For the EV infrastructure, these four cities have built a number of charging facilities, ranking them the highest among the total pilot cities. The charging infrastructure construction in each city as of 2013 is shown in Table 7-8. It can be seen that these four cities have invested heavily in their charging infrastructure, and the charging stations and spots in these cities account for nearly 55% of the total number of charging stations and 35% of the total number of charging spots nationally. However, according to the views from the experts, the current infrastructures are still far below

consumer requirements, which have resulted in low utilisation rates for the charging facilities. According to the electric vehicle data acquisition and operation monitoring centre at Shanghai Jiading Automobile City, the actual utilisation rate of the charging spots was only 6.2% in Shanghai as of June 2013). In Hangzhou, there were 67 charging and battery swap stations built by the end of 2012, however, but only 12 of them are in operation now. Considering both the numbers and utilisation rates of the charging facilities, Shenzhen has the best performance in infrastructure, followed by Beijing, Hangzhou and Shanghai.

Table 7-8 The charging facilities in each city as of 2013

	Beijing	Shanghai	Hangzhou	Shenzhen
Charging stations (Including battery swap stations)	69	12	67	82
Charging spots	1,350	890	620	3,300
Normalized scores	2040	1010	1290	4120
In order to normalize the charging stations and Charging spots for evaluation, this paper assumed each charging station installed 10 charging spots, or have the equivalent capacity of 10 charging spots.				

All four cities were measured on these three market condition criteria. It should be noted that even though Shenzhen had the worst performance in vehicle promoted numbers, it still had the best overall performance in market conditions, mainly owing to its successful business model and outstanding infrastructure construction (See Figure 7-3). In contrast, although Shanghai sold the most EVs and has already more than fulfilled its Phase 2 EV penetration plan, it still ranked last in market conditions because of its poor business conditions and infrastructure construction (see Figure 7-3). It is because that the experts considered that the business model and the infrastructure construction were more valuable than merely increasing the number of EVs. Shenzhen had the best performance in market conditions, followed by Beijing, Hangzhou and Shanghai. This ranking is same as that for infrastructure construction, mainly because infrastructure construction contributes the highest weight to market conditions. For example, Hangzhou performed better than Shenzhen in business conditions and market penetration but ranked after Shenzhen because of Shenzhen's outstanding infrastructure construction. Based on the weight changes, the impact of

the business conditions in the environment scenario is less than that in the market scenario (see Figure 7-3).

7.4.3 Policy

In addition to the subsidies from the central government, the local governments all introduced their own policies to encourage local promotion of EVs. The local policy support in the four studied cities was analysed based on three aspects: purchase, operation and infrastructure (see Table 7-9). The performance of each city regarding policy support aspect is shown in Figure 7-4. Shenzhen had the highest local subsidies in 2014 and 2015, followed by Beijing, Shanghai and Hangzhou. It should be noted only BEVs and FCVs are eligible for the local subsidies in Beijing, and this is considered local protection. This policy is because the EV manufacturer BAIC in Beijing has focused only on the research and development of BEVs. Some experts considered that Beijing's local subsidy program is not consistent with the national strategy of simultaneously developing BEVs and PHEVs in Phase 2. Therefore, the performance of Beijing in purchase subsidies is ranked lower than that for Shanghai (see Figure 7-4).

Table 7-9 The policy incentives in the four cities in Phase 2 of the demonstration program

	Purchase (For BEV passenger car)	Operation	Infrastructure
Beijing	1:1 matching of the central government's subsidies (based on driving range); The subsidies in 2014 fell by 5%, and they will fall by 10% in 2015. Only BEVs and FEVs receive subsidies; PHEVs are not included.	BEVs are exempt from the traditional vehicle license lottery; they are licensed through a separate lottery.	Charging facilities for personal use in residential areas charge residential electricity prices; it is not necessary to pay the price beyond the limit. There is a plan to provide subsidies (up to 30% of the cost) to qualifying charging facilities
Shanghai	BEV: 40,000 CNY/vehicle PHEV: 30,000 CNY/vehicle FCV: 200,000 CNY/vehicle	BEV and PHEV operators receive free driver's licenses.	Subsidies are provided (up to 30% of the cost) to qualifying charging facilities
Hangzhou	BEV: 30,000 CNY/vehicle PHEV: 20,000 CNY/vehicle FCV: 190,000 CNY/vehicle	Hangzhou began limiting vehicle licenses in May 2014. EV drivers are exempt from the license limitation	Subsidies of up to 20% of the cost) will be provided to qualifying charging facilities
Shenzhen	1:1 matching of the central government's subsidies (based on driving range) Subsides did not decrease in 2014 or 2015 BEVs, PHEVs and FCVs are all included	Subsidies to EV buyers for operation: BEV: 10,000–35,000 (based on driving range) PHEV: 10,000 Shenzhen began vehicle licensing on 29 Dec 2014. EV drivers can obtain their licenses through a separate lottery.	Subsidies of up to 30% of the cost) will be provided to qualifying charging facilities

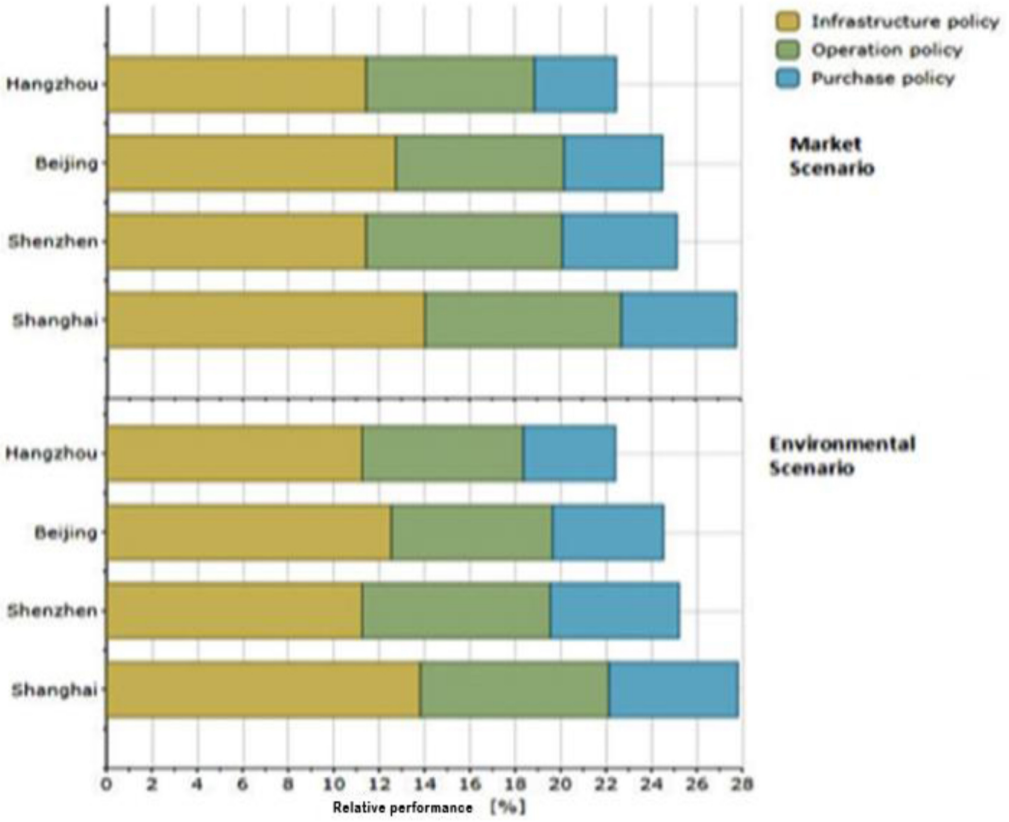

Figure 7-4 The policy performance of the four cities

For the operation process, both Beijing and Shanghai limit vehicle licenses in order to reduce traffic congestion. In Beijing, driver's licenses can only be obtained through a vehicle license lottery; a limited number are issued from among many applications). BEV buyers do not need to join the traditional vehicle license lottery but participate in a separate lottery that is exclusively for BEVs. Because of the currently small numbers of private BEV consumers, the success rate of the BEV licenses is nearly 100% in Beijing. In Shanghai, the limited vehicle licenses are sold by auction, and the

traditional vehicle licenses are auctioned at 80,000–100,000 CNY. However, EV buyers can obtain free vehicle licenses, so that these consumers save an additional 80,000 CNY compared with purchasing petroleum vehicles. Therefore, Shanghai ranks highest among the four studied cities with regard to consumer cost savings (licenses and subsidies).

Figure 7-4 shows that all four cities had similar performance in their operation policies. Shanghai and Shenzhen had the best performance in that Shanghai's incentives are more comprehensive (BEVs, PHEVs and FCVs) and Shenzhen provides extra subsidies to EV buyers. There was a lack of policy support for infrastructure construction in the pilot cities; only Shanghai had already issued a clear policy of providing direct subsidies to the charging infrastructure operating company to construct charging facilities (see Table 7-9). The other three cities are planning to launch similar incentives for infrastructure construction, but these have not yet begun; there has only been guidance on the electricity prices for the charging facilities. Considering all three of these criteria, Shanghai has the best policy

performance in terms of the three policy incentives. Shenzhen's performance is similar to that of Shanghai with regarding to EV purchasing and operation, but it ranks behind Shanghai because of its lack of infrastructure policy (See Figure 7-4).

7.4.4 Environment

According to the results from existing studies on the life cycle analysis of EVs in different regions of China (Zhang, 2013; Wu et al., 2013; Huo et al., 2015), the CO_2 emissions of ICEVs are approximately 265g/km, and those of BEVs and PHEVs differ depending on each city's local electricity generation mix. Among the cities studied, Beijing and Shanghai have the worst performance in the reduction of CO_2 and other air pollutants because of their high proportion of coal-based thermal power (more than 90%). In addition to the CO_2, there are also other pollutions emitted by the road transport, such as NOx, SOx and PM2.5. However, due to the lack of data at local level and also the limitation of calculation workload, this study only chose the PM2.5 as the indicator measured for other air pollution. According to studies by Huo et al (2013) and Huo et al. (2015), BEVs can emit 3 to 4 times more $PM_{2.5}$ than ICEVs in China

because of the significant share of coal in the power mix. During the EV life cycle analysis, 64% of the total $PM_{2.5}$ pollution derives from the power generation and 32% derives from the coal mining and transport process (Huo et al., 2013); there is a lack of data on the $PM_{2.5}$ emissions of PHEVs, and this study evaluated the air pollution performance based on the BEVs in these cities (Table 7-10). It can be seen that BEVs in Beijing produce more CO_2 emissions than ICEVs because of the high proportion of coal-based power. Even Beijing and Shanghai still have a high proportion of coal-fired power; although PHEVs do show good performance on CO_2 reduction in both cities (see Table 7-10). By multiplying the numbers of each type of EV in each pilot city, the author simulated each city's performance on reducing CO_2 and other air pollutants (see Figure 7-5). It should be noted that the weights of CO_2 emissions and air pollutants are equal in both the market and environment scenarios. Therefore, the environmental performance of the four studied cities is the same in both scenarios and can be shown in one diagram (see Figure 7-5)

Table 7-10 The environmental performance of each city

	Vehicle type	Beijing	Shanghai	Hangzhou	Shenzhen
CO_2 emissions (g/km)	ICEV	265	265	265	265
	BEV	270	265	250	215
	PHEV	225	220	215	190
$PM_{2.5}$ pollution (g/km)	ICEV	0.025	0.025	0.025	0.025
	BEV	0.1	0.09	0.09	0.07
	PHEV	N/A	N/A	N/A	N/A
EVs sold (2013–2014)	BEV	9200	2700	10977	1496
	PHEV	177	8483	150	3698

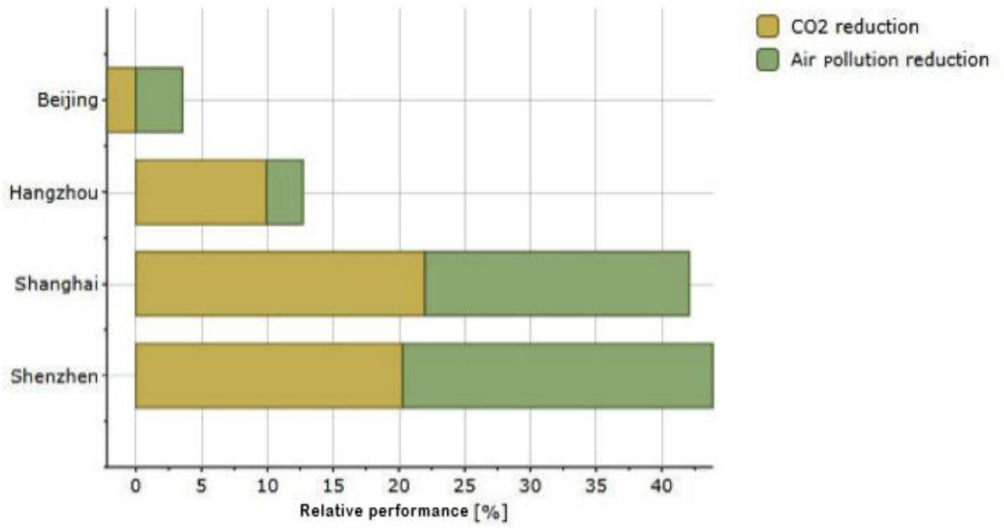

Figure 7-5 The environmental performance of each city

From Figure 7-5, it can be seen that Beijing did not contribute to CO_2 emissions reduction and in fact produced more CO_2 emissions because of the large number of BEVs the city promoted. Shanghai has a similar power mix to Beijing's, but Shanghai's EV promotion achieved the largest reduction in CO_2 emissions among all 4 of the cities under study because of the large number of PHEVs that were promoted there. Shenzhen had the lowest EV sales of the 4 cities and ranked 2nd in CO_2 emissions reduction, largely because Shenzhen uses less coal-fired power generation than the other 3 cities. In addition, BEVs resulted in more $PM_{2.5}$ pollution than did ICEVs during the period under study (Table 7-10). Hangzhou showed the worst performance in $PM_{2.5}$ reduction because it has the largest number of BEVs of the 4 cities. Shenzhen had the best performance in both CO_2 and $PM_{2.5}$ reduction, likely because of its power mix and high volume of PHEV promotion. Shanghai also benefits from its many PHEVs in terms of $PM_{2.5}$ reduction levels.

7.4.5 General evaluation results

By comparing and scaling the performance of each city on each criterion, the total performance of the studied cities regarding the EV demonstration program can be evaluated by considering the weights of the different scenarios (see Figure 7-6 and Figure 7-7). Similar with the results in each aspect, the total performances of the 4 cities are also represented as the relative performance histogram. The relative performance of each city is expressed as a percentage, and adds up to 100% (1.0).

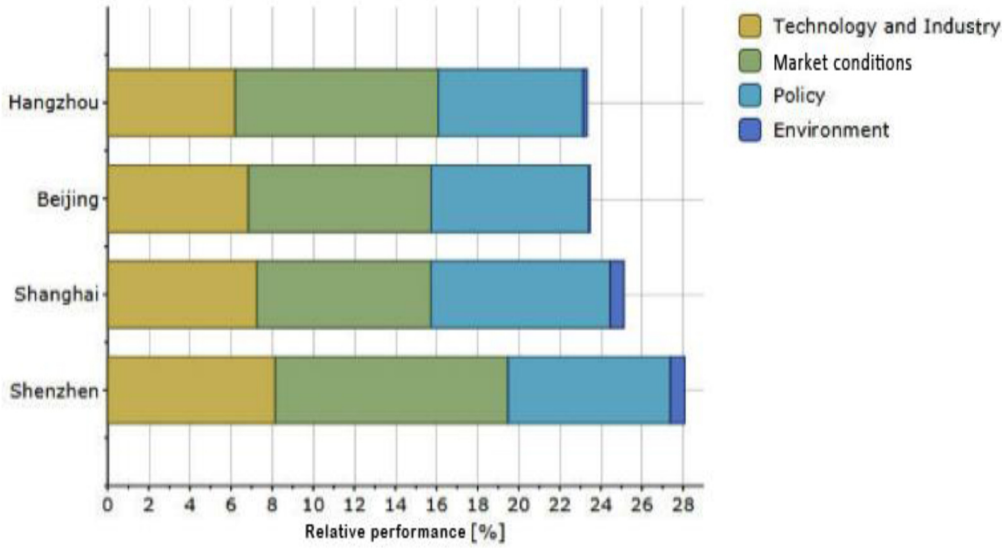

Figure 7-6 The rankings of the 4 cities in the market scenario

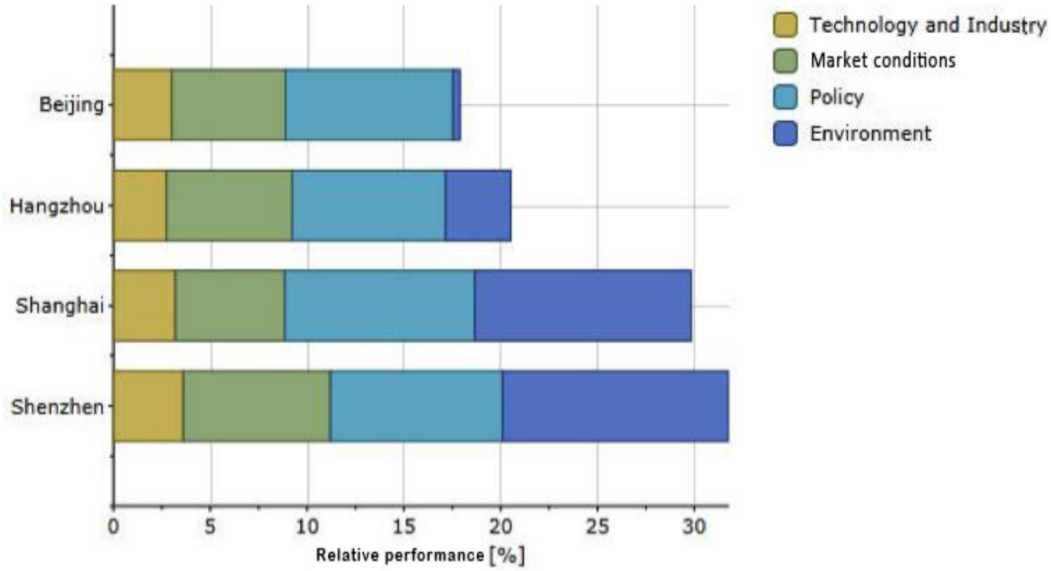

Figure 7-7 The rankings of the 4 cities in the environment scenario

The overall performance of Shenzhen ranked 1st among the 4 cities in both scenarios, which is contributed by its best performance in technology-industry, market conditions and environment. Shanghai ranked 2nd among all these cities in both market scenario and environment scenario. Shanghai had the best performance based on policy but the worst market conditions). In the market scenario, more weights are given to the technology- industry and market conditions, which make the weakness of Shanghai in market conditions becoming more obvious (See Figure 7-6). In the environment scenario, policy and the environment were more heavily weighted than they were in the market scenario, while the weights of technology-

industry and market conditions are relatively reduced. It not only makes the advantages of Shanghai in the policy aspects become more significant than other cities, but also narrows the gaps between Shanghai and Shenzhen in technology-industry and market conditions aspects (See Figure 7-7). Therefore, Shanghai's overall performance is more close to the one of Shenzhen in environment scenario.

By comparing Hangzhou and Beijing, Beijing had some advantages in the technology-industry and policy sectors, while Hangzhou showed better performance than Beijing in market conditions and the environment (See Figure 7-6 and 7-7). In market scenario, the market conditions are heavily weighted, which make Hangzhou has more obviously advantages the Beijing in the market aspect. However, due to the weakness on technology-industry and policy, its overall performance was slightly lower than that of Beijing. The differences in the environment aspect were negligible because of the low weight of the environment criteria in the market-based scenario (see Figure 7-6). In the environment scenario, the weights of policy criteria and environment criteria are increased, while the weights of market conditions are

reduced, which makes Beijing enlarge the advantages in policy and narrow the shortcomings in market conditions compared to Hangzhou. Beijing has more obvious performance than Hangzhou if only considering the technology-industry, market conditions and policy aspects (See Figure 7-7). However, if considering the environment aspects, the overall performance of Hangzhou is significantly ahead of the one of Beijing due to Beijing's worst performance on environment aspect (See Figure 7-7).

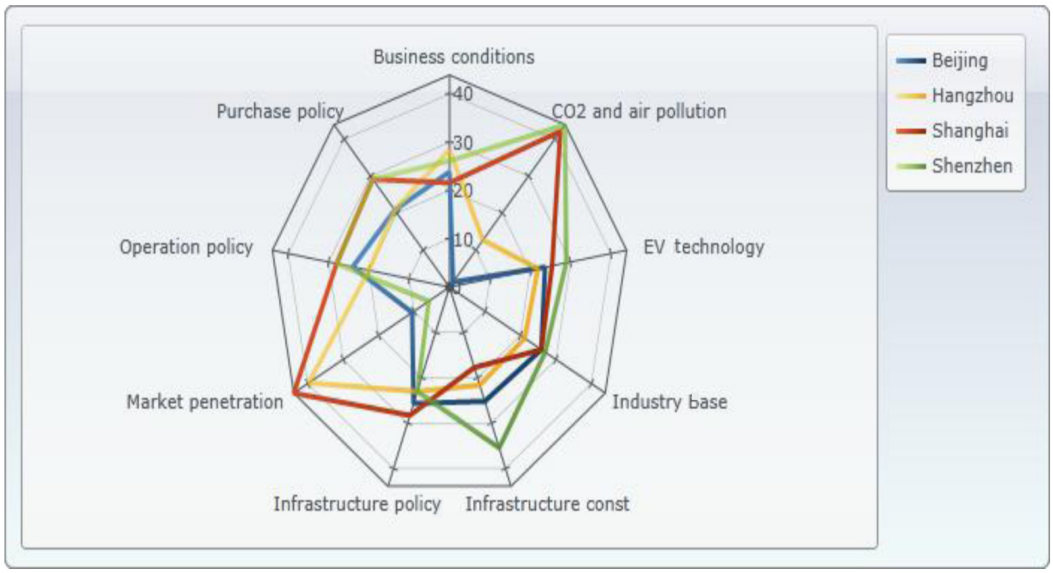

Figure 7-8 The comprehensive comparison of all four cities in all main unweighted criteria

Table 7-11 The scores and the total ranking of each city (unweighted criteria)

Criterion	Beijing	Hangzhou	Shanghai	Shenzhen
Market penetration	10.52	39.73	43.92	5.83
Industry Base	25.91	21.2	25.91	26.99
EV Technology	23.68	21.93	25.44	28.95
Business condition	23.86	28.41	21.59	26.14
Infrastructure construction	25.19	21.61	17.75	35.46
Purchase policy	20.83	20.83	29.17	29.17
Operation policy	24	20	28	28
Infrastructure policy	25.66	23.03	28.29	23.03
CO_2 and air pollution	1.35	12.7	42.09	43.86
Total Scores	**181**	**209.44**	**262.16**	**247.43**
Ranking	**4th**	**3rd**	**1st**	**2nd**

Figure 7-8 shows the comparison of all four of the studied cities in terms of the main unweighted criteria; that is, it does not reflect either scenario specifically or the specific values for each dimension. The scores of each city on the criteria and the ranking of 4 cities have been shown in Table 7-11. The scores of each city represent their relative performance in each criterion, and the total scores of 4 cities in each criterion add to 100 (See Table 7-11). It can be known from Table 7-11 that Shanghai got the highest total scores among 4 cities, which is also reflected in the Figure 8 that Shanghai occupies the largest area in the spider diagram. It means if only considering

the comprehensive performance on all criteria (without weights), Shanghai had the best overall performance in these 4 cities; it had good scores on most of the criteria and only had weaknesses in infrastructure construction and business conditions. Shenzhen also had very good performance and ranked at the top for most of the selected criteria. However, the area that Shenzhen occupies in the spider diagram (Figure 7-8) is slightly smaller than that of Shanghai because of the gap in the market penetration criteria. Beijing had the worst performance overall in that it did not achieve good scores in most of the criteria and it is significantly behind the other cities in CO_2 and other air pollutant reduction (see Figure 7-8 and Table 7-11).

7.4.6 Sensitivity analysis and limitations

The different weights for the different criteria changed the final ranking results. For example, in the environment scenario, the overall values from Shanghai and Shenzhen were much higher than those from Hangzhou and Beijing, and Hangzhou only ranked above Beijing because of its significant advantage in the environment aspect. Shenzhen had the best performance in technology-industry, market

conditions and the environment, which means that this city scored highly regardless of the weight changes; only if much more weight were given to market penetration and infrastructure policy would Shanghai possibly rank above Shenzhen (see Figures 7-3 and 7-4). Therefore, under normal circumstances, the rankings of Shenzhen (1^{st}) and Shanghai (2^{nd}) would not change. The rankings of Beijing and Hangzhou could be affected if the weights were changed. If more weight were given to technology-industry and policy, Beijing would have a significant advantage over Hangzhou in overall value. In contrast, Hangzhou would rank above Beijing if the environmental and business conditions were allocated greater weight.

There are some limitations in this study based on the method that was used to score the criteria. The 9-point scale used in the AHP method was used to determine the scores of the four cities on each criterion, allowing the experts to clearly select the best alternative in each criterion. However, the cities' scores on each criterion are based on the mutual comparison between their performances, which does not prove that their performances were sufficient for the EV demonstration program targets.

For example, for infrastructure construction, Shenzhen had much higher scores than the other three cities (see Figures 7-3 and 7-8). This reflects that Shenzhen showed better performance than the other three cities, but the infrastructure construction (sales numbers and utilisation rates) in all four cities was both unsatisfactory and far below the performance that was expected from the demonstration program, and similar situations also applied to vehicle reliability, infrastructure policy and environmental criteria. Therefore, in order to resolve this limitation, there need to set up a benchmark to exam whether the performance of the pilot cities meet the requirements. The government should develop a series of standards and targets to more closely meet the expected performance requirements, such as the EV failure rate and the utilisation rate of the charging infrastructure. Then, these standards could be considered the benchmark for future evaluations within the evaluation framework. Additionally, the performance of the different cities on each criterion could be compared with the benchmark to show whether these cities have met the standard requirements. Currently, aside from the number of promoted EVs, there is no such standard or target for other aspects in the demonstration program. It is thus

difficult to identify the baseline owing to the lack of data in this study, but it could be developed in future studies.

7.5 Recommendations

Based on the comparative analysis and the evaluation of the four cities in the case study, the advantages and disadvantages of each city on each criterion were explored, and the impacts of the different criteria on the cities' comprehensive performance were discussed. Based on the results of the evaluation, there are some recommendations for improving the EV demonstration program's performance in pilot cities and also for improving the evaluation of the program.

7.5.1 Targeted development according to local circumstances

The evaluation framework clearly highlights the specific advantages and weaknesses of four pilot cities in the demonstration program. Local governments can further improve their performance based on their local circumstances. For example, even though Shenzhen had the best performance among the four cities and ranked 1st in

most of the criteria, it was still weak in market penetration and infrastructure policy (see Figure 7-8). Shanghai showed good comprehensive performance, but it still needs to improve its performance in business conditions and infrastructure construction; more innovative business models, such as EV rental, EV taxi, public EV sharing rental, should be applied and more charging facilities should be built to support the EV promotion in Shanghai. Hangzhou had the worst performance in both EV technology and the EV industry. Most of the experts considered that developing the EV industry was not an important objective for the demonstration program at the regional level. Therefore, the industry base received low weight in both the market and the environment scenarios. Hangzhou's poor performance in the technology-industry aspect was mainly caused by the city's low EV technology level. Because of local protectionism, most of the electric cars that were promoted in Hangzhou are low-end EVs or mini-EVs that were produced by local EV manufacturers. Therefore, eliminating local protectionism and introducing more high-tech EVs from foreign EV manufacturers may be an effective way for Hangzhou to improve its EV fleet. A similar situation occurred in Beijing; compared with the other three cities, Beijing

showed very poor CO_2 emissions and air pollution reduction. This occurred not only because of the city's high proportion of coal-fired power but also because Beijing has focused excessively on developing BEVs but has ignored the benefits of developing PHEVs. The policy incentives in Beijing only apply to BEVs, again as a result of local protection. Therefore, the Beijing local government should adjust its policies, liberalise restrictions and focus more on the environmental impacts of EVs.

7.5.2 Launch more comprehensive standards and goals for the EV demonstration program

The comparative analysis in this evaluation framework can only select the best choice from among all of the alternatives. In order to evaluate whether a given city meets the standard requirements of the EV demonstration program, the government must implement more comprehensive standards and goals for the program. However, in both Phase 1 and Phase 2, the number of EVs sold is the local governments' only planned goal and also the only indicator for evaluating the performance of the pilot cities in the EV demonstration program. In this study, the four case study cities all

ranked highly in both Phase 1 and Phase 2 of the demonstration program. However, the fieldwork in this study showed that even the performance in these cities has been far from satisfactory on some of the criteria, such as the utilisation rates of their charging facilities, their infrastructure support policies and the reliability of the EVs. Therefore, it is necessary and important to establish sound standards and plans in the demonstration program that include technology, infrastructure, policy and the environment. This will not only establish a consistent baseline that can further improve the evaluation framework. This evaluation can become a driving force for local governments to focus more on a comprehensive range of variables in order to implement the more balanced development of EVs in the demonstration program.

7.6 Conclusion

This study established an evaluation framework for China's EV demonstration program using a multi-criteria approach. Through the case studies, it was shown that the evaluation framework effectively compared and analysed the performance of each pilot city in all related aspects, establishing each city's strengths and weaknesses

during the demonstration process. In addition, through the analysis of each city's performance, common issues, prerequisites and useful experience for EV penetration in China were identified. However, the government has not conducted a thorough monitoring and evaluation process for the demonstration program. The new policy that was launched after Phase 1 stipulated that the pilot cities should be subject to annual examination and evaluation, but this policy is still not being implemented. The number of EVs is still the only demonstration program indicator of a given pilot city's performance. That is, local governments have overlooked important criteria such as the utilisation rate of the infrastructure, the reliability of EVs, and the impacts on CO_2 emissions and air pollution; the primary concern has been to increase the number of electric vehicles sold. Therefore, a comprehensive evaluation framework is a valuable and necessary part of the EV demonstration program, and it can also contribute to the individual policies of each local government by revising the criteria and weights (such as the different scenarios in this study). The evaluation framework in this study provides a reference for the government's monitoring and evaluation. Because of limitations in the data collection, only a small number of experts were interviewed for

this study, and the indicators were established based on the available data. For the next step, more detailed criteria could be incorporated into the evaluation framework, such as consumer attitudes and other EV technology indicators. More reasonable indicators can be identified to evaluate the criteria if the relative data can be collected. In addition, following the recommendations discussed in this study, the baseline can be incorporated into the framework based on future comprehensive government standards and goals.

Chapter 8: Discussion and Conclusion

Understanding the impacts and current effectiveness of the EV development in China can contribute to helping the government further improve the strategic direction and policy support for EV promotion, enhance the co-operation between the state, local government and industry, and also act as an exemplar for other developing countries in the EV development process. This dissertation has investigated and analysed the current impacts and challenges of EV development and promotion in China from several different perspectives such as policy, energy, environment, and market potential. This Chapter brings all the findings in each of the core chapters (Chapter 4-6) together in order to answer the research questions posed in Chapter 1. The Chapter also addresses the overall storyline, and how the different chapters link together, highlighting the overall messages that cut across the individual chapters. The contributions and implications of the research for future research directions and policy are also described.

8.1 Synthesis of the core chapters

This section described the main findings in this dissertation and how each research question is answered by these findings.

Research Question 1: the current status and issues for EV development and promotion in China

Chapter 4 and Chapter 7 jointly address this research question from the national and regional levels, respectively. Chapter 4 has applied an overview introduction of the policy background of EV development in China. The large demonstration program "Ten cities Thousand vehicles" has been introduced, and based on the results of the "phase 1" program which operated from 2009 to 2012. In Chapter 7, the latest information of the "phase 2" demonstration program has been introduced, and the current development statuses of the 4 pilot cities have been analysed in detail as case studies. For the national level, the issues and challenges occurred in the EV promotion process have been analysed and discussed, and this has covered in several

aspects: vehicle performance, market condition and consumer behaviour; policy issues; and infrastructure issues.

This dissertation found that in addition to the limitation of the battery technology, the low reliability of the local brand EVs also seriously affected consumers' acceptance of the EVs in the "phase 1" demonstration program. Due to the specific limitations and particular consumers behaviour (such as high residential density and low car ownership), the consumers in China have demanding requirements on the EVs' driving range, convenience and also the charging facilities. The current charging facilities cannot meet the requirements of the EVs promotion, and this can be explained by two main reasons. One is that the high residential density means that it is impossible to install the charging spot for each EV buyers' family, and the current public car parks don't have a specific grid system to support the charging load. The other reason is that there is lack of policy support and regulation to guide the construction of the charging infrastructure, and the Grid Company has a monopoly over the current charging infrastructures. All these issues can be resolved by policy

guidelines. However, there is lack of a comprehensive monitoring and evaluation system for the EV promotion, and this can be seen as one of the main reasons for the neglect of the concern over the reliability of EVs and related charging infrastructures. The current policy strategy is too much focusing on the scale of EV promotion, but less on the analysis of the consumer requirements, demonstration mode, and policy implementation. Due to the lack of monitoring, local protectionism has become a common problem in the demonstration program, as the local government only provides subsidies to their local manufacturers without considering their strengths and weaknesses, and this in turn means that the good performing EVs cannot receive fair treatment and cannot enter the local market. This dissertation has pointed out that there is also lack of evaluation of the energy consumption and GHG emissions of EVs development in China.

Based on these findings from national level, Chapter 7 developed a comprehensive evaluation framework to exam the effectiveness of the EV demonstration projects in selected pilot cities by considering the aspects mentioned in Chapter 4 (technology,

market, policy, environmental and infrastructure aspects). The evaluation process of Chapter 7 has reinforced the findings in Chapter 4. For the technology and industry aspects, Chapter 7 found that in addition to the EV driving range and cost, the concerns over EV reliability and safety issues are very common among consumers. However, based on the experience from "phase 2" demonstration projects, the current reliability of the domestic EVs is still not good, and traditional vehicle parts, such as air conditioning, lights, electrical control system, between them have caused 90% of the EV reliability problems. This shortcoming can be explained by the low level of quality control in the production technology among the domestic EV manufacturers. Meanwhile, local protection results in a lack of competition and does not address quality, and together this explains the reasons behind the low reliability. For the infrastructure aspects, in addition to the two issues pointed out in Chapter 4, Chapter 7 found that the low utilization of charging facilities is very common in the pilot cities, and almost half of the existing infrastructures are not normally used. The lack of planning and management is considered to be the main cause of this situation. Local protectionism was also considered to be a very serious problem in the "phase

1" demonstration program, but it still occurred in the "phase 2" demonstration program. Through the case studies in Chapter 7, the EVs operations in the pilot cities are mainly chosen from their local brand manufacturers instead of selection by performance and quality. In some cities such as Beijing, the local subsidies and public charging infrastructures are limited to providing for foreign brand EVs. Combining the findings in Chapter 4 and Chapter 7, it can be summarised that although some issues were identified in the "phase 1" demonstration program, they were still not effectively resolved in the "phase 2". This dissertation concludes that this mismatch is mainly caused by the lack of evaluation and monitoring system established by the central government, and that there is lack of comprehensive standards and targets for the demonstration program. There is too much focus just on the EV promotion numbers.

Research Question 2: the performance of EVs on fossil fuel use and GHG emissions, given China's specific electricity generation structure

Due to the coal-based energy mix, evaluating the performance of EVs on the energy consumption and CO_2 reduction criteria is very important for the government so that a suitable development strategy can be launched. To estimate the EVs' lifecycle energy consumption and emissions in both national level and regional level, Chapter 5 has applied the GREET model to simulate the fuel lifecycle energy use and CO_2 emissions of three types of EVs (BEV, PHEV and HEV), and compared their performance with that of the traditional ICEV. The findings in the Chapter 5 have also been considered in the evaluation process of the environmental aspects in Chapter 7.

This dissertation has concluded that the BEV could achieve the best fossil energy saving among PHEV, HEV and ICEV, and that this is mainly attributed to its lowest fossil energy consumption in the vehicle operation process (Tank to Wheel (TTW)). In the Well to Tank (WTT) process, the BEV consumes much more fossil energy than the other types of EVs and even ICEV, and this is caused by the high coal consumption in electricity generation in China. However, the BEV is still saving much more fossil energy than other vehicles through the whole fuel lifecycle, and it also has the

greatest potential to save more in the WTT process, as a result the energy mix changing and generation efficiency improvements in the future. For the CO_2 emissions, BEV has very low emissions during the vehicle operation process. During the WTT process, the BEV has produced more CO_2 emissions than the PHEV and HEV, but it still produces less than the ICEV. As coal-based power decreases in the future, the BEV will have the most significant reduction potential for CO_2 emissions. Based on the assumption in this project, the CO_2 emissions for BEV are still higher than the one for HEV up to 2030. Due to the high fuel economy, the HEV shows the best performance on CO_2 reduction in the next two decades, and the BEV may have best performance in the long-term future, if it fulfils its potential. A break-point analysis has been applied in Chapter 5 to understand the relationship between the proportion of coal-fired power and the EV's CO_2 emission in China's situation. It has been found that the BEV will produce even more emissions than the ICEV once the coal-fired power proportion increased to over 92%. The BEV and PHEV can only produce less CO_2 than the HEV when the proportion of the coal-fired power generation is reduced to 61%. According to the historic trend of last decade, the BEV may product more

emissions than the HEV up to 2040. Therefore, this study has concluded that the policy that accelerates the restructuring of energy mix in China is key, and will directly improve the effectiveness of EV promotion on energy savings and GHG emissions reduction. Promoting a transition technology such as PHEV and HEV seems to be necessary to achieve the CO_2 reduction goals in short term.

At the Regional level, this dissertation chose 5 pilot cities from five different regional grids as case studies. These are Beijing (North grid), Changchun (Northeast grid), Shanghai (East grid), Chongqing (Central grid or Southwest grid) and Shenzhen (South grid). Due to the different power mix in different regional grids, the different performance of the EV promotion on energy saving and CO_2 reduction in different pilot cities has been assessed. The results from Chapter 5 have demonstrated these differences. It was found that the CO_2 emissions for BEV could be even higher than those for ICEV in Beijing and Shanghai due to their high proportion of coal-fired power (more than 96%). The fossil energy consumption of BEV in Beijing and Shanghai is also higher than those for PHEV and HEV, but lower than the one for ICEV.

In contrast, due to the abundant water resources in the southwest of China, hydropower can account for 41% of the total power mix in Chongqing, which makes the performance of BEV much better than other vehicle types on both criteria (fossil energy saving and CO_2 reduction).

This dissertation has suggested that the EV development strategy in different regions should be based on the performance of different EV types on energy saving and CO_2 reduction. The focus on the promotion of a single technology (BEV) is not suitable for all the pilot cities given current power mix, and it may even cause more serious CO_2 pollution than the ICEV (for example in Beijing and Shanghai). However, the current EV demonstration program has not evaluated the different performance of the EVs on energy and environment in the different pilot cities. The findings in Chapter 5 have been supported by the evaluation results in Chapter 7. According to the results in Chapter 7, the current EV promotion in Beijing may even have caused more CO_2 emissions in Beijing, due to its large number of BEVs. It has been caused by the local government policy that only provides subsidies to the BEVs. In contrast, Shanghai has

a similar electricity mix as Beijing (Chapter 5); but Shanghai has achieved a very good performance on environmental aspects among the pilot cities. The large number of PHEVs promoted in Shanghai contributes to this situation.

Research Question 3: How EVs penetration can potentially evolve in China, and the key factors influencing future EV diffusion

The vehicle market in China has been specified by the simulations and consumers' behavior in China, and it is also highly policy oriented. To understand the diffusion trend of BEVs in China's vehicle market, a diffusion model developed from the Generalized BASS model has been applied in Chapter 6. More external variables such as driving range, charging infrastructure, vehicle cost and oil price, have been added to the basic model in this dissertation, so that a more comprehensive perspective can be given. There is lack of sales data for BEVs as a new technology product, so this dissertation has used both the historical data of the ICEV diffusion in China and the HEV sales data in the US for the forecasting. The historical data of the ICEV diffusion in China may help to exhibit the characteristics of China's auto market, and the HEV

sales data in the US can exhibit the characteristics of EVs, as the HEV and BEV are similar new products in the auto market. The results found that if the current situation has not changed (vehicle cost, driving range, infrastructures and oil price), the BEV penetration will still be in the early introduction period by 2040 (Scenario 1). However, if the driving range and charging infrastructures continuously improved in the next 30 years, and the fuel cost saving of BEV becomes more and more significant, particularly if the oil price increases (Scenario 2), then the BEVs will come into a quickly growth period start round 2030 (HEV in US) and 2032 (ICEV in China). The third scenario (Scenario 3) in this study assumed that a breakthrough of the battery technology means that the driving range can be greatly improved, and also good policy incentives are provided to reduce the vehicle cost and support the construction of the necessary supporting infrastructures. The results of Scenario 3 have shown that the introduction period of the BEV would be shorted by 5-6 years compared to that in Scenario 2. The diffusion of the BEV will also grow dramatically, and it would finally reach maturity around 2040 (HEV in US) and 2038 (ICEV in China). Based on the comparison of these three scenarios, this dissertation has concluded

that the improvement of battery technology, strong policy incentives and convenient charging infrastructures are the necessary conditions for the promotion and commercialization of the BEV. Otherwise, BEV diffusion is hard to realize, as scale production will not take place, and it will not enter the growth stage in the next 2 decades.

To further understand how the different variables affect the diffusion curve of the BEV, a sensitivity analysis has been carried out. Chapter 6 has analyzed the effectiveness of each factor (driving range, vehicle price, infrastructure and fuel cost) on accelerating the promotion of the BEV. It is found that increasing the driving range of the BEV can accelerate the diffusion speed, especially in the early stages. The diffusion trend can be significantly improved once the driving range increases from 180km to 280km, but the impacts caused by the driving range will become less and less important once the driving range increase over 380km. For the vehicle price, the results showed that the decrease of the vehicle price does not significantly affect the BEV diffusion trend until it reduces to a low level. For example, this dissertation found

that the diffusion curve does not change much when the vehicle price is reduced from 230k RMB to 130k RMB. However, it was also found that the BEV diffusion will be greatly accelerated by the vehicle price reduction once it reaches this low threshold level (130k CNY). Compared with other variables, the increase of the charging infrastructures has the most significant effects on the diffusion of the BEV in the early stages. This dissertation has found that the introduction period of the BEV can be shortened by almost 10 years once the proportion of the charging infrastructure (compared with petrol stations) increases from 5% to 25%. The rate of the improvement on the diffusion speed will become smaller when the infrastructures become more comprehensive.

Based on these results, an interesting conclusion can be made: The different factors will have different impacts on the BEV's diffusion trend, as some factors will be more effective in the early stage, and some will only become useful once they grow (or reduce) to a certain level. Based on the four factors considered in this dissertation, the purchase price reduction is not that effective at the early stage, because it is hard

to reduce the vehicle price to a low level, even considering the government subsidies. Based on current situation, accelerating the construction of the charging infrastructures can obtained the most effective benefits in the short –medium term future. This finding has also been reported in Chapter 7, where the infrastructure construction aspect is given a high weight among the evaluation criteria, and the related infrastructure policy support are weighted higher than the policy subsidies on purchasing process.

Research Question 4: The effectiveness of current policy incentives and instruments in EV promotion

The lack of a comprehensive monitoring and evaluation system can be considered as the basic reason which has caused the government, local government and EV manufacturers to pay less attention to the effectiveness of the development of EVs. As the EV is a kind of new technology, there is lack of existing experience on the evaluation of the effectiveness of the EVs' penetration. Chapter 7 has developed an evaluation framework using a multi criteria approach (MCA) to evaluate the

effectiveness of the EV's demonstration program in China. This chapter has combined the findings from all the previous chapters (4-6), where technology-industry, market conditions, policy and environmental aspects are all considered. Two different scenarios (Market based and Environmental based) have been used for evaluation in order to consider the different perspectives from the different stakeholders in the EV development. Four pilot cities (Beijing, Shanghai, Hangzhou and Shenzhen) in the demonstration program have been chosen as case studies to test the evaluation framework, and the latest data in the "phase 2" demonstration program (2013-2015) has been used. As a comprehensive evaluation, the results of the performance of the pilot cities are not just based on the numbers of EVs promoted. For example, Hangzhou has already promoted 11,127 EVs during 2013 to 2014, and this means that it has already completed its promotion target in "phase 2"demonstration program (2013-2015). However, for the comprehensive evaluation, Hangzhou ranks last among all four cities for the Market based scenario and ranks third in the Environment based scenario. It is because the performance of the EVs promoted in Hangzhou is low technologically, and this is a result of the local protectionism. There

is also a lack of diversification policy on the vehicle operation process and infrastructure construction in Hangzhou, as compared to the other 3 cities.

In summary, the policy subsidies and the demonstration program in China has helped EV development in China; the total EV ownership in China has reached 120,000 EVs (2015). However, this figure is a long way from the “promotion target of 500,000 EVs by 2015” announced by the State Council in 2012 (Energy-saving and new energy vehicles development plan for 2012-2020). From the discussion of Chapter 4 to 6, it can be summarized that the policy strategy and support in China is still not effective, and there are still some issues arising from the energy and environmental aspects, the infrastructure and the market conditions have not been given enough attention. Combining the findings of Chapter 4 and Chapter 7, there is lack of policy incentives for infrastructure support from the central government both in “phase 1” and “phase 2” demonstration projects. However, as the findings in Chapter 6 demonstrate, the increasing number of charging points is the most effective way to accelerate the EV diffusion trend in the early introduction stage. For the local level, the local

government has provided more subsidies and incentives for the EV purchasing and operations process; there is still lack of clearly policy support of the charging infrastructures in most pilot cities.

The current policy support in China is considered to be too much dependent on direct subsidies. Compared to the experience from the advanced developed countries (summarized in the Literature Review- Chapter 2), other forms of policy incentives, such as tax credits, priority for road space, parking for free, and charging facilities subsidies, have not been properly utilized in the current policy incentives and instruments. Based on all these chapters, it is concluded that although the Chinese government has attached great importance to the development of EVs and provided abundant financial support, it is not enough to accelerate the development and promotion of the EV in China without a deeper investigation and analysis of the effectiveness. This dissertation has concluded that a more detailed policy should be developed, along with a set of analytical instruments based on the specific circumstances of the country and the regional level. These should be supplemented

by a comprehensive evaluation framework for EVs, and these measures together can be a driving force for the government to pay more attention on the balanced development of EVs in the future.

8.2 Reflections on the Contribution

The topic of this dissertation is the electric vehicle development pathway in China from the past to the future, and the most notable contribution of this research project is the addition of the Chinese case to the body of comparative studies on EV deployment. Most academic studies either focus on situations regarding the electro-mobility sector in the leading automobile countries (such as Europe, the US and Japan), or investigating the chances of EV success in the global market (Malcolm, 2011; Tran et al., 2012). There are fewer public studies investigating the development status and issues of EV development in developing countries and emerging economies. This dissertation has added to related scientific literature by providing a thorough and up-to-date overview of the policies, development status and potential future of EVs in China, especially the effectiveness of the political interventions in the

EV promotion process. In addition, due to the short history of EV commercialization, there is a lack of data on the electric vehicle market process. Most of the EV-related studies focus either on the discussion of technical barriers and prospects of electric vehicles and batteries, or investigation into the policy incentives and market potential of EVs. There are a lack of studies focusing on the evaluation of the EV deployment process based on existing data and practical experience. Relying on the large-scale EV demonstration program in China from 2009 to 2015, this dissertation provides actual data and information to demonstrate the choices and the barriers in the EV deployment process, and adds to related literature by contributing an updated and practical experience to EV development studies.

In addition to the pressure placed by energy and environmental factors, it is the pace of the technological, political, market conditions and industry developments that determines the success or failure of the EV's deployment. Although the political system has the potential to push electro-mobility to success, the lack of charging infrastructures and the technological limitations of EVs and batteries have still caused

concern over whether the EV market will develop to maturity in the future. With regard to the EV development status and plans in China, this dissertation has provided evidence that the incentive-based political intervention can help to promote the EV to the market; however, the EV (especially the BEV) will not be widely promoted in the short-term. This research has quantified the effectiveness of the current policy incentives and instruments in China at both the local and national levels, and forecasted the potential future based on China's market situation. It has shown that the current EV deployment progress in China is not successful, and China's ambitious short-term plans for EV promotion are being implemented relatively inefficiently, and as such, it has been difficult to achieve the initial targets. The financial-based policy incentives launched from the central government have been inefficient and rather ineffective during the implementation process, and an evaluation and monitoring framework is necessary to supervise and control the effectiveness of EV deployment.

Currently, the incentive-based policy instruments have provided the main means by which governments have promoted the EV. Most of the major automobile-manufacturing countries have developed their own EV development strategies and varieties of policy incentives for EV deployment. Most of these strategies and policy instruments are launched by the central government, which relies wholly on top-down regulation. This situation also occurred in China, and the incentive-based policy instruments have been increasingly applied by the government over the past few years. However, the result of this dissertation shows that more flexibility in EV development strategy should be applied at the local level, as the different situations (such as economic level, electricity mix, market conditions and industry level) can significantly affect the deployment of EVs in different regions. Therefore, this dissertation considers that more complementary flexibility mechanisms should be developed to give local governments greater freedom and flexibility to develop the corresponding electric vehicle development strategy and incentives, based on the local situation. For the central government, the main task should be to develop long-term sustainable development strategy, to give support to local government, and to

develop evaluation and monitoring systems to review and control the progress of the local EVs promotion.

For the EV technology, 4 main EV modes (BEV, PHEV, HEV and FCV) are considered the most promising technologies by governments and the automobile industry. Governments have developed an electric vehicle development strategy and technology roadmap in accordance with their national conditions (See Chapter 2). For example, the strategic approach for vehicle transition in the US has shown that the first step is to promote the flex fuel gas/diesel engine hybrid (HEV); the second step is to focus on the advanced engine and plug-in hybrid (PHEV); the third step is to develop domestic fuel and advanced hybrid; and finally, the fourth step is to achieve zero petroleum and emissions (FCV or BEV). Japan's government considered the HEV as a very important transition technology from the ICEV to the final clean vehicles (FCV or BEV). In its Next Generation Vehicle Plan (2010), HEVs will account for 20%-30% of the total vehicles in the private market, and the BEV and PHEV will together account for 10%-20% of the total vehicles (in the private sector). In China, the BEV

has been considered as the ultimate goal of the EV strategy approach. In the “Energy-effective and Alternative Fuel Vehicle Industry Development Plan (2012-2020)”, the electric-driven new energy vehicles are defined as a state key pillar industry, and the future direction of EV development. The scope of “new energy vehicle” in China has been re-defined as BEV, PHEV and FCV, and the HEV is no longer considered as a new energy vehicle. In addition, although the BEV, PHEV and FCV are all considered as the main focus and are supported by the policy incentives, the government’s political support and content are more biased in favour of BEVs. China still has low levels of technological innovation in the engine hybrid design compared to other countries, and its FCV technology is still not mature enough for commercialism. The approach of transiting from the ICEV to the BEV directly is still believed by some experts and policymakers as a good choice for the Chinese automobile industry, to enable China to compete at the global level. However, the results of this dissertation do not agree with this point of view. It is found that neither the performance of energy consumption and CO_2 emissions, nor the current market conditions and technologies, make the BEV the best choice in the short- to mid-term, over the next 25 years or so.

In contrast, the role of the PHEV has been highlighted by this dissertation for its good performance on energy savings and CO_2 emissions, as well as its long driving range and low dependence on charging infrastructures. All these factors make this option more acceptable to consumers. Therefore, identifying the technical approach and helping the government to rethink the technological roadmap of EV development in China is also a notable contribution of this dissertation.

In sum, this dissertation has summarized the current EV development and analysed the potential for EV diffusion in China. It has also evaluated the existing policy strategy and instruments for supporting EV deployment. The crucial and urgent issues surrounding the EV promotion process have been investigated, and these elements have formed the focus of this dissertation. The findings and conclusions have provided a number of views and suggestions that may suggest different pathways for the future. These views and suggestions can offer a complementary perspective for policymakers and also provide new avenues for future academic studies.

8.3 Policy Implementation

From the discussion in the previous chapters, it can be seen that the current performance of the EVs still lacks competitiveness compared to the traditional ICEV. The key technological bottlenecks of battery design and cost still hinder the development of EVs. In order to successfully introduce EVs into the market, positive development situations should be established. A flexible development strategy should be developed based on the different period and situations in the different regions. Based on the findings in this dissertation, this section provides some recommendations to policy makers for further policy implementation surrounding EV promotion in China.

In the short- or mid-term time frame, the most important thing is to improve the effectiveness of political instruments and demonstration program. As the results of this dissertation show, although the Chinese government has invested a great deal to support EV deployment, the current policy instruments and demonstration are inefficient. Based on the experience of this research, the author considers that the

most effective way to solve this issue is to establish a comprehensive evaluation and monitoring system. The current issues surrounding EV promotion (such as lack of infrastructure, lack of vehicle reliability, local protection phenomenon and inefficient CO_2 emissions) are all considered resultant of the lack of a sound supervision and management system. First, the government needs to carry out more comprehensive standards and targets for EV deployment and EV numbers. Second, an organization needs to be established to evaluate and review the implementation of the demonstration projects on a regular basis. This can be a special organization established by the central government or can be a research institution. In order to ensure the independence and neutrality of the organization, the author considers that the universities or other research institutions are better options for this evaluating and monitoring. For example, the university or research institution can be responsible for the data collection and evaluation process, and publish an authoritative report annually to reveal the evaluation results of the pilot cities. In order to share the powers of the evaluation and monitoring system, a special organization or experts' group can be jointly set up by the four ministries (MOF, MIIT,

MOST and NDRC), and can be responsible for field inspection and supervision in the pilot cities based on the reports provided by the university. The pilot city that ranked at the bottom in the report or did not meet national standards can be given punishment or have its pilot qualifications cancelled. According to the findings in this dissertation, the development of EVs needs to meet a number of prerequisites. Instead of widely but inefficiently promoting the EV in vast areas, it is better to focus on several key development regions which have good conditions for EV deployment, to obtain more effective results and experiences.

In addition, this dissertation pointed out that it should not be trying to shift directly from ICEVs into BEVs, because it is difficult and inefficient to develop the BEV in the short- to mid-term given the current situation (such as technology level, electricity mix and market conditions). This dissertation proves a view that in the short- to mid-term, the role of PHEVs in EV development needs to be paid more attention. A more feasible roadmap of EV technology development in China has been identified in this dissertation (See Figure 8-1). According to the changing speed of the current energy

mix and the market conditions, the BEV can achieve better performance than the PHEV (Chapter 4) and is also coming into a market growth period (Chapter 5) around 2030-2040. Therefore, the PHEV should be considered as the main transition technology and be focused on in the next 20 years. The FCV can be considered as the potential direction of technology development until its technology is mature enough for large-scale commercialism.

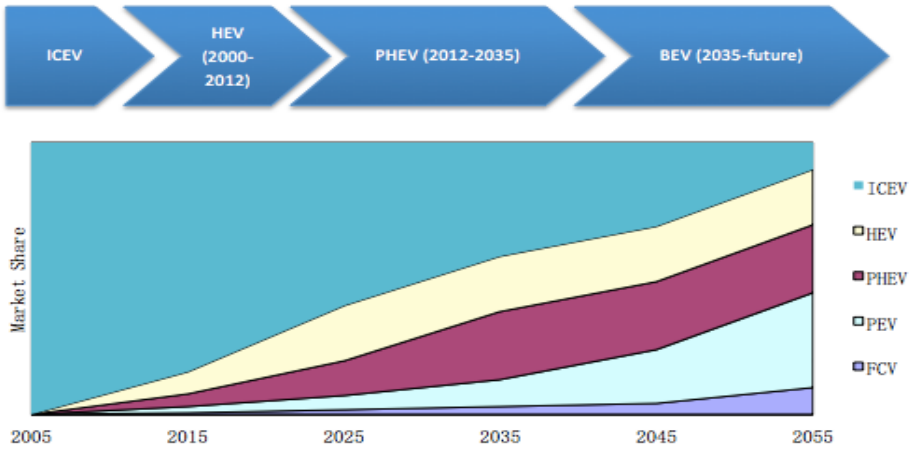

Figure 8-1 The roadmap and the trend forecasting of EV technologies in China

However, this roadmap will become different in various regional dimensions due to the different regional situations. In southwest and south China, the current electricity mix is relatively good due to the abundant hydro resources and nuclear power plants.

In addition, warm weather, high-level economic and EV industry conditions also make electric cars more likely to be promoted in the south of China. Therefore, the author considers that the EV in south China can achieve fast deployment in the next 10-20 years. Large-scale production will reduce the manufacturing costs, and EVs will represent competitive performance compared to the ICEV and HEV, not only on energy and environmental aspects, but also the market aspect. In contrast, north China currently does not have the suitable electricity mix for EV development over the next 30 years. Therefore, improving the energy mix and reducing coal-fired electricity is the main challenge for north China. The potential hydropower in the northeast could be further developed, but due to the cold weather, it still seems that EVs won't be rapidly promoted in the short-term unless the operating temperature range of the battery technology is greatly improved.

Therefore, the government should invest more on battery R&D projects to improve the battery technology and reduce the manufacturing costs. In addition, the development of the BEV needs to reflect changes in the electric generation mix. The

optimization of the electricity mix needs to be seen as part of the EV development strategy. Reducing the fossil energy used (coal-fired power) in the electric generation structure is the most effective way for China to improve the performance of EVs with regard to energy savings and CO_2 emissions. In addition to using more clean energy (such as wind, hydro, and solar), the clean coal technology and other decarbonised technologies in the electricity generation process (such as carbon capture and storage (CCS)) need to be the focus of research and promotion, as the coal-based energy mix in China is unlikely to be changed in the short- to mid-term future.

Although there are some issues as summarized by this dissertation, the previous EV demonstration program still made a contribution to EV promotion in China. In the current period, the government should continue to promote the development of electric vehicles through demonstration programs; however, the direction and instruments of the policy support should be adjusted to be more flexible and comprehensive. As the findings in this dissertation show, the development strategy of EVs needs to reflect the regional variations, which include the regional electric mix,

economic level, and local industry level. The good performance of the PHEV promotion in Shanghai discussed in Chapter 7 strongly supports this view. Therefore, the traditional top-down political regulation is not efficient enough in the large-scale demonstration program, and as such, the central government needs to give more flexibility to the local-level EV strategy based on the different situations. The government should encourage and support local government in launching their EV development strategy based on their local situations. The central government should be more focused on the direction of the long-term development, and control and monitor the performance of the deployment progress at the local level. In addition, the government should provide more comprehensive policy incentives, especially in charging infrastructures, instead of only providing direct subsidies for the EV purchasing process. As the findings in this dissertation show, the improvement of driving range and charging infrastructures are more effective in the early period of EV introduction than is the reduction of the vehicle price. In addition, other non-subsidy incentives, such as priority of road driving, free parking, and exception from driving limitations, are all considered as effective policy incentives in EV promotion.

In summary, the author considers that EV deployment in China is feasible in the future. From the market perspective, EVs are gradually being considered and accepted by consumers as a result of the strong policy incentives and instruments. The production and sales of EVs are also gradually expanding, which is helpful to reduce the manufacturing cost and improve enthusiasm about the industry. However, for the environmental aspect, although EVs have great performance on energy saving, especially the oil saving, it is hard to achieve great GHG emission reduction through EV deployment in China. Promoting the rapid spread of electric vehicles might not be a good choice if the government considers the CO_2 reduction as the most important motivation for EV deployment. But the author still considers that the development of EVs in China is valuable, as it can have great potential for environmental impacts in the future. EVs' varied use of energy sources eliminates the car's dependence on single fossil fuels. This dissertation has proved that the diffusion of EVs still highly depends on battery technology, EV performance, and construction of charging infrastructures. To realize the commercialization of electric vehicles, it

requires continuous investment in EV R&D, policy incentives, infrastructures, and demonstration projects to minimize the competitive disadvantage between the EV and conventional vehicle in the early period. This should not only be contributed to by the central government, but also by cooperation among all related stakeholders, such as the central government, local governments, EV industry, battery suppliers, R&D institutions, infrastructure constructors, grid companies and other service providers (bus operation companies, taxi companies and vehicle rental companies).

8.4 Limitations in this dissertation and recommendations for future study

Limitations

Due to the lack of data and information, there are some limitations in this dissertation. In the life-cycle assessment of the energy consumption and CO_2 emissions of EVs, data have been collected on the energy industry and grid system to replace the original parameters and inputs of the GREET model. However, there are still some data (such as the share of advanced coal technology and biomass

technology) that are not available due to the lack of public and published information. These data are still using the original setting of the GREET model, which is based on the US situation, and should be replaced in future studies to achieve more accurate simulation. In addition, this study only simulated the fuel life cycle of the fuel pathways of EVs and ICEVs, and the vehicle manufacturing life cycle is not considered in this study. Although the literature has shown that the fuel life cycle accounts for the major part of the whole life cycle, there are still differences between EVs and ICEVs in the vehicle manufacturing life cycle due to the different materials and energy consumption between the battery and motor production and the ICE production. This study has only simulated CO_2 emissions (Chapter 4), and only considered CO_2 emissions and PM2.5 as the indicators in the evaluation framework (Chapter 7). However, in addition to CO_2 and PM2.5, other forms of air pollution, such as NOx, SOx and PM10, are also common forms of air pollution caused by road transport. In addition, for simulating the regional energy consumption and CO_2 emissions of EVs, this dissertation assumed the electricity was all locally produced, and did not consider the electricity imported from other provinces. This is because

currently, most electricity is produced locally or from neighbouring provinces or territories, and the electric mix is considered to be similar with the local electric mix. If the long-distance high-voltage transmission (LHT) is widely used in China in the future, the imported electricity from other regions should be considered through the simulation process in future studies.

In the diffusion analysis of EV penetration in China, this dissertation has considered four main factors, including the driving range, vehicle price, fuel price, and infrastructures, which is more than previous studies have considered. However, there are still many other factors that can affect the diffusion of EVs, such as charging time, vehicle reliability, maintenance, and consumers' word of mouth. These factors are the key elements that affect consumers' decisions about purchasing EVs, which should be considered when forecasting the diffusion trend of EVs. However, due to the short history of EV commercialism, there is a lack of data on these factors, or it is hard to measure them.

This dissertation has developed an evaluation framework for the demonstration program in China. Because there is almost no existing experience from previous studies, the evaluation framework used in this study may not be mature, and some criteria are not considered in the evaluation due to the lack of data. In addition, this dissertation collected the opinions from 11 experts for evaluating the effectiveness of the pilot cities in current demonstration projects. Due to the limitation of the workload, the scale of the interviewees is not large. However, all the experts chosen are high-level experts from government, institutions, EV manufacturers and other service operators, who are considered to represent the views of their respective stakeholders. The current evaluation framework used in this dissertation is mainly focusing on the comparison analysis of the pilot cities, and it can provide the relative performance among the pilot cities and analysis of their respective advantages and disadvantages. However, due to the lack of benchmarks, it cannot give a direct judgment of whether the effectiveness of pilot city is good enough for the demonstration program. Currently, no comprehensive standards and targets of the

demonstration program are provided by the central government except the promoted EV numbers.

Recommendations for future studies

Based on the limitations concluded above, a future study could focus on a more comprehensive analysis of the EV life-cycle analysis by considering the vehicle life-cycle assessment and other air pollution types to provide a deeper understanding of the environmental impacts. In addition, the life-cycle analysis of the infrastructures is also a valuable topic for future study, to investigate the different energy and environmental impacts between the different kinds of charging infrastructures and traditional petroleum stations, and to further understand the potential impacts of the large-scale EV promotion on energy savings and GHG emissions.

For the market potential of the EVs, more variables (such as word of mouth, charging time, vehicle performance, non-subsidy incentives and so on) could be included to provide a more comprehensive forecasting of the diffusion of EVs, together with

measurement of the impacts over different periods. Some factors (such as infrastructures and driving range) will be more effective in the early stage, but their influence will become smaller and smaller over time, as more people start to use EVs. These factors have been defined as “early effect factors”. In contrast, some other factors will only become useful once their value grows (or reduces) to a certain threshold level (such as vehicle price). These factors have been defined as “delayed effect factors”. However, the causal processes that determine the difference between these two kinds of factors are not known. It may result from the different weights allocated to the innovation factors and limitations factors. A future study could focus on this, and finding out what is the root reason caused behind the different effective performance of the various factors in the different periods. The findings will be helpful to determine the changes in political support levels in the different periods.

In addition, future studies could add further changes and adjustments into the evaluation framework developed in this dissertation, based on more comprehensive data and expert opinions. For example, as the EV market is a emerging market, some

criteria is hard to evaluate due to the lack of data, and is not added into the framework, such as the acceptation and awareness of consumers, and the maintenance and service and frequency of use of EVs. These criteria would be helpful to provide a more comprehensive evaluation, and could be considered in future studies if the data is available. If there are some standards and targets (such as charging infrastructure numbers and utilization rate, EV reliability, and business modes) released by the government, the benchmark could be developed in future studies to modify this evaluation framework to examine whether the performance of the pilot cities meets the qualified line.

For the policy perspective, this dissertation pointed out that traditional top-down regulations of the political instruments are not efficient enough in EV deployment in China; a new complementary flexibility mechanism should be developed between the central government and local governments. The evaluation framework, developed to evaluate the effectiveness of the EV demonstration programs, will contribute to help the central government set up its supervision and management system for EV

deployment. The next steps here could help the central government establish a mechanism, and help local governments carry out their functions to develop electric vehicle development plans based on local conditions. It is also valuable to study the effectiveness of the policy instruments in the EV deployment process in other countries, to determine whether this finding is a common phenomenon, or unique to China due to its specific situations and political system.

Appendices

Appendix 1

The pilot cities and cities groups in the Phase 2 demonstration program

City	Beijing, Tianjin, Taiyuan, Jincheng, Dalian, Shanghai, Ningbo, Hefei, Wuhu, Qingdao, Zhengzhou, Xinxiang, Wuhan, Xiangyang, Guangzhou, Shenzhen, Haikou, Chengdu, Chongqing, Xi'an, Lanzhou, Shenyang, Changchun, Harbin, Zibo, Linyi, Weifang, Liaocheng, Luzhou	
Cities groups	Hunan province cities group	Changsha, Xiangtan, Zhuzhou
	Hebei province cities group	Shijiangzhuang, Tangshan, Handan, Baoding, Xingtai, Langfang, Hengshui, Cangzhou, Chengde, Zhangjiakou
	Zhejiang province cities group	Hangzhou, Jinhua, Shaoxing, Huzhou
	Fujian province cities group	Fuzhou, Xiamen, Zhangzhou, Quanzhou, Sanming, Putian, Nanping, Longyan, Ningde, Pingtan
	Jiangxin province cities group	Nanchang, Jiujiang, Fuzhou, Yichun, Pingxiang, Shangrao, Ganzhou
	Guangdong province cities group	Foshan, Dongguan, Zhongshan, Zhuhai, Huizhou, Jiangmen, Zhaoqing
	Inner Mongolia cities group	Hohhot, Baotou
	Jiangsu province cities group	Nanjing, Changzhou, Suzhou, Nantong, Yancheng, Yangzhou
	Guizhou province cities group	Guiyang, Zunyi, Bijie, Anshun, Liupanshui, Qiandongnan
	Yunnan province cities group	Kunming, Lijiang, Yuxi, Dali

Appendix 2

The EV promotion plan of each city or cities group in Phase 2 demonstration program

Pilot city	Public sector	Private sector	Pilot city	Public sector	Private sector
Taiyuan	3900	1100	Haikou	3000	2000
Chengdu	5000	0	Lanzhou	3750	1250
Jinzhong	3000	2000	Xinxiang	3000	2000
Xiangyang	1190	3810	Dalian	3600	1400
Ningbo	2900	2100	Shenyang	4000	1000
Changchun	4500	500	Harbin	4600	400
Zibo	3100	1900	Linyi	3000	2000
Liaocheng	1500	3500	Luzhou	4100	900
Weifang	5010	0	Wuhu	3460	1650
Qingdao	5200	0	Zhengzhou	4900	600
Hefei	1220	4500	Shanghai	3200	6800
Chongqing	9000	1000	Guangzhou	6000	4000
Wuhan	4300	6200	Xi’an	5700	5300
Tianjin	11500	500	Shenzhen	19000	16000
Beijing	5020	30000			
Inner Mongolia cities group	3980	1020	Guizhou province cities group	4350	650
Yunnan province cities group	4196	804	Jiangxi province cities group	5100	200
Hunan province cities group	4650	1450	Fujian province cities group	6950	3050
Guangdong province cities group	6000	4000	Zhejiang province cities group	6000	4000
Hebei province cities group	9000	4000	Jiangsu province cities group	13235	1900

Appendix 3

The EV sales in the major countries from 2011 to 2013

Country	2011			2012			2013		
	BEV	PHEV	Total	BEV	PHEV	Total	BEV	PHEV	Total
American	10144	7671	17815	14592	38585	53177	47589	49043	96632
Japan	13449	0	13449	15943	7241	23184	16661	14122	30783
China	5576	613	6189	11375	1416	12791	14604	3038	17642
France	4012	36	4048	9215	225	9440	8260	85	8345
Norway	2000	0	2000	3945	165	4110	7207	89	7296
Netherland	520	14	534	611	3142	3753	2559	3000	5559
UK	930	0	930	1167	522	1689	2464	819	3283
Germany	1800	241	2041	2976	863	3839	2846	360	3206
Canada	193	275	468	436	1288	1724	638	1143	1781

Appendix 4

The major EV models in current China's EV market

EV model	Manufacturer	Power type	Weight (kg)	Battery Capacity (kWh)	Top Speed (km/h)	All-electric driving range (km)	Battery Warranty	Sale price (10000 CNY)	Government subsidy (10000 CNY)
Heyue iEV	JAC	BEV	1200	19.2	95	160	5 years or 100,000 km	16.98	4.75
Roewe E50	SAIC	BEV	1080	18	120	120	5 years or 100,000 km	23.49	3.325
Roewe 550	SAIC	PHEV	1699	11.8	200	56	5 years or 100,000 km	24.88~25.98	3.325
Springo	SAIC-GM	BEV	1385	21.4	130	130	5 years or 100,000 km	25.8	3.325
E150	BAIC	BEV	1370	24.4	125	150	5 years or 100,000 km	22 ~ 23	4.75
Saab EV	BAIC	BEV	1760	N/A	130	130	N/A	35.48	4.75
M1 EV	Chery Auto	BEV	1060	16.2	120	100	5 years or 100,000 km	16.98	3.325

E6	BYD	BEV	2360	61.4	140	300	Lifetime Warranty	30.98~36.98	5.7
Qin	BYD	PHEV	1720	13	185	70	Lifetime Warranty	18.98~20.98	3.325
DENZA	DENZA (BYD-Daimler)	BEV	2090	47．5	150	253	5 years or 100,000 km	36.9~39.9	5.7
Volt	GM	PHEV	1700	16	160	64	6 years 150,000 km	49.98	N/A
Model S	Tesla	BEV	2100	60~85	190~210	390~502	8 years 200,000 km	64.8~85.25	N/A

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