Electric Cars in China: Energy, Infrastructure and Market Potentials

Jian Liu

School of Geography and the Environment

Brasenose College

University of Oxford

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Abstract

The electric vehicle (EV) has been regarded as one of the most promising alternative fuel vehicle technologies that could reduce China's energy reliance on imported oil and transport sector carbon emissions. The success of EVs in China will depend on a series of determinants including their energy consumption and emission reduction potentials, battery performance and costs, charging infrastructure provision, the driving behaviour and the commercialization strategies. Some issues have been intensively investigated by previous research whilst some others gradually receive academic and governmental attentions. Instead of covering all determinants, this thesis focuses on four key aspects of the electric car development in China: the energy consumption and carbon emissions of electric cars based on the country's energy mix; the expected electric car driving behaviour and its impacts on the power grid; the deployment strategy of charging infrastructure and the business operation models that could reduce the purchase cost of electric cars and accelerate their market diffusion.

The research finds that according to the current energy mix and driving behaviour in China, the introduction of electric cars would largely reduce the transport sectors' oil consumption. However, the carbon emission saving of electric cars requires a synchronized progress in the energy industry and the power grid infrastructure. Without the growing adoption of renewable sources in the electricity generation mix

and the high efficient power transmission infrastructure, electric cars could achieve little environmental benefits particularly for carbon emission reduction. This research also finds that the current external costs of carbon emissions from cars are not high enough to justify financial policies that would favour electric vehicles. Moving towards cleaner technologies at present may not be justified on economic terms but it is justified on political and environmental terms.

In addition, the performance of current electric cars, the driving range per charge in particular, is still significantly inferior to conventional vehicles running on petroleum fuels, which poses a remarkable challenge for electric cars' market acceptance and implies the importance of charging infrastructure provision. This research estimates the charging impact of electric cars on the power grid in two case study cities through comparing charging infrastructure deployment strategies integrating three charging methods in both cities. Some innovative business operating models that aim to reduce the high initial purchase costs of electric cars are simulated. It shows all these models require substantial political and financial interventions to stimulate both supply (charging service and infrastructure provision) and demand (consumers purchase) in the early stage of market penetration for electric cars. Finally, the thesis provides recommendations for the policy implementation timing and stresses the importance of the parallel development in the upstream low carbon energy supply and the downstream vehicle (battery) research and development (R&D) in the near term.

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Acronyms

AFV – Alternative Fuel Vehicle

ANL – Argonne National Laboratory

CAAM - China Association of Automotive Manufacturers

CASS – China Academy of Social Science

CCS – Carbon Capture and Storage

CD/CS Mode – Charging Depleting/Charging Sustaining Mode for PHEV

CICEBD – Compression Ignition ICE Vehicle

CNG – Compressed Natural Gas

CNOOC – China National Off-shore Oil Company

DKT – Daily Kilometres Travelled

DME – Dimethyl Ether

DOE – Department of Energy (United States)

E85 – Blender of 85% ethanol and 15% petrol in volume

E90 – Blender of 90% ethanol and 10% petrol in volume

EPRI – Electric Power Research Institute (United States)

EV – Electric Vehicle

FCV – Fuel Cell Vehicle

FTD – Fischer Tropsch Diesel

GCHEV – Grid Connected Hybrid Electric Vehicle

GDP – Gross Domestic Product

GHG – Greenhouse Gas

GIHEV – Grid Independent Hybrid Electric Vehicle

HEV – Hybrid Electric Vehicle

ICE – Internal Combustion Engine

ICT – Information and Communication Technology

IEA – International Environmental Agency

IGCC – Integrated Gas Combined Cycle

IPCC – Intergovernmental Panel on Climate Change

LCA – Life Cycle Assessment

LNG – Liquefied Natural Gas

LPG – Liquid Petroleum Gas

MIIT – Ministry of Industry and Information Technology (China)

MOC – Ministry of Commerce (China)

MOST – Ministry of Science and Technology (China)

MPG – Miles Per Gallon

NBS –National Bureau of Statistics (China)

NDRC – National Development and Reform Commission (China)

NGCC – Natural Gas Combined Cycle

NiMH – Nickel Metal Hydride

NREL – National Renewable Energy Laboratory (United States)

PEV – Pure Electric Vehicle

PHEV – Plug-in Hybrid Electric Vehicle

PTW – Pump to Wheel

PM – Particulate Matter

PVC – Present Value of Cost

RPR - reverses-to-production ratio (RPR)

SCC – Social Cost of Carbon

SFFICEV - Spark Ignition Flexible Fuel ICE Vehicle on E85

SGCC – State Grid Corporation of China

SICECNG – Spark Ignition ICE on Compressed Natural Gas

SICED – Spark Ignition Direct Injection Vehicle using Gasoline

SICEG – Spark Ignition ICE Vehicle using Gasoline

SMR – Steam Methane Reform

SOC – State of Charge

V2G – Vehicle to Grid

VOC – Volatile Organic Compound

WTP – Well To Pump

WTW – Well To Wheel

Chapter 1 Introduction

1.1 Background

The transport sector was responsible about 61% of world's oil consumption and 28% of total final energy consumption in 2007 (IEA, 2009). The combustion of transport fuels accounts for 14% of global anthropogenic greenhouse gas (GHG) emissions to which road transport alone contributes 76% (King, 2007a). Under the business as usual scenario, road transport emissions will double by 2050 and will become one of the main causes of global warming (HM Treasury, 2007a).

Growth in transport energy use has been highest in developing economics, including China, East Asia and parts of Latin America (Yan and Crookes, 2007). Since the Chinese economic reform and the opening up policy introduced in 1979, China has experienced a continuous and strong economic growth with an annual GDP growth rate of 9.3% between 1978 and 2005 (National Bureau of Statistics, 2006a), and it has become the world's second largest economy. Even during the financial crisis in 2009 and 2010, China still achieved 8.7% and 10.3% GDP growth in these two years and the high growth rate is expected be sustained. The strong economic rise in turn has

and will continue to drive car ownership growth. In 1978, there were 1.36 million civilian vehicles[1] in China, of which privately owned cars were 0.2 million. In 2005, the total civilian vehicles reached 31.6 million (23.2 times 1978's level), of which private cars were 18.48 million (92.4 times of 1978's level) (NBS, 2006b). Under the current growth rate, civilian vehicles in China are expected to exceed 200 million by 2020 (Ministry of Industry and Information Technology, MIIT, 2010).

Meanwhile, as the fastest growing automobile market in the world, China's oil demand has increased dramatically over the recent decades. The statistics of the National Development and Reform Committee (NDRC) (Energy Bureau, 2006b) showed that in China, 97.5% petrol and 52.1% diesel are allocated to transport energy use. In 2009, China's dependence on foreign oil reached 55.6% (China Association of Automotive Manufacturers, CAAM, 2010). The transport energy demand in China has increased from 25.2 million tonnes of oil equivalent (Mtoe) in 1980 to 191.2 Mtoe in 2007 with an average annual growth rate of 7%, making transport the fastest growing energy-consuming sector in China (Wang, 2009). More than 80% of transport energy demand is generated from road vehicles in the United States (Davis and Diegel, 2009) and 83% in the European Commission (EU, 2007). Although this figure in China is still relatively low (65%), it would increase to 71% in 2015 and 77% in 2030 according to the projections from International Energy Agency (IEA, 2008).

[1] "Civilian vehicles" is a vehicle classification in China. It includes all private and public owned vehicles and is distinguished to military, police, governmental and agricultural vehicles.

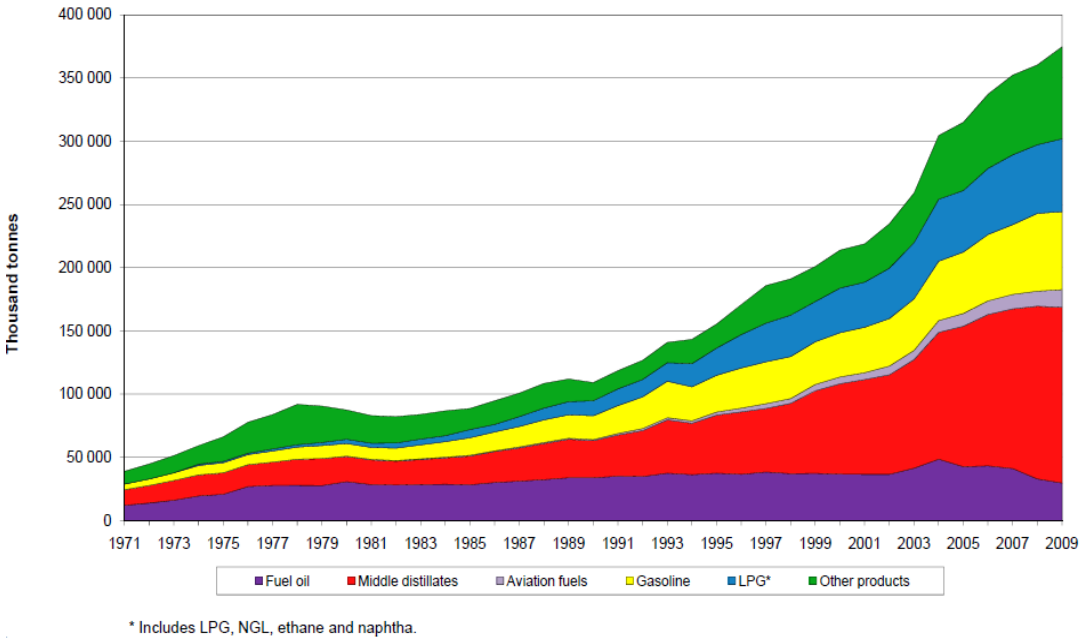
With domestic financial subsidies to stimulate the vehicle production/sales in China and the economic recession in the developed economies, China became the world's largest vehicle manufacturer and consumer in 2009 (Xinhuanet, 2010). Nevertheless, the current vehicle ownership rate in China (77 per thousand capita, NBS, 2010) is still much lower than that in developed countries (about 700 and 480 per thousand capita in the United States and the European Union, IEA, 2011) and the world average (257 per thousand capita, World Bank, 2011), indicating a large potential for further vehicle ownership increase. With the rapid car ownership growth, transport sector's oil consumption and GHG emissions is also expected to continue to increase and this would pose a serious energy security concern for China (Cai, 2008).

Despite being the second largest oil consumer in the world, China has a relatively limited oil reserve. Oil consumption continued to increase on average by 5% per annum over the past three decades, and it has reached 376 Mt in 2008 (British Petroleum, 2009). However, the domestic oil production has been increasing at a much lower rate, resulting in heavy dependence on imports. According to the Energy Bureau of China (2006a), the proven crude oil reserve in China is 2.34 billion-tonnes, which only represents 1.4% of the world's total amount, and the country's reverses-to-production ratio (RPR)[2] is only 12.9 years from 2005. On the other hand, the oil demand in Chinese continues to grow at an accelerating rate (see Figure 1). China's annual demand exceeded the demand for oil in Japan in 2002 and it became

[2] Reserves-to-production ratio (RPR) is a ratio expressed in terms of years indicating the remaining lifespan of a natural resource.

the second largest crude oil consumption country after the United States. According to IEA's projections, 80% of China's oil demand will rely on oil imports in 2030 (IEA, 2007). Because the imports are mainly from politically volatile regions (for example, the Middle East and some African countries), the high reliance on oil imports threatens national oil security (Wu, et, al, 2007). To mitigate this reliance, China has started to diversity its oil imports and to establish the national strategic oil reserve.

Figure 1 Consumption of Oil Products in China



Sources: IEA, 2011

In addition to the energy security concern, the rapid increase of vehicle ownership has also caused serious environmental pressures. The consumption of fossil fuels inevitably produces emissions, which contain both pollutants deteriorating urban air quality and GHG emissions threatening the global climate. Transport fuels, including

petrol and diesel, produce a large amount of GHG emissions which have long been regarded as the main reason of global warming, and GHG emissions have considerable negative effects on the natural environment, such as sea level rising, desertification, extreme weathers, glacier retreat, species extinction, and disease increase (Intergovernmental Panel on Climate Change, IPCC, 2007). China has become the country with the largest carbon dioxide (CO_2) emissions and it is facing unprecedented international political pressure to reduce GHG emissions. The Chinese government has announced strong goals for reducing 40%-45% CO2 emission per unit of GDP by 2020 compared with the 2005 level (State Council, 2009). The State Council of China also announced a "Decision to Enforce Energy-Conservation" in 2006 and a "Comprehensive Work Program on Energy-Conservation and Pollution Reduction" in 2007, which identified transport as a key sector in the national plan to meet the energy and air quality goals and highlighted strategies such as developing public transit, strictly enforcing the vehicle emission standards, and promoting the research and development (R&D) for alternative fuel vehicle (AFV) industry (State Council, 2007).

Apart from GHG emissions, vehicle tailpipe emissions are also the major source of criteria pollutants including nitrogen oxide (NO_x), carbon monoxide (CO), volatile organic compounds (VOC or hydrocarbon, HC) and particulate matter (PM), along with the un-burnt fuel emissions, directly poisonous to human health in many cities (Barletta, et al, 2005; Bo, et al, 2008; Liu, et al, 2008; Xie, et al, 2008). Air pollution

in urban areas is also one of the most severe environmental concerns in China. The rapid growing vehicle stock has gradually replaced the coal-based power plants as the dominant emissions source in China (Yan, 2008). In the city of Beijing for instance, the automobile vehicles account for 23.3% of total particulate matter emissions and more than 50% of total NO_x and CO emissions. In the urban area of Shanghai, 66% particulate matter, 90% NO_x and 26% VOC are emitted from vehicles' tailpipes (BAIN and Company, 2009). Creutzig and He's study (2009) further shows the social costs of motorized transport in Beijing account for 8% to 15% of the city's gross domestic product (GDP), though the major cost is originated from traffic congestions.

In sum, the transport sector in China now faces a range of challenges including growing vehicle ownership, concerns over energy security and environmental pressures. The rapid road vehicle growth now accounts for about one-third of the country's petroleum fuel use, and vehicle tailpipe emissions have become the major source for urban air pollution. Furthermore, due to the less advanced vehicle technologies, lower fuel quality and less stringent vehicle fuel economy regulations, the average vehicle emissions in China are significantly higher than those in developed countries. In order to mitigate the negative environmental impacts, alternative fuel vehicles (AFVs) are being proposed as a substitute option for conventional internal combustion engine (ICE) vehicles. This study finds that grid-connected hybrid electric vehicles (GCHEVs) and grid independent hybrid electric vehicles (GIHEVs) are the two alternative fuel vehicle options that we would

recommend in the US in the next ten years because they would achieve significant carbon emission savings and they are not significantly more expensive than the conventional gasoline car. The government in the US, however, probably looking at the longer run, seems to have taken a different view, demonstrated by the generous subsidies it currently provides for the purchase of electric vehicles.

The Chinese government is also favouring electric vehicles, and has chosen them as the major technology to substitute conventional petroleum vehicles based on the decarbonisation potential of transport electrification and the country's energy sources. With the rapid technological development of the energy industry in China, electricity is expected to be increasingly generated from natural gas and renewable and low carbon sources (solar, wind and nuclear). In addition, the large coal reverse in China offers the energy supply security for the electrification of the road transport sector. Also to decarbonise the production of the conventional fossil fuels, the Chinese government has introduced a range of measures to mitigate emissions from the electricity generation stage, including the introduction of Integrated Gas Combined Cycle (IGCC) and Natural Gas Combined Cycle (NGCC) technologies (Yan and Crookes, 2009). In the early 1990s, the Chinese government began to fund R&D projects on alternative fuel vehicle technologies, and since 2002, EVs have been promoted as the main development pathway.

Since the early 1990s, low-carbon alternative vehicle/fuel technologies have gradually

captured the attention from the government and academia. The Chinese government has made great efforts to mitigate the energy demand and emissions from the road transport sector, by introducing a number of vehicle emission regulation and economic incentive policies. The Ministry of Science and Technology (MOST) and the National Development and Reform Committee (NDRC) launched the Clean Vehicle Action Plan as part of the eighth five-year plan (1991-1995), and the China 863 program covered a variety of AFV technologies. The 863 program is carried out through a collaboration of dozens of universities, research organizations and vehicle manufacturers in China. Some alternative fuel vehicle (AFV) technologies have already been applied for bus fleets in some cities. Liquefied Petroleum Gas (LPG) buses, compressed natural gas (CNG) buses and methanol buses have been under operation in some cities since 1999 where the required energy feedstock is abundant. Hybrid electric buses, electric buses and fuel cell buses are still in the RD&D (Research Development and Demonstration) stages (Wan, 2008; Wang, 2006; Ouyang, 2006). China has introduced E10 (blend of 10% bio-ethanol and 90% petrol in volume) for vehicles in the southern provinces since 2001 (Leng, et al, 2008), and it has become the third largest ethanol fuel producer following Brazil and the United States (Yan and Crookes, 2009). According to the Ministry of Industry and Information Technology's (MIIT) target, the annual production of new energy vehicles will reach 500,000 in 2020 (accounting for 5% of total vehicle production) and the total new energy vehicle stock will reach 5 million (accounting for 2% of total vehicle stock) in 2020 (MIIT, 2011). In more recent years, EVs (including hybrid electric and pure

electric) have been regarded as the most promising option among various alternative fuel pathways and the “electric” option has been increasingly stressed in the governmental and local authorities’ development plans for the automotive industry.

Compared with ICE and many alternative fuel vehicles, EVs have a large potential in saving petroleum fuel consumption and GHG emissions. The fuel cycle energy efficiency of typical EVs using electricity generated from natural gas is about 30%, which is significantly higher than 13% of a common conventional ICE vehicle (BAIN and Company, 2009). The adoption of EVs also has the advantage in reducing the gap between the peak and trough of a power grid’s load profile, which ranges from 40% to 50% of the daily electric power peak demand in Beijing and Shanghai (BDRC, 2006). The marginal power demand during peak-hours requires a large investment on grid infrastructure upgrade; whist the electricity generation redundancy at night causes a substantial waste. Taking Beijing as example, the gap between the city’s daily peak and off-peak power demand now is about 11 million kW and the potential electricity capacity during off-peak is 27 million kWh per day, which means that 1.5 million EVs with 0.2 kWh/km consumption can be accommodated through overnight off-peak charging without significant modification of the current power grid system (Liu, 2011). In addition, a mature EV charging/discharging configuration with V2G (Vehicle-to-Grid) technology is expected to further integrate the intermittent electricity generated with various renewable sources and balance the daily peak and trough load of the power grid. Finally, EVs could promote the development of whole

green energy industry chain and stimulate sustainable economic growth in China. The prosperity of the EV industry would stimulate the domestic battery manufacture industry. China is already the world's major producer and exporter of lithium batteries and electronic devices. Given the vast automobile market, EVs and associated battery and infrastructure industry could lead the development of China's entire low carbon industry.

As a result of the benefits described above, EVs have been regarded as the most promising AFV technology for future China's automobile industry development. China's R&D activities for EVs begin in the eighth Five-Year Plan (1991-1995), where the government set targets and directions for the country's economic development. The "EV technology research" was also firstly promoted as a national key scientific and technological project by the MOST (Chen, et al, 2003). In the following ninth Five-Year Plan (1996-2000), a "National Clean Vehicle Action" program was launched, where EVs were considered as the medium to long term vehicle technology option (MOST, et al, 1999). In the tenth Five-Year Plan (2001-2005), EV research projects were firstly included in the 863 program[3] that chose EV technology as the major AFV development pathway for China's automotive industry (MOST, 2002). In the 863 program, the "Three Transverses" (refer to three types of AFV – fuel cell vehicles (FCVs), hybrid electric vehicles (HEVs) and pure electric vehicles (PEVs)) and "Three Longitudes" (refer to three vehicle power-train

[3] China's 863 program is a national high technology development plan funded and administered by the government.

technologies – multiple energy power-train system, drive motor and power battery) R&D strategy were proposed for EV development (MOST, 2006). Then the eleventh Five-Year Plan (2006-2010) firstly investigated the commercialization potential of EVs (MOST, 2006b). During the tenth and eleventh Five-Year Plans, the MOST invested a total of 2 billion RMB in EV R&D activities via the 863 program (Wan, 2008). A R&D alliance that links universities (including Tsinghua University and Beijing Institute of Technology) and car manufacturers (including First Auto Works, Dongfeng Motor Corporation, Chana Auto Ltd, Chery and BYD) has also been created. Currently, 48 EV models have been officially allowed to be sold on the China's automobile market. Some EV models, including Chana Auto Xunjie HEV, BYD F3DM and E6, are already available in the private automobile market.

In March 2009, the State Council issued the "Automotive Industry Shaping and Recovery Plan" as one of the major components of national economy stimulus package during the global economic depression (State Council, 2009). The plan set an annual target of 500,000 EVs production capacity (including HEV, PHEV and PEV) and 5% AFV share of vehicle sales between 2009 and 2012. The plan included an investment of 10 billion RMB for the automotive technology development, including AFV RD&D activities, and finances AFV programs/projects (including adopting AFVs in public affairs, sanitary, post service, airport and public transport sectors) in the demonstration cities[4]. In addition, it firstly stressed the importance of EV

[4] There three groups of cities are selected for the AFV demonstration. The first group of demonstration cities includes: Beijing, Shanghai, Chongqing, Changchun, Dalian, Hangzhou, Jinan, Wuhan, Shenzhen,

charging infrastructure and improving the power grid capacity for EVs' charging demand. The plan chose EVs (including HEVs, PHEVs and FCVs) as the major type of AFVs to be deployed in the demonstration cities (MOF, et al, 2009), aiming to subsidize one thousand EVs development in each participating city in four years (2009-2013). The plan distinguished itself from previous EV development efforts as it is a critical transition from RD&D activities to actual EV implementation and mass production.

In 2009, the central government also introduced the "Automobile Industry Development Master Plan", where the new energy vehicles were officially proposed as the developing direction for the China's automobile industry (NDRC, 2009). A number of policies aimed at facilitating EV industrialization and commercialization were introduced, including pilot projects (MOST et al, 2009), standard announcements (MIIT, 2009) and purchase subsidies (NDRC and MOF, 2010). In the industrial sector, a group of car manufacturers have announced their EV models and mass production plans. In the local level, EVs have started to take a share in public transport and public service vehicle fleets due to the governmental support. Private sector action in six cities has been further implemented EV purchase subsidies with a maximum of RMB 60,000 per vehicle in the private car market. MOST predicted that the EV stock would exceed one million and the production cost of EVs would reduce

Hefei, Changsha, Kunming and Nanchang. The second group includes: Tianjin, Haikou, Zhengzhou, Xiamen, Suzhou, Tangshan and Guangzhou. The third group includes: Shenyang, Chengdu, Hohehot, Nantong and Xiangfan (Wu, 2009).

50% by 2015 compared with the 2010's level due to the improved battery technology (MOST, 2010). The production capacity of EV battery would reach 10 million kWh. There will be over 70 EV demonstration cities by 2015, and the total number of charging stations and charging posts will exceed 2000 and 400,000 respectively. Apart from the central government's targets, power grid companies and local governments have also released their EV charging infrastructure deployment plans (see Table 1).

Table 1 Scales of EV Charging Infrastructure

	Electric Vehicles	Charging Posts	Charging Stations	Battery Swap Stations
State Grid Corporation of China		6,209	75	
China Southern Power Grid		556	12	
Ministry of Science and Technology (2015)	1,000,000	400,000	2,000	
Accenture (2020 estimate)	100,000	200,000	1,000	200
Beijing (2012 plan)	30,000	36,000	385	
Hangzhou (2015 plan)	20,000	3500	38	145
Shenzhen (2015 plan)	150,000	227,500	84	
Tianjin (2015 plan)		1,000	13	128
Chongqing (2015 plan)		1,000	30	
Zhejiang (2015 plan)	100,000	20,200	115	738
Shandong (2015 plan)		3,000	166	540
Guangzhou (2015 plan)		80,110	54	
Henan (2015 plan)		77,800	220	
Nanjing (2015 plan)		600	30	
Changsha (2015 plan)	21,000	14,000	240	20
Hubei (2015 plan)		3,000	100	

Source: Sina, 2011.

EVs have large potential in reducing the petroleum fuel and carbon emissions levels, and various alternative fuel vehicle technologies have been promoted by the Chinese government. However, although EVs have been regarded as the most promising AFVs option in China, their development still faces many barriers, including the lifecycle

emissions concerns, the charging infrastructure inadequacy and high battery costs.

EVs have few tailpipe emissions during vehicle operation but may cause significant upstream emissions during fuel (electricity) and vehicle production. In China, the total installed power generation capacity has reached 793 GW and total electricity generation has reached 3.43 trillion kWh in 2008, of which coal-based thermal power accounted for 80.95%, followed by hydropower (16.41%), nuclear (0.65%) and others (0.65%) (CEC, 2008). The high proportion of coal in China's electricity mix results a large amount of carbon emissions for electricity generation, which could significantly reduce the overall greenhouse gas (GHG) saving potential of EVs. In order to measure the exact energy use and emissions from electricity generation to consumption, a life-cycle assessment of energy consumption and GHG emissions has become an essential measure that helps policy decisions and implementation (Jaramillo, et al, 2009). In addition to the energy feedstock, the energy consumption and GHG emissions from electricity generation and supply are also highly dependent on the generation technologies. For example, the energy conversion efficiency of a typical coal-based power plant with standard steam boilers in China is 34%, whereas the figure could reach 50% where the integrated gasification combined cycle (IGCC)[5]

[5] An Integrated Gasification Combined Cycle (IGCC) system converts coal to synthesis gas, and then combines a gas turbine (combusting the cleaned gas) and steam turbine (using the recovered hot exhaust gas from the gas turbine to boil water) to generate electricity. The system converts coal to synthesis gas and uses the cleaned gas to generate electricity. As China is one of the most active countries developing energy efficient combustion technologies and leading the research, development and demonstration pilot programs in the world, this study uses a relatively high prediction of IGCC penetration in 2020.

system is applied (Wang and Huo, 2009). There have been some analyzes on the life cycle of EV energy use in China (Ou X, et al, 2010a; Huo, et al, 2010; Ou X, et al). However, comprehensive analysis that combines the estimates for electricity generation mix with the driving profile features in China is still absent. The comprehensive lifecycle assessment for EVs in China would significantly facilitate the selection of low carbon vehicles for the country's road transport sector.

Moreover, the lack of charging infrastructure is another practical concern for the EV market diffusion. In contrast to conventional ICE vehicles that are refuelled via gas refuelling stations, EVs could be recharged at home, workplace or public places. Different charging methods would require different charging infrastructure with distinctive grid impacts and costs. The configuration of charging infrastructure will therefore directly influence the charging behaviour and charging impacts on the power grid. For example, recharging at home, particularly during the off-peak period overnight can enable EV drivers to use cheaper and lower carbon intensive electricity. Maximizing off-peak charging also makes the best use of currently available capacity of the power electricity (Department for Transport of the United Kingdom-DfT, 2011). In order to lower the negative impact of EV charging on the power grid, the grid-friendly charging behaviour should be encouraged via appropriate charging infrastructure deployment and intelligent charging management adopting information and communication technology (ICT). On the other hand, a certain scale of EV fleet could also provide substantial capacity needed for the power grid to better integrate

the electricity generated from various renewable sources. Therefore, to fully understand the potential for the charging infrastructure design and deployment, it is essential to investigate the current driving profiles and to discover the potential peak and off-peak of charging demand caused by the EV fleet. However, there are currently still few studies on the charging infrastructure for EVs in terms of the selection of charging infrastructure and their geographical distribution, and the potential different power grid impacts between diverse charging infrastructure configurations are still uncertain (Liu, 2011 and Liu 2012).

Furthermore, the high cost of EVs has been considerable and it is still a prominent barrier. EVs are equipped with expensive batteries resulting in a high total price for the vehicle. The continuous decrease of battery cost due to the technological progress and the relatively low electricity price compared with petrol and diesel means the cost of EVs would decline in the long run. However, EVs currently are still not able to compete with ICE vehicles in terms of cost. To reduce the high upfront cost of EVs, a series of innovative business operation models have been proposed, including battery leasing and vehicle leasing schemes. For example, the Better Place[6], cooperated with the car maker Renault, recently launched an offer for EV consumers in Demark with fixed-price packages based on kilometres driven (Better Place, 2011). The Better Place provides fixed monthly prices and home private charging spots for EV drivers. In China, vehicle manufacturers, including Zotye, Lifan Motors and Ankai, have also

[6] Better Place is an American-Israeli company that is one of the leading companies developing electric vehicle market and charging infrastructure.

launched their battery leasing proposals to stimulate EV sales (Li and Ouyang, 2010). Nevertheless, the selection of appropriate business operation models (combinations) and their potential in promoting EV market still requires further research.

This thesis therefore chooses four key aspects that determine EV development in China, namely EVs' lifecycle energy use and carbon emissions savings, EVs' driving profile and its impacts, charging infrastructure deployment and business operation models. More specifically, Chapter 2 reviews previous EV research and related literature. Chapter 3 refines the research aims and objectives of the thesis. Chapter 4 makes a general introduction of applied research methodologies. Chapter 5 conducts a breakeven analysis of low carbon vehicle/fuel systems for the US for the year 2020, taking into consideration both private and external costs, and Chapter 6 investigates potential energy use and GHG emissions savings based on the China's energy mix and driving profiles. Chapter 7 compares different EV charging infrastructure options and explores infrastructure deployment strategies according to their unique roles in the EV charging system. Chapter 8 focuses on the potential of business models in facilitating the early market penetration for EVs. Certainly, the future development of EVs also depends on many other factors, including benefits in creating employment opportunities and economic growth; the development of upstream energy industry and power grid infrastructure, and the battery cost reduction due to the battery technology progresses, as well as concerns in oil and car industry impacts and governmental tax revenue. These factors are introduced in Chapter 2.

1.2 Chapter Outline

Chapter 1 Introduction

The first chapter aims to build a research framework for the thesis and provide an overview of EV development status in China in a worldwide context. It disuses how the surging energy demand and climate change concerns would affect China's EV industry development. It also illustrates the potential benefits and main uncertainties of EV development at the current stage. Chapter 1 also highlights problems in EVs' energy consumption and carbon emission assessment, charging infrastructure deployment strategies and high battery and infrastructure costs. The Chapter also outlines the structure of the whole thesis.

Chapter 2 Literature Review

The literature review firstly summarizes the previous energy and environmental studies for China's EVs and reveals the current research gaps. This is followed by a discussion covering EV history, classifications, energy sources and the related industrial development in China. The chapter then makes a comparison between EVs and other low carbon vehicle fuel technologies and other low carbon transport management measures.

Chapter 3 Research Aims and Objectives

This chapter outlines research aims and objectives of thesis and explains roles of each objective in the whole study. The research objectives constitute of four main aspects including key determinants for electric vehicles: lifecycle energy consumption and carbon emissions of electric vehicles, EV driving profiles, electric vehicle charging infrastructure and business operation models. Each research objective is further developed in the individual chapters.

Chapter 4 Research Methodologies

Chapter 4 introduces research theories and methodologies applied in this research. As the thesis involves different research aspects, different research methods are applied. For example, the concept of neoclassical economic theory is adopted to estimate the user acceptance of different alternative fuel vehicle technologies and to compare the market potential of different business operation models. On the other hand, the geospatial optimization method is applied to build a spatial model that estimates the scale of EV charging infrastructure. Details of each research method are further discussed in corresponding chapters (Liu and Santos, 2009; Liu and Santos, 2010; Liu, 2011 and Liu, 2012).

Chapter 5 Decarbonising the Road Transport Sector: Breakeven Point and Consequent Potential Consumers' Behaviour

In Chapter 5, a life cycle assessment for energy consumption and carbon emissions of a number of alternative energy vehicles are conducted for the United States 2020 with

a breakeven analysis of each carbon vehicle/fuel system compared to the business-as-usual ICE vehicle, taking into consideration both private and external costs. The external costs associated with the whole fuel and vehicle lifecycles are converted to the monetary terms using the estimated social cost of carbon (SCC)[7]. Although some vehicle/fuel systems are not viable for 2020 due to the immature technology and high capital costs, others may have a chance if an appropriate set of economic incentives is implemented by the government to change consumers' choice, particularly under a life cycle perspective that considers the total cost savings during vehicle operation over the entire life of that vehicle.

The reason for including a chapter that refers to the United States rather than China is two-fold: (a) to estimate benefits from adopting different alternative technologies with a well-established database for the United States, and (b) to provide a comparison with China. The empirical study is done for the United States rather than China because all the necessary data and information is readily available for the United States. The basic objective of this chapter is to map potential pathways and identify the benefits and feasibility of each one. Although EV does not come out as a strong alternative for such a short-term scenario (less than 10 years), hybrid electric vehicles do, and these could be seen as a first step before the introduction of EV. This

[7] The SCC measures the full global cost today of emitting an additional tone of carbon now and sums the full global cost of the damage it imposes over the whole of its time in the atmosphere (Department of the Environment, Food and Rural Affairs, DEFRA, 2007, p.1)

conclusion, combined with the potential for use of electricity in road transport in China, led the author to focus on this technology for the rest of the thesis.

Chapter 6 The PHEV Potential for Urban Transport in China: the Problem of Energy Sources and Charging Behaviour

Chapter 6 investigates the lifecycle energy consumption and emissions of Plug-in Hybrid Electric Vehicles (PHEVs) for China in 2020 and undertakes a "Well-to-Wheel" (WTW) lifecycle energy consumption and carbon emission analysis using the GREET model. The analysis is based on China's energy mix, petrol and electricity production pathways and the observed driving behaviour in urban area from surveys. The study demonstrates the substantial potential of EVs in reducing energy consumption and GHG emissions in China, given the relatively short daily travel distances and expected industrial shift in energy industry. This benefit could however deteriorate if travel distances increased, which will happen as China's car ownership rises and vehicle operating costs go down.

Chapter 7 Analysis of Charging Infrastructure Assignment for the Preliminary Electric Vehicle Market in Beijing

Chapter 7 estimates the charging demand of a preliminary EV market in Beijing and proposes an assignment model to distribute the EV charging infrastructure. It concludes that the service radius of charging (or battery swap) stations directly influences the overall infrastructure assignment pattern, and in the early market with

limited charging demand, a short service radius will have a relatively small negative impact on the electric power grid. It also suggests an electric vehicle charging network that combines community charging posts and densely but small-size distributed battery swap stations.

Chapter 8 Establishing Electric Vehicle Charging Infrastructure and Associated Operation Models for Shanghai

As discussed in Chapter 7, the various charging options of EV offer a large potential to offset the current barriers through appropriate infrastructure deployment associated with corresponding business operating models to lower the initial capital costs. Chapter 8, therefore, estimates the EV growth in Shanghai and forecasts the charging infrastructure costs in different scenarios as well as the correspondent impacts on the city's power grid. The chapter further simulates the cost-benefits of some innovative business operation models.

Chapter 9 Conclusions

The final chapter summarizes the research findings from each chapter according to the research aims and objectives outlined in the Chapter 3. It stresses that the EV development in China must take place in parallel with energy industry upgrading, where more renewable sources should be adopted and take a larger share in the entire energy mix than the current level. The chapter also demonstrates some key issues that need to be addressed in the near term for the EV development. Some of these issues

are relatively new and need further investigation. The chapter finally discusses the research methods applied in the research and offers some recommendations for future research.

Chapter 2 Literature Review

2.1 An Introduction for EVs

2.1.1 The History of Electric Vehicles

The first EVs were made in the 1830s and used non-rechargeable batteries. With mass production of rechargeable batteries by the end of 19th century, electric vehicles became fairly widely spread. In the early 20th century, compared with their ICE or steam powered rivals, EVs' electric motor can be instantly started and was relatively reliable. By the 1920s, several hundred thousand EVs had been produced. However, due to the cheap oil and the invention of ICE self-starter[8], ICE vehicles became more attractive than EVs and eventually dominate the vehicle market (Larmini & Lowry, 2003).

Compared with EVs, an obvious advantage of ICE vehicles is the high energy density[9] of their petroleum fuels. The energy density of petroleum fuels for ICE

[8] An ICE self-starter is an electric motor used to rotate the ICE to initiate its operation. The ICE self-starter is regarded as the device that helped make ICE dominant technology.

[9] "Specific energy" means the energy stored per kilogram and is usually measured as watt-hour per kilogram (Wh/kg)

vehicles is normally more than 9000 Watt hour/kg, whereas the energy density of a lead acid battery is only around 30 Watt hour/kg. Even though the relatively low efficiency of the ICE, gearbox and transmission (typically around 20%) and high efficiency of electric motor (typically around 90%), the energy density of petroleum fuels is far higher than the that of lead-acid batteries which means electric vehicles need to be equipped with many large and heavy batteries to achieve a comparable driving range of ICE vehicles. Another drawback of electric vehicles is the long charging time. It usually takes several hours to fully charge an EV battery. In contrast, a 45 litre fuel tank can be fully refuelled within one minute. Although the high voltage direct current (DC) charger can be used to deliver rapid charging, which contracts the charging time to less than 1 hour, it is still considerably longer than refuelling an ICE vehicle.

Due to the disadvantages noted above, EVs have only been used in some niche markets, for example, electrical trolley bus, sanitary vehicles and golf carts. In recent years, with the increasing concern over global warming and oil peak, EVs have come to the attention of public, government and academia as one means by which transport can reduce its dependence on oil and improve its emissions. Currently, almost all big car manufactures have released their hybrid electric vehicles or pure electric vehicles. For example, Toyota introduced the world's first mass-produced hybrid electric vehicle - Prius in 1997 (Taniguchi, et al, 2001) which has become the world's best selling hybrid model. More recently, with the progress of lithium-ion technology, car

manufacturers have begun to introduce plug-in hybrid electric or pure electric models that are able to fully operate on electricity. For example, General Motors released the Chevrolet Volt, which integrates a 16 kWh lithium-ion battery and 1.4 L cylinder, in the United States market in 2010 (Chevrolet, 2011). In the meanwhile, Nissan Motors introduced the pure electric Nissan Leaf in the United States market. Nissan Leaf is powered by a 24 kWh lithium-ion battery and the maximum range reaches 175 km (NEDC[10]) (Nissan, 2011).

2.1.2 EV Classifications

For the convenience of the study, this research divides EVs into four classes: hybrid electric vehicles (HEVs), plug-in electric vehicles (PHEVs), pure electric vehicles (PEVs) and fuel cell vehicles (FCVs).

Hybrid Electric Vehicles (HEVs)

HEVs are currently the most common hybrid vehicles that combine an ICE with a battery, electric motor and generator. The electric power-train is applied to provide an improved fuel economy. There are two basic configurations for hybrid vehicles, the series hybrid and the parallel hybrid. In the series hybrid the driving force is entirely generated from the electric motor(s), whereas in the parallel hybrid configuration, the driving force is generated either from the ICE or the electric motor(s). The batteries of

[10] NEDC: The New European Driving Cycle is a driving cycle consisting of four repeated ECE-15 driving cycles and an Extra-Urban driving cycle (EUDC).

HEVs can be recharged by the engine and generator during the vehicle operation which reduced the required capacity of batteries. A common advantage of HEVs is regenerative braking, which enables the motor to perform as a generator while the vehicle is slowing down and the battery can be recharged from the energy generated. The mechanical power generated from regenerative braking is then converted to electricity by the generator and stored in the battery (Moreno, et, al, 2006). The electric motor converts the stored electric energy to mechanical power to assist ICE operation when additional power needed. For a HEV, the ICE provides most of the vehicle's power; electric motor provides additional power to assist low-speed operation, acceleration and passing. Therefore, HEVs are particularly suitable for urban traffic environment where acceleration, braking and stops are frequent, and so a higher fuel economy can be achieved by HEVs.

In theory, HEVs can adopt either conventional petrol/diesel or biomass-based fuels. Currently, HEVs with a petrol ICE are in the majority. Due to the introduction of electric drive, HEVs have a significant benefit in fuel economy and tailpipe emissions as compared with conventional ICE vehicles. From estimates of the Argonne National Laboratory (ANL) (Wang, 1999), the future electric cars would achieve a fuel economy about 3.5 times that of conventional petrol vehicles in the United States. The fuel economy of HEVs under ICE mode can be approximately 50% higher than the fuel economy of conventional petrol vehicles and the emissions can be about 20% lower on per mile basis. In comparison, a research by Thomas et al (1998) presented a

more moderate MPG improvement of 25% to 70% for natural gas-fuelled HEVs and 39% to 93% for diesel-fuelled HEVs.

HEVs are typically more expensive than conventional vehicles. However there are some savings can be made for HEVs. In the series hybrid configuration there is no need for a gear box, transmission can be simplified and the differential can be eliminated by using a pair of motors fitted on opposite wheels. In both series and parallel configurations, the conventional battery starter arrangement can be eliminated. There are a number of HEV models currently available on the market and HEVs have constituted a significant share in some regions' vehicle fleet. One famous example is Toyota Prius. Since it was firstly launched in 1997, Toyota has introduced three generations for Prius which topped the automobile sales in Japan 2010 (Japan Automobile Dealers Association, 2010) and the worldwide cumulated sales have reached 3 million units by 2011 (Ariel, 2011).

Plug-in Hybrid Electric Vehicles (PHEVs)

A plug-in hybrid electric vehicle (PHEV) has the ability to recharge its battery directly from the power grid. With a long range battery using external charged electricity, PHEVs could operate mainly on electricity and consume a minimal amount of petroleum fuel, and thus reduces tailpipe emissions during vehicle operation. Certainly, electricity is generated from various energy resources including coal, natural gas, oil and other renewable sources, and some of them involve a large

amount of upstream carbon emissions. Due to the higher requirement of electricity storage than HEVs, PHEVs face major obstacles of battery cost, volume and life. The high energy storage offers the longer electric driving range which not only determines the vehicle's performance in carbon emissions reduction but also its operating cost for consumers.

PHEVs can work in two operation models: charge-sustaining (CS) mode, in which the ICE works to recharge the battery and state-of-charge (SOC[11]) of the battery may increase and decrease over a driving cycle; charge-depleting (CD) mode, where the vehicle is powered by the battery only and SOC of the electricity storage system always decreases over a driving cycle. The total energy consumption benefit of a PHEV is the combination of the CS and CD mode operation (Markel and Simpson, 2006).

There are currently several PHEV models available on the market. General Motors released the PHEV Chevrolet Volt with 56 km all electric range per charge in 2010 (Plugincars, 2010). The Chevrolet Volt is also the worlds' top selling PHEV. In China, the car manufacturer BYD Auto launched the PHEV F3DM with 100 km all electric range per charge in 2008 (Balfour, 2008), and the vehicle has become publicly available since March 2010 (Edmunds, 2010). Furthermore, Toyota is scheduled to release the plug-in version of Prius – Prius Plug-in Hybrid in January 2012. The

[11] State-of-charge (SOC) of the energy storage system is the fraction of total energy capacity remaining in the battery

design is based on the third generation Totyota Prius (model ZVW30) and equipped with a 4.4 kWh lithium-ion battery (21 km maximum EV cruising range) produced by Panasonic (Toyota, 2011).

Pure Electric Vehicles (PEVs)

The concept of pure electric vehicles (PEVs), or battery electric vehicles (BEVs), is essentially simple. The power-train system of a PEV consists of an electric battery for energy storage and an electric motor to power the wheels. The battery is recharged directly from the power grid. The battery charging unit can either be carried onboard or fitted at the charging point. As with HEVs and PHEVs, the regenerative braking is usually applied by PEVs to recoup energy.

There is a range of PEVs currently available on the market. For example, the small electric bicycles and tricycles have already been widely seen in China since the early 2000s. PEVs have also been used in niche sectors for a long period, including golf buggies, delivery trucks and buses. However, due to the expensive and immature batteries technologies, PEVs currently only account for a small share in the private car market. The latest PEV models include Mitsubishi MiEV, BMW Mini E and Nissan Leaf. Because electricity is the only energy source to power the vehicle, PEVs typically have a battery with larger storage capacity than HEVs and PHEVs. Nissan Leaf, for example, is equipped with a 24 kWh lithium-ion battery which is about 5 times the capacity of that of Prius Plug-in Hybrid. In China, BYD auto introduced the

PEV E6 in Shenzhen (2011) after an 18-month taxi test in the city. The vehicle is equipped with a 48 kWh $LiFeO_4$ battery and the battery range reaches 300 km per charge (Ying and Stanley, 2010).

Fuel Cell Vehicles (FCVs)

Instead of using rechargeable batteries, FCVs use fuel cells to generate on board electricity to power the vehicle. The power-train system of fuel cell vehicles differs to conventional ICE vehicles and HEVs. Instead of an ICE, a fuel cell is used to generate electricity for vehicle propulsion. Fuel cell is a device that is able to directly convert the chemical energy contained in fuels and oxidants to electricity without combustion. However, normal fuel cells cannot store the electricity, and so a battery is also required. Compared with ICEs, fuel cells have following advantages: high energy efficiency, extremely low emissions, no vibration and compatibility with various potential fuels, including hydrogen, natural gas, petrol and methanol to generate electricity. For non-hydrogen fuels, such as natural gas, petrol and methanol, an extra fuel processor is required to produce hydrogen through reforming. The most promising on-board fuel cell for vehicles is proton exchange membrane (PEM) fuel cell (Brinkman, 2005). Based on the ANL's forecast (Wang, 1999), hydrogen-fuelled FCVs can achieve a fuel economy of 2.5 times of conventional petrol vehicles. For methanol-fuelled FCVs, the fuel economy is determined by the efficiency of on-board methanol processors. Although both steam reforming and partial oxidation reforming can be used to produce hydrogen from methanol, the steam reforming technology is a

relatively mature technology for vehicles. The recent development in partial oxidation reforming has indicated a potential for using other fuels such as petrol, natural gas, and ethanol to produce on-board hydrogen. However, reforming these fuels has more technological and cost difficulties than methanol (Feng, et al, 2003). Therefore, the fuel economy of FCVs fuelled with petrol, natural gas or ethanol via partial oxidation reforming will be a relative long-term option.

Many major motor companies have developed fuel cell powered cars. Honda, for example, released the first FCV - FCX in the United States to be registered as a zero emission vehicle with the Environmental Protection Agency (EPA) in 2002 (Larminie and Lowry, 2003). This four-seat vehicle has a top speed of 150 km/h and 270 km range. The hydrogen fuel is stored in on-broad high pressure tank. In addition, Daimler has developed a fuel cell car based on the Mercedes A series, equipped with Ballard[12] fuel cells that run on liquid hydrogen stored on-board.

2.1.3 Energy Sources for EVs

PEVs have zero carbon emission during vehicle operation (during all-electric mode for plug-in EVs). Their life cycle carbon emissions are all embedded in the well to pump (WTP) electricity generation stage. Among various types of power plants, those fuelled by residual oil, natural gas and coal produce carbon emissions at plant sites. Nuclear power plants do not yield onsite carbon emissions, but emissions are

[12] Ballard Power Systems is a PEM (proton exchange membrane) fuel cell manufacturer based in Canada.

generated along the upstream uranium production and preparation stages. Moreover, electricity can also be generated from hydropower, solar energy, wind and geothermal energy which have nearly zero emissions.

China has six interprovincial power grids[13] with are not strictly independent as they can purchase power from each other. Among these power grids, coal and hydro are the major energy sources though the split between them varies by region. The Northeast and North grids use more coal (95% to 98% of the total generation), while more than 22% of the Northwest, Central and South generation comes from hydro power. In addition, unclear power constitutes 5% power generation in the South and East grids (National Statistics Bureau, 2009).

For different types of electricity feedstock, a range of combustion technologies can be used: residual oil-fired plants usually use steam boilers, while natural gas-fired power plants apply steam boilers, conventional gas turbines and advanced combined-cycle gas turbines. According to the Spath and Mann's (1999) research in lifecycle assessment for coal-fired power plants, the plants with utility boilers and integrated gasification combined cycle (IGCC) turbines have obviously low emission levels. IGCC, firstly demonstrated in 1980s, is able to recycle the heat produced along with the electricity generation process. However, although IGCC technology generates extremely low emissions, the capital cost of the infrastructure is still high.

[13] The six provincial power grids include Northeast China, North China, Central China, East China, Northwest China, and South China

Coal plays the dominant role in China's electricity mix, with coal-fired power plants having accounted for more than 97% of total thermal power capacity and 80% to 83% of total electricity generated since 1990 (CEC, 2008; Chen and Xu, 2009). In recent years, advanced clean-combustion technologies for the coal-fired power plants come to the attention. Although at present, there are still many small and low efficient power plants in China, the super-critical plants (the capacity greater than 600 MW) have been the dominant type of newly installed. Also, the first IGCC unit with the capacity of 250 MW has started operation in 2011 (Xu and Jia, 2011).

Although currently coal is the dominant source of electricity supply, China has ambitions to rapidly increase the power generation from renewable sources. The National Energy Administration (NEA) has launched the national renewable and nuclear targets for 2020 with 150 GW of installed wind capacity, 20 GW of solar, 380 GW of hydro and 80 GW of nuclear as the means by which increase non-fossil fuel energy to 15% of the total primary energy consumption by 2020 (IEA, 2011). It means wind and solar energy should increase 12.5 GW and 2 GW per annum to 2020. Since the enactment of the Renewable Energy Law in 2005, the renewable industry, particular for wind power, has developed rapidly. By 2009, wind power has accounted for 1.8% of the country's total installed capacity and provided 0.7% of total power supply (MIIT, 2010; CEC, 2010). In 2010, a wind farm project with 3.8 GW generation capacity was built as the first stage of a 10 GW project. The government is

pursuing wind energy development with the same effort they delivered for hydro power. It added 13 GW to total capacity (5.5 GW in Inner Mongolia) making the country the world's largest wind power installed capacity (Financial Times, 2010).

However, variable renewable energy poses challenges to the power system operator. Because electricity cannot be stored on a massive scale in an economic way, the system operator has to balance the power supply and demand all the time to maintain system stability and power quality. The interruptions caused by the mismatches between supply and demand could cause an operation failure in power system. Conventional power plants are powered by coal, oil or natural gas so that offer steady and predictable input for the grid. However, wind and solar plants' output is intermittent and difficult to be accurately predicted or schedules. A major proportion of renewable energy in the power grid could be a potential challenge for the system operator to coordinate the demand and supply. In Inner Mongolia for example, wind energy has already provided 6TWh of electricity in 2009 taking 6% of the total electricity generation in the region (Economic Observer, 2010). To smoothly integrate renewable energy to the power grid, the current power industry needs to improve its power generation, interconnections, transmission and distribution, storage, as well as demand side management. The distributed generation, which generates electricity from small energy sources and avoid the integration to the main grid, would be a solution for renewable sources. However, the introduction of distributed generation requires a competitive electricity market, which is dependent on the successful market

reform of China's energy industry.

On the other hand, the development of EV industry is expected to accelerate the electric power demand growth in China. The annual increase of electricity consumption was 13.5% from 2000 to 2007 (National Statistics Bureau, 2008) and is estimated to remain 5% from 2010 to 2030 (Development Research Centre of the State Council of China, et al, 2009). The increasing power consumption is driven by the growth of industrial, residential, commercial and transport demand. However, despite being one of the demand forces in China, EVs would not be a prominent electricity consumer compared with other sectors. According to the electricity generation projections in China (EIA, 2007 and IEA, 2007), the spare capacity of newly built power plants in China would be able to meet the EVs' demand in a medium term. Even with under the aggressive EV growth scenario, EV would not produce marginal effects on power generation capacity (Huo, et al, 2010).

In addition to electricity, hydrogen has long been projected as a promising alternative vehicle fuel for both FCVs and ICE hydrogen vehicles. Hydrogen is non-toxic and its flames are invisible and smokeless. At present hydrogen is mainly produced from natural gas through steam methane reforming (SMR) process, water electrolysis or coal gasification (producing a large amount of CO_2). The combustion of hydrogen only produces water and a low level of NO_x without carbon emissions. Hydrogen can be used as fuel for both ICE and fuel cell batteries. However, hydrogen storage and

refuelling for automobiles are the major barriers for the hydrogen vehicle development and the distribution of hydrogen through pipelines is thus required.

In addition to natural gas reforming, the hydrogen can also be obtained through water electrolysis. As hydrogen production requires a large amount of electricity, this production pathway could be economically feasible where electricity is cheap. An extensive electricity distribution system is already established and emission intensity of electrolysis highly depends on the energy source from which the electricity is generated. In China today, electricity is mainly generated from coal, natural gas and renewable sources such as hydro-power and wind. Over the last decades, the energy efficiency of many fossil fuel power plants has been improved by low-polluting combined-cycle turbines. However, due to the price of natural gas and substantial coal resources, coal-fired power plants still take the majority of electricity generation sources in China.

It can be found that different types of EVs are currently under different development stages. At present, HEV technologies have been relatively well developed and widely applied by many car manufacturers. The price of HEVs currently is also comparable with that of their ICE counterparts. Given the significant improvement in fuel economy, HEVs are more likely to bring an overall cost saving than a conventional ICE vehicle over the vehicle's lifecycle. However, HEVs are still entirely powered by petroleum fuel, hence still lead to vast oil consumption and GHG emissions. For

FCVs, the fuel-cell technology is still under the R&D stage and requires a long period to reduce its cost for commercialization. Currently, hydrogen's transport and distribution are remarkable barriers for FCV development. In contrast, due to the ability to directly use electricity from the power grid and relatively well-developed battery industry, both PHEVs and PEVs have large near-term market potential while reducing vehicles' oil consumption and carbon emissions. The development of PHEVs and PEVs are currently still impeded by the battery's low capacity and high cost, as well as the lack of charging infrastructure.

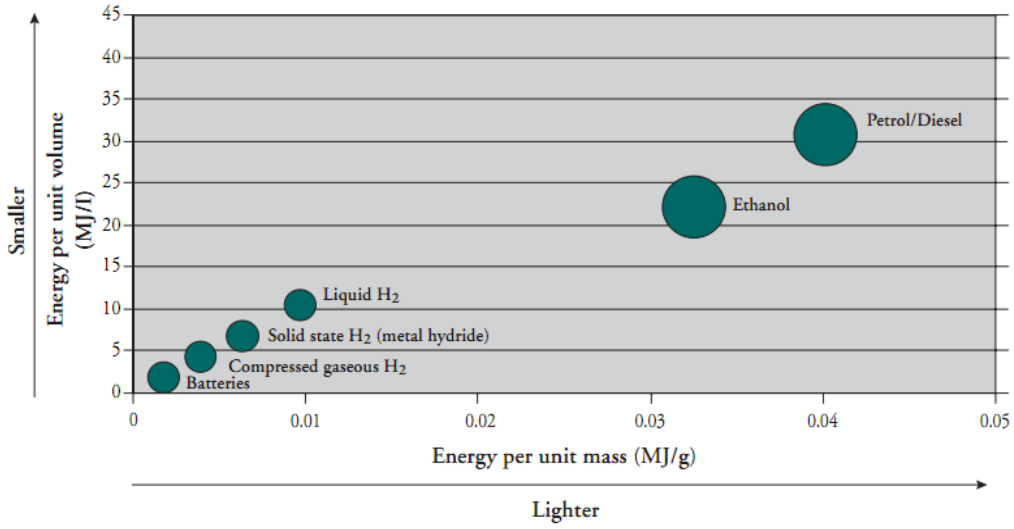
2.2 EVs and ICE vehicles

Currently, ICE vehicles are dominant in the road transport sector and constitute almost worlds' entire automobile stock. The modern automotive industry, which is formed by ICE vehicles, has also developed a well-established upstream petroleum fuel industry and modern automobile culture. To achieve a market commercialization, EVs have to be comparable or even superior to ICE vehicles in terms of performance, cost and convenience. This section makes the comparison between ICE vehicles and electric vehicles from different perspectives.

ICE vehicles running on petrol and diesel fuels are the dominant vehicle technology in China's automobile and fuel markets. Compared with alternative fuels, petrol and diesel are energy dense, easily storable, non-corrosive and inexpensive. After decades

of development, an efficient industrial chain of fuel production, distribution and use for petrol and diesel has also been formed. Over the last century, ICE vehicles have continuously improved their performance, comfort and safety. More importantly, with the rapid growth of automobile market and mass production, the manufacturing costs of ICE vehicles has been effectively reduced, and this in turn has encouraged vehicle production and it has facilitated the rapid growth of vehicle ownership. Cars have also become increasingly reliable and incorporate more safety and convenience features, such as airbags and air conditioning.

Figure 2 Energy Density of Alternative Vehicle Fuels

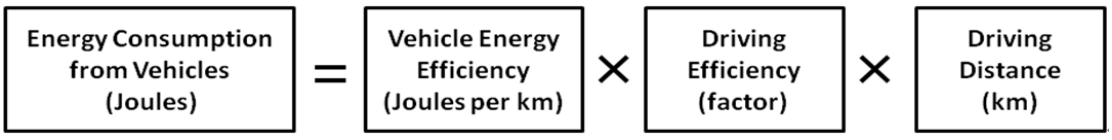


Source: King Review, 2006

Figure 2 shows that both petrol and diesel fuels have higher volume-energy and mass-energy density compared with other alternative vehicle fuels. Fuels with high energy density are appropriate for vehicle use due to high energy conversion efficiency. Furthermore, car manufacturers have gradually improved the fuel economy

of automobiles responding to the pressure of high fuel costs. The improvement of vehicle fuel economy has effectively reduced the vehicle emissions. Although the total vehicle fuel consumption is decided by the fuel economy of engine, driving behaviour and driving distance, the fuel economy of engine has been regarded as the key factor that decides the vehicle fuel economy (see Figure 3). In spite of the trend of pursuing larger and more powerful vehicles, the average fuel efficiency and carbon emissions of ICE vehicles have gradually improved. A range of technologies have the potential to further improve the environmental performance of vehicles, such as the fuel economy improvements in current engines, better power-train technologies and the adoption of lightweight materials. Many technologies have been applied by some car manufacturers and some are expected to appear in the near future ICE automobile market, such as start-stop and direct injection.

Figure 3 Automobile Energy Consumption Factors



Increasing the fuel efficiency of the conventional ICE is regarded as a direct pathway to achieving reduced fuel use and emissions savings. Conventional ICEs are relatively inefficient in energy conversion during vehicle operation and particularly in the urban traffic environment, where engines work at a relatively low power output and cannot

operate at an optimum condition. ICE engines usually have a most energy efficient operating mode at an optimal speed but cannot fully adapt the variable driving environment in an energy efficient way. A large amount of chemical energy stored in fuels is wasted and generates worthless thermal energy. In addition, compared with electric vehicles with battery and electric motors, ICE vehicles produce a substantial volume of noise and harmful emissions, including sulphur dioxide, oxides of nitrogen and particulates. However, a number of vehicle technologies hold out the prospect of significantly improving the engine efficiency and mitigate the pollutions of ICE vehicles. These include stop-start technology, direct injection, variable valve actuation (VVA), boosting (turbo/supercharging), downsizing, regenerative braking and electrical motor assistance.

Start-stop

A start-stop system automatically shuts down and restarts the ICE during the idling time, hence reducing the fuel consumption and tailpipe emissions. The effect is particularly significant when the vehicles travel in a congested traffic. The start-stop technology was firstly tested since 1970s by Toyota, which installed a primary start-stop model for their Crown sedan (Dunham, 1974), and tests showed the vehicle achieved a 10% improvement in fuel economy under the urban traffic. This technology currently has been widely applied in both hybrid electric vehicle and conventional ICE vehicles, and the fuel economy improvement typically ranges from 5% to 10%.

Direct injection

Direct injection, is a fuel injection technology that applies lean-burn principle to mix fuel with air in ICE to improve the fuel combustion efficiency in the engine. Via this technology, the petrol is highly pressurized and injected via a common rail fuel line directly into the combustion chamber of cylinders, rather than the port fuel injection where the fuel is injected in the cylinder port. This technology can improve fuel efficiency and power output due to the precise control of injected fuel volume and injection timings that vary according to driving load conditions. Direct injection was invented by Swedish engineer Jonas Hesselman in 1925. After decades of development, this technology has been applied by almost all major car manufacturers and each of them has a series of direct injection vehicle models. The average fuel efficiency improvement from the direct injection can reach 10% to 13% (King, 2006).

Variable Valve Actuation (VVA)

VVA is a mechanism that changes the timing and duration of a valve lift event in an ICE, which has a significant effect on the engine's performance. A VVA system controls valve events to balance the engine's power, torque and fuel economy according to the driving loads. The first VVA timing system was applied on steam engines in 19th century and then introduced to automobile market in 1960s. Currently, a number of car makers, including BMW, Fiat, Mitsubishi and General

Motors, have their VVA patents and devices equipped on their vehicle models. The common fuel economy improvement by a VVA system ranges from 5% to 7%.

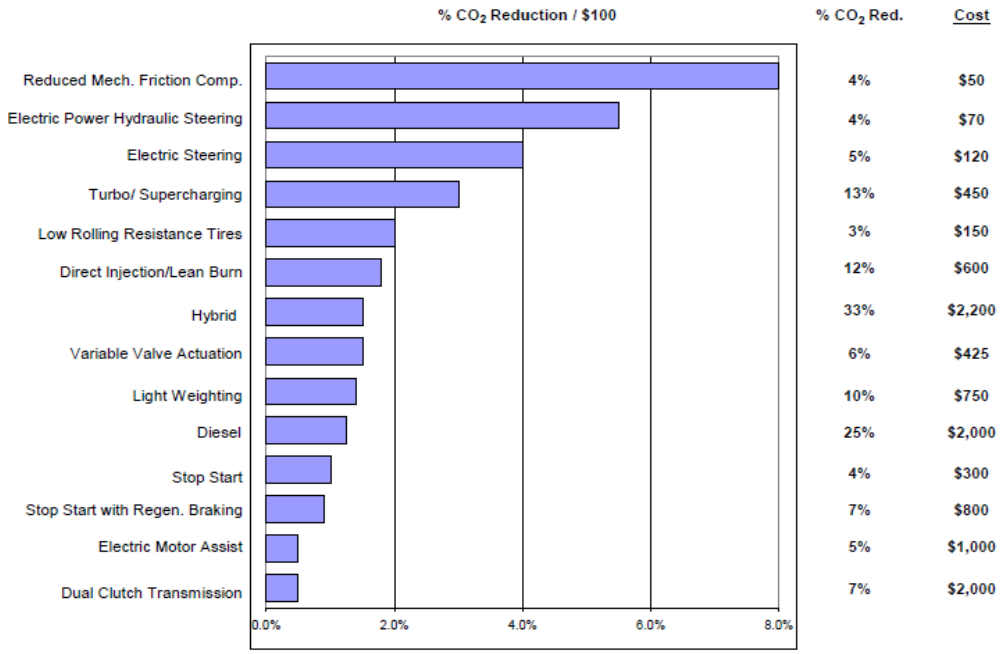
In addition, there is also a series of non-propulsion vehicle options, including lightweight materials, advanced aerodynamics and low rolling resistance tyres, to improve vehicle's fuel economy. Despite a relative low energy and emission saving compared to advanced engine technologies, they need much less power-train upgrading work and cost.

The propulsion and non-propulsion technologies above are already available in the market and expected to further improve the fuel economy and CO_2 emissions in the next decade. Vehicles can also apply combinations between different technologies to achieve an aggregated benefit. For example, direct injection may also be accompanied by other engine technologies, like VVT.

From Figure 4, it can be found hybrid and diesel technologies could offer the most significant reduction in CO_2 emissions (33% and 25% respectively), followed by turbo/supercharging, direct injection/lean burn and light weighting which can achieve over 10% CO_2 savings. In terms of cost-efficiency, reduced mechanical friction components, electric power hydraulic steering and electric steering top the list. Most technologies and measures recommended in Figure 4 have been introduced by car manufactures though the introduction varies by region. For example, VVA and hybrid

technologies are relatively more applied by Japanese car makers while diesel and turbo charging are often adopted by the vehicles in Europe where diesel fuelled vehicles account for about 50% of overall vehicle fleet (IEA, 2006).

Figure 4 Technologies for Improved Fuel Economy and Reduced CO2 Emissions

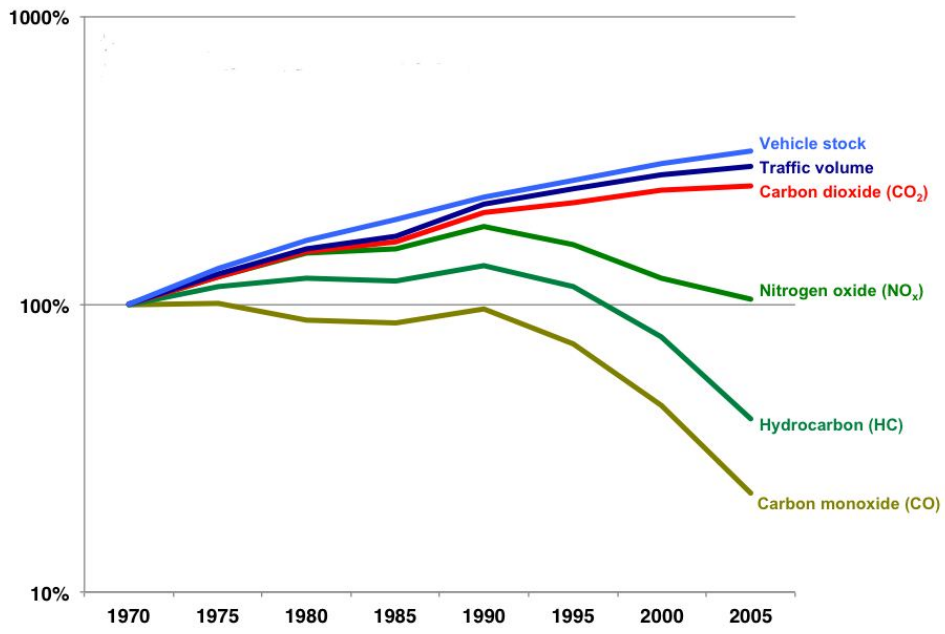


Sources: King Review 2006, Deutsche Bank and NHTSA (United States National Highway Traffic Safety Administration)

The gradually tightening of vehicle emission standards has also played an important role in reducing ICE vehicles tailpipe emissions. For example, both the total vehicle number and traffic volume (vehicle kilometres travelled per year) have tripled in Western Europe between 1970 and 2005. However, the correlation between traffic volume and the level of emissions on the road has shown a decoupling pattern. According to OECD statistics with recent data from the Emission Database for Global

Atmospheric Research (EDGAR) project, NOx emission followed the increasing trend with traffic volume until the middle of 1980s. Motor vehicles' NOx emissions were first regulated in the Europe in 1977 and emissions were significantly lowered when the Euro 1[14] stage was introduced in 1992. From 1990, a downward trend in NOx emissions can be observed, which corresponds with the tightening emission standards (see Figure 5). Vehicle HC and CO emissions were regulated earlier than NOx. In Europe, the regulation of passenger car emissions of HC and CO emissions started in 1970s and the permitted levels have been reduced since then (European Commission, 2012).

Figure 5 Vehicle Emissions in European OECD Countries



[14] European Emission Standards regulate the emissions of new vehicles sold in the member states in Europe Union. The legal framework consists in a series of directives that define the vehicle emissions. There have been released six standards since 1992 (Euro 1 to Euro 6) and the latest Euro 6 will come into force in 2014.

However, the CO_2 emission from road transport has steadily increased, and this closely follows the growing profile of traffic volume and directly links to vehicle fuel consumption. In 2009, the European Union passed a law requiring the motor vehicle fleet to reach an average of 120 g/km by 2012 (United Nations Environment Program, UNEP, 2012; European Federation for Transport and Environment, T&E, 2010). With more emission standards in place, CO_2 emissions from the road transport could be decoupled from the traffic volume, as has been the case for NO_x, HC and CO.

With continuous demand in energy efficiency improvement and increasingly stringent emission regulations, the conventional fuel efficiency technologies for ICE vehicles will be not enough to achieve future fuel economy and tailpipe emission standards. Compared with ICE engines, electric motors simply convert electrons to mechanical energy with much higher energy conversion efficiency.

The fuel savings potential of HEVs is largely dependent on the extent to which it can operate on electric power. This, in turn, is typically limited by the capacity (energy and power) of the battery. At present, HEVs can be divided into three classes, namely micro electric hybrid, mild hybrid electric and full hybrid electric vehicles. Micro hybrid electric vehicles stop the operation of the power-train during an idle period and the engine only operates at a minimum load to power vehicle ancillaries. The engine can instantly start after the idle by which provides 5%-10% fuel saving. Mild hybrid electric vehicles are able to capture the energy loss through regenerative braking. The

captured energy is stored in batteries and then provides additional power during vehicle acceleration, achieving fuel efficiency gains ranging from 10% to 20%. Compared with micro and mild hybrid electric vehicles, full hybrid electric vehicles are able to operate purely on electric energy and batteries provide all required power for relatively low load and low speed driving environment. The consequent energy efficiency improvement from this configuration ranges from 25% to 40%. HEVs combine at least two energy sources (fuel and electricity) and a computer aided power flow control system is provided to balance the operation between an ICE and electric motors to achieve an improved operation efficiency and fuel economy. With the help of electric motors and power batteries, a typical HEV is able to downsize the ICE and switch between the engine, the electric power-train, or running both in order to achieve a maximum power output. The energy saving potential for hybrid electric vehicles should attribute to the complementary energy efficiency curves between ICEs and electric motors. A conventional ICE usually functions at low efficiency (5%-10%) when the vehicle is running at a low speed and in congested conditions. Whereas in high speed and high power demand environment, an ICE can operate at a full throttle and the fuel efficiency can be largely improved to 28%. For ICEs using diesel fuels, the optimal energy efficiency can reach 33%, but their energy conversion efficiency is also significantly lower in a low speed environment resulting in an average 23% fuel efficiency. However, as more vehicles run in the urban environment, this results in low overall fuel efficiency.

In contrast, electric motors are able to produce a high torque when the vehicle starts and have a relatively flat efficiency curve until they reach a high speed. Therefore, the dual power-train configuration of hybrid electric vehicles with both ICE and electric motors has the capacity of enabling the use of the electric power-train at slow speed, and shifting to the ICE at high speed, correspondingly maximizing the fuel efficiency for the vehicle as a whole. For example, the fuel economy of Toyota Prius 2011 version can reach 50 MPG (EPA estimated) that is significantly higher than that of current ICE vehicles (Toyota Prius, 2011).

Plug-in Hybrid Electric Vehicle (PHEV) technology builds upon the experience of HEV technology. The battery capacity of a typical PHEV is usually 5 to 10 times larger than that of an EV but less than 1/4–1/3 of that of a typical PEV (Tate, et al, 2008). Due to the reduced size of the battery, PHEVs cost relatively less than battery electric vehicles, while providing all-electric operation for short-range driving and electricity-petroleum hybrid operation for long-range driving. On the other hand, PHEVs have greater electric storage capability than HEVs. They are characterized by the ability of charging the vehicle with electricity from the power grid, which allows PHEVs to run purely on the electric energy generated from power plants. Because many urban drivers have a driving pattern with a short daily driving distance, the all-electric driving capacity of PHEVs can accommodate a large proportion of people's overall driving demand, and hence to effectively reduce the petrol and diesel consumption accordingly. In contrast to the HEVs that produce electricity from fossil

fuels through generators, the electricity consumed by PHEVs for short driving ranges is obtained from the power grid, which indicates a zero emission for the vehicle operation stage. For longer distances, PHEVs would function as full HEVs powered by the ICE and electric motor. All-electric ranges of a typical PHEV in the current market can offer 20 km to 40 km driving per charge. The overall fuel economy improvement of PHEVs is expected to reach 40% to 65% compared with that of conventional ICE vehicles and the improvement could be greater for those driving in urban conditions.

Instead of a dual power-train system of PHEVs, battery electric vehicles only have an electric power-train system consisting of a power battery module and electric motors. Therefore, a PEV fully relies on the electricity from the power grid and delivers zero tailpipe emissions during the vehicle operation stage. In contrast to an ICE vehicle, the power-train system of a PEV has relative few moving parts and is more reliable. As discussed above, the electric motors can deliver high torque at low speeds, and provide an improved driving experience for drivers. PEVs highly rely on the deployment of charging infrastructure network. The latest Nissan Leaf released by Nissan is equipped with a 24kWh battery package and the maximum range per charge is 160km. Despite representing the high level in the EV market, it is still much less than the ICE vehicles' driving range which is usually higher than 500 km per refuel. As a result, PEVs may involve a high frequency of high charging behaviour and need a reliable charging infrastructure network.

The rapid market penetration of EVs depends on the high energy density, cost effective and reliable batteries. Different to ICEs, the energy storage capacity of a battery is usually measured in kilowatt hour (kWh), and the EV driving range and performance are determined by the battery's energy density that indicates the amount of electricity stored per unit of mass or volume of the battery. The performance of automotive batteries is also measured in terms of their power density (kilowatts per kilogram) and energy density (kilowatt hour per kilogram). For different types of EVs, the battery requirement would differ. HEVs need high power density batteries to cope with the relatively high power demand during starting and accelerating, whereas PEVs need high energy density batteries for long driving ranges.

To provide a comparable driving performance to ICE vehicles, many battery types have been tested and applied by EVs. The conventional EVs usually use lead acid batteries which are the most widely available and least expensive option. However, the energy density of lead-acid batteries is low and a typical EV powered by a lead-acid battery usually has a range less than 80 km. It means that lead-acid PEVs cannot offer enough performance capacity for the distances people drive. Therefore, in the current EV market, HEVs are usually equipped with nickel metal hydride (NiMH) batteries, for example the Toyota Prius and Honda Civic Hybrid.

In general, NiMH batteries have a lower environmental impact than lead-acid

batteries and they do not contain toxic substances. Most nickel can be recycled due to its high market value. NiMH batteries have larger electricity storage capacity than that of lead-acid batteries, while providing a reliable and high discharging power output. The expected life of NiMH batteries is long. However, NiMH batteries are more expensive and heavier than lead-acid batteries. The energy conversion efficiency of NiMH batteries is still relatively low because of heat generation during the operation. Another obvious drawback of NiMH batteries is a significant self-discharging and capacity degradation effect, if the batteries are over charged or discharged.

Among various battery chemistries for EVs, lithium-ions have been regarded as the most promising option. Lithium is a non-toxic element with high energy density and it contains the lightest metal. Nearly all of the latest projections of EV manufacturers show lithium-ion batteries will be the mainstream for their EV models, including the latest models by Toyota, Nissan and Tesla. Some car manufacturers have further released their battery production plans, including the joint companies between General Motors and LG Chemical (Brooke, 2011), as well as Toyota and Panasonic (Kassatly 2010). Because of the high energy density, lithium-ion is the preferable material to produce EV batteries. A typical 300 kg lithium-ion battery model for an EV offers more than 150 km range. Lithium materials are also less expensive than nickel and they have a low self-discharge rate of approximately five per cent per month compared to 30% per month from nickel-metal hydride batteries (Scrosati and Garche 2010). To ensure the life of a lithium-ion battery, it should be charged at a

regular and frequent basis and should never be depleted below their minimum voltage and operate in a cool environment. The lithium element exists as lithium carbonate (Li_2CO_3) in the natural environment. Currently, a large amount of lithium is produced from salt lakes in Chile (55%) and Argentina (16%) (Grosjean, Miranda et al. 2012). With regarding to lithium reservoir, the distribution largely concentrates in Chile, Argentina, China and United States. A large scale of lithium resource exploration is under progress in China, which is projected to boost the global lithium production in the near future. At present, lithium is mainly used to produce Li-Ion batteries for consumer electronics and power tools, lubricating greases, and ceramics (Kennedy, Patterson et al. 2000). With the expected growth of the EV market, the world lithium demand will remain at a high and increasing growth rate, driven almost exclusively by the EV market.

Table 2 Battery Technology Summary

Type	Energy	Power	Voltage/cell	Electrode	Electrolyte	Price	Manufacturer	EV model
Lead-acid (VRLA)	35Wh/kg	200W/kg	2V	PbO2	Pb	150$/kWh	GS, Hawker, Johnson Controls, Panasonic, Sonnenschein, Trojan, YUASA	Chrysler Voyager， Citroen C15, Daihatsu Hijet, Ford Ranger, GM EV1, Mazda Bongo Friendee, Mercedes-Benz MB308, Puegeot J5, Suzuki Alto, US Electricar, Volkswagen Citystormer.
Ni-Cd	56Wh/kg	225W/kg	1.2V	Ni	Cd	300$/kWh	Saft, VARTA	Chrysler TE Van, Citroen AX, Mazda Roadster, Mitsubishi EV, Peugeot 106, Renault Clio, HKU U2001.
Ni-Zn	60Wh/kg	300W/kg	1.6V	NiOOH	Zn	200$/kWh	YUASA & Kyushu	
Ni-MH	60Wh/kg	200W/kg	1.2V	NiOOH	Metallic	275$/kWh	GM Ovonic, GP,	Toyota Prius

					Oxide		GS, Panasonic, SAFT, VARTA, YUASA	
Zn-Air	180Wh/kg	96W/kg	1.2V	O2(Air)	Zn	105$/kWh		Mecedez-Benz 180E
Al-Air	250Wh/kg	7W/kg	1.4V	O2(Air)	Al			
NaS	170Wh/kg	390W/kg	2V	NaS	Na	350$/kWh	General Electric, Prudent Energy, Sumitomo Electric	
Na-NiCl2 (Zebra)	86Wh/kg	150W/kg	2.5V	Chloride	Na	290$/kWh	AEG Zebra	Mercedes Benz 190E
Li-Polymer	155Wh/kg	315W/kg	3V	Vanadium Oxide	Li		3M	

Li-ion	120Wh/kg	260W/kg	4V	Lithium oxide	Li-C	200$/kWh	GS，Hitachi，Panasonic，SAFT，SONY，VATRA，A123, BYD, LG-Chem, Nissan -NEC, MGL	Nissan Leaf, BYD F3DM, BYD e6, BMW Mini E, GM Chevy Volt
V (Vanadium, VRB)	15-25Wh/kg						Sumitomo Electric, Prudent Energy	

Sources: Larminie and Lowry, 2004; Wu, J.A and Wu.Y, 2009

A list of current available battery technologies for EVs is summarized in Table 2.

In conclusion, although the cost of advanced fuel efficient ICE vehicles is relatively low, EVs have a clear advantage in energy conversion efficiency during the vehicle operation stage. China has already developed a vast battery market that is expected to facilitate future EV growth. Compared with other battery technologies, lithium batteries are regarded as the most promising option in the current EV market. China also has a reserve advantage of plentiful lithium resources, which could accommodate a large amount of EV production.

2.3 Key Determinants for Electric Car Development

Section 2.2 has shown the market penetration of EVs and the competition from ICE vehicles. The successful electrification of road transport further depends on a range of factors, including environmental consensus, charging infrastructure provision, driving profile characteristics, and the economic implications. Each factor plays a decisive role in the transition process from ICE vehicles to EVs. For example, when it comes to the clean energy or alternative fuels for the road transport, the advanced vehicle technologies are always stressed and focused. It should be noticed that the technological break-through is critical for the commercialization of new energy vehicle. However, there are also a variety of other elements that also influence the

transition process. Moreover, a lot of these elements are also closely interrelated, and for a comprehensive study of road transport electrification, it is important to have an overview of all these key elements and their relationships. Therefore, this section aims to outline the key determinants for the EV development and explore their potential links.

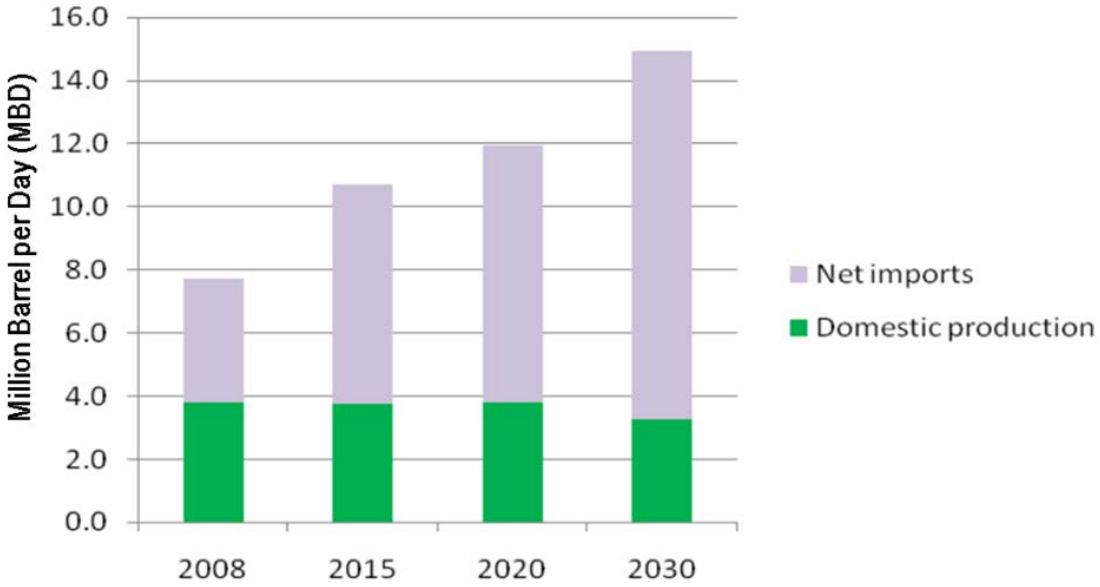
2.3.1 Energy and Environmental Benefits

The fast economic growth leads to a vast amount of energy consumption. China's current economy is dominated by energy-intensive raw materials production, manufacturing industries, and public infrastructure/construction projects, which drive the substantial energy demand. In 2009, China has already become the worlds' largest automobile market and the growing fleet of private vehicles further stimulates the petroleum demand. According to IEA research, almost 50% of global oil demand growth in the next 5 years will stem from China (IEA, 2010). In the IEA's World Energy Outlook 2010, China is expected to import 79% of the oil it consumes by 2030.

In contrast to the surging demand, the oil fields in China are aging. The reserves-to-production ratios are low and the domestic oil production is approaching the peak. China therefore has to increasingly depend on the international oil market to meet its fast growing demand. Since 1993, China has become the net oil importer and

the import oil share has continuously increased. The gap between import and domestic production would extend due to the limitation of domestic feedstock (see Figure 6).

Figure 6 Long Term Estimate of China's Oil Production and Imports

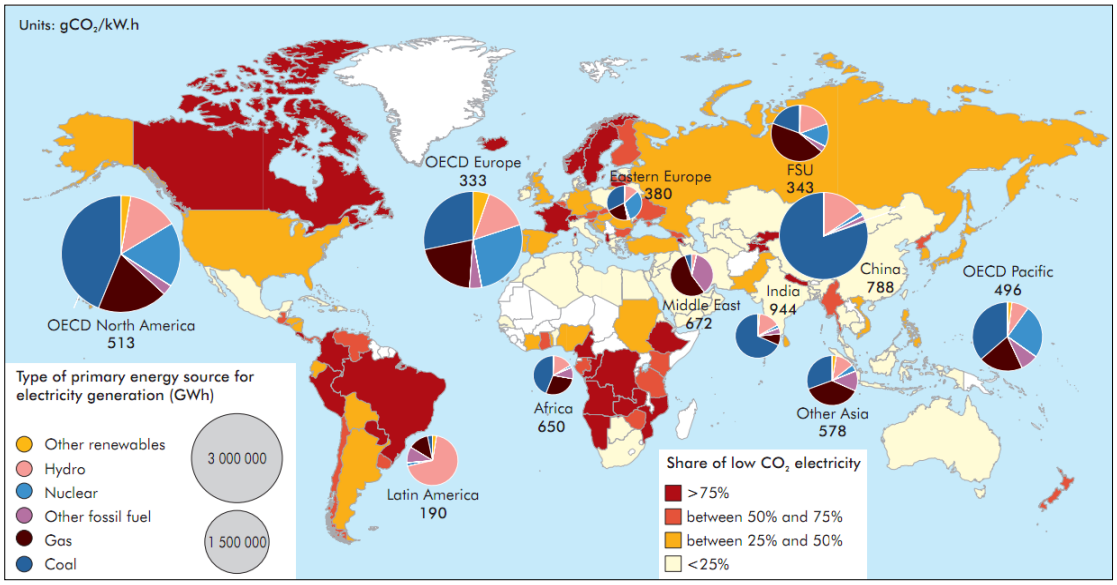


Source: IEA, 2010

As many other countries in Asia, China relies on oil imports from Middle-East region, which supplied 47% of total oil imports in 2009 (Xinhua News Agency, 2010). In 2009, the top ten crude oil suppliers to China were Saudi Arabia, Angola, Iran, Russia, Sudan, Oman, Iraq, Kuwait, Libya and Kazakhstan. The high dependence of import oil threatens China's domestic energy securities and become an unstable factor for the country's economy. Figure 7 outlines the electricity generations by energy source in different countries. It shows the electricity generations in China largely rely on coal

(80%), followed by hydro-power. Other fossil fuels (oil and natural gas) and renewable sources (biomass-based fuels, wind and solar) together only provide about 3% of total power generation.

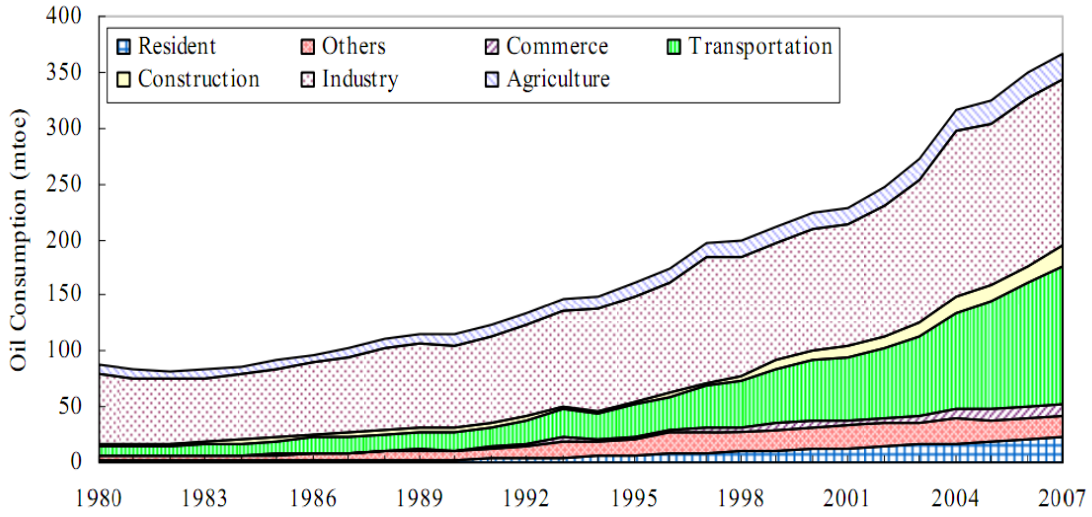
Figure 7 Electricity Generations by Energy Source, 2006



Source: Transport, Energy and CO2, IEA, 2006

Industry and transport are the main oil consumers in China, and these together take 74.7% of China's total oil consumption. The industrial oil proportion has continuously declined from 70.1% to 40.1% from 1980 to 2007, but transport has the highest oil consumption increasing rate among all the different sectors (from 10.4% to 33.6%) (see Figure 8).

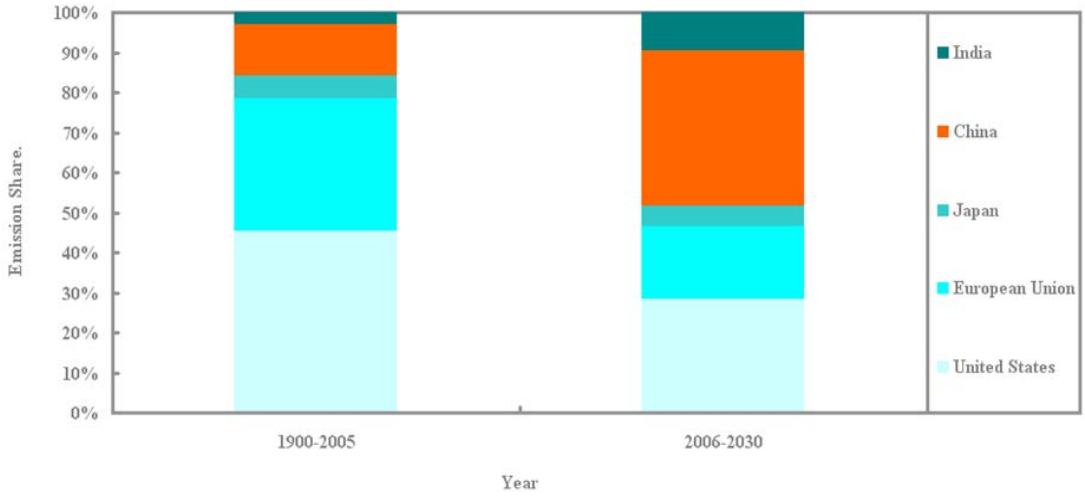
Figure 8 China Oil Consumption in Different Sectors 1980-2007



Sources: National Statistics Bureau, 2008

Figure 9 shows that transport is responsible for the majority of the oil demand growth in China. Given the recent growth in travel demand and car ownership, the fast growth of energy demand in transport sector is expected to remain, and this adds pressure to reduce transport carbon emissions. China has become the world's largest carbon emitter in 2008 (IEA, 2011), and according to IEA's predicts, China would take more than 40% of total carbon emissions from top five emitters in the world by 2030 (see Figure 9) (IEA, 2008).

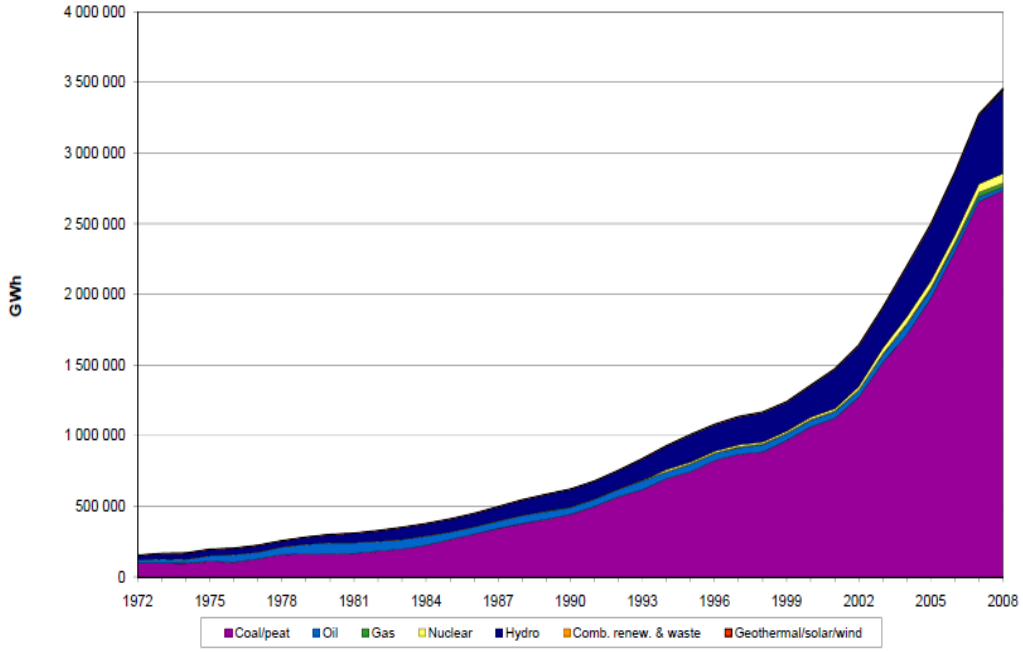
Figure 9 1900-2005 & 2006-2030 Five Areas CO2 Emissions Share



Source: IEA Greenhouse Gas R&D Program, 2008

In order to reduce the oil reliance and carbon intensity of transport, a number of alternative fuels have been recommended as possible substitutes for petrol and diesel vehicles. Instead of using petroleum fuels, EVs rely on electric power, which in China is mainly generated by coal and hydropower. With the rapid increase of energy demand, coal takes a growing share in the generation mix over the recent decades (see Figure 10). As energy feedstock for power plants is dominated by coal, the CO_2 intensity is usually greater than 900g/kWh among different regions (see Table 3). Reducing carbon emissions of power generation is a great challenge in China. Although those natural gas power plants with combined-cycles strategies have higher energy conversion efficiency (42%), it is still much lower than that in petroleum fuel refineries (Pezzini, Gomis-Bellmunt et al. 2011).

Figure 10 China Electricity Generation Mix



Source: IEA, 2008

Table 3 Carbon Intensity of China Power Grids

Regional Power Grids	CO_2 Intensity (g/kWh output)
North China	1235
North East	1230
East China	889
Central China	821
North West	917
South China	845
Hainan	963

For the power grid infrastructure in the United States and China, the current electricity

transmission and distribution losses are roughly 8%. Therefore, although the efficiency of an EV's electric power-train can reach approximately 86%, the upstream electricity generation and transmission will cause significant carbon emissions. According to the lifecycle assessment in China (Hong, et al, 2010), EVs tend to have a less carbon emissions than conventional ICE vehicles do in the south, central, and north-western regions of China, where coal accounts for 65% to 77% of the local electricity mixes. For the power grids in other regions, the high feedstock reliance on coal indicates an increase of carbon emissions during shift from ICE vehicles to EVs. According to the calculations from the Innovation Centre for Energy and Transportation (ICET, 2011), the vehicle fleet average GHG emission rate for major domestic and multinational car manufacturers in China 2009 was about 179g/km or about 219 g/km. It also concluded that the GHG emissions of Nissan Leaf are lower than the average of ICE vehicles in 2009 (World Bank and PRTM, 2011). In the long term, EVs are able to consume the electricity that is generated from renewable energy including hydropower, wind and solar energy, and in these cases, they would achieve zero carbon emission throughout the whole lifecycle and mitigate the reliance on fossil fuels. Therefore, with the improvement of power plant efficiency and the introduction of renewable energy in the electricity mix, the carbon emission intensity is expected to decline and the potential carbon saving from vehicle electrification could be further improved.

The development of EVs also has a large potential to improve generation efficiency

and stability of the power grid. Different to petroleum fuels, electricity cannot be stored on a massive scale in an economic way. Power grid operators hence have to balance the power supply and demand incessantly in order to ensure the power supply quality in the transmission system. Mismatches between electricity supply and demand could cause power fluctuation and in some cases, even stall the whole power system. The conventional thermal power plants mainly use coal, oil or natural gas and the electricity generation is relatively stable and predictable so that their power output can be scheduled according to the expected demand. On the other hand, the power generation of renewable energy, wind and solar in particular, is intermittent and the accurate prediction is still facing challenges. Traditional measures to smooth the output fluctuation include enlarging the power grid covered balancing area, load shifting management and increasing generation flexibility. Usually, these measures involve an extensive infrastructure upgrading for power transmission, and thus cause a large amount of investment. The charging demand of EVs follows the drivers' travel profiles, where the peak-demand usually occurs from late evening to the early next morning. This charging demand performs a reverse pattern as compared with the base load, where the peak-load often happens during the daytime and early evening. These two inter-complementary demand profiles indicate EVs' potential in accommodating the extra generation from the power system, particularly from renewable sources, and improve the generation efficiency consequently (Liu, 2011).

From the discussion above it can be found EVs have large potential in oil

consumption saving. When the power grid is feed by renewable sources, including solar, wind, hydro and nuclear power, a thorough WTW carbon emissions mitigation can be further achieved. However, the current electricity generation mix in China is dominated by coal, and EVs are expected to achieve carbon reduction only in some regions where the share of renewable source in the power grid is relatively high. The power grid's adoption of renewable sources means that the power grid needs to be substantially upgraded, and this in turn means major new grid infrastructure investment.

2.3.2 Driving Profile

The market acceptance of EVs also depends on people's driving profile. Although the electric range of EVs currently is still lower than the average range of ICE vehicles running on petrol or diesel, they can substitute for many trips. If an EV has an electric range equal to or larger than the average daily driving distance, a large amount of driving mileage could be powered by electricity via low speed chargers distributed at homes or workplaces. According to the United States Department of Transport (DOT) survey, about 50% of drivers in the United States travelled 40 km per day or less and 80% of them have a daily driving distance less than 80 km (DOT, 2011). Similar analysis conducted by Department of Energy (DOE) who applied the 2001 National Household Survey to estimate EV substitution potential to ICE vehicles and the result shows that nearly 75% vehicle driving kilometres could be substituted by EVs with a

battery capacity of 96 km per charge (DOE, 2006). In order to precisely measure on road vehicle driving distances, GPS devices were applied in the St. Louis Regional Travel and Congestion survey in 2002 where National Energy Research Lab derived 227 full-day driving profiles representing 13,927 km of travel (NREL, 2007). It shows that only about 5% vehicles in the survey were driven more than 160 km per day. Moreover, the 2007 Transportation Energy Data book found the average trip distance in the U.S. was 16 km, and the average daily driving distance was 53 km (DOE, 2007).

EVs could be better accepted in countries with low urban geographic dispersion and shorter daily driving profiles, such as European countries and Japan. In Western European 25 countries, the average daily driving distance is approximately 27 km, while in the United Kingdom, more than 75% of car trips are less than 16 km and 93% are less than 40km (Eberle and Helmolt, 2010). Similarly, according to the global EV survey conducted by Deloitte in 2010, 81% of drivers have a daily driving distance less than 40 km and 94% of daily distances are less than 80 km. This is less than the EVs' electric ranges in the current market (Deloitte, 2010).

There also have been a number of surveys focusing on the people daily driving distance in China. According to Deloitte's 2011 global EV survey, the average driving distance in 23 surveyed Chinese cities is 54 km/day (Deloitte, 2010). Ernst & Young also published its survey result for Chinese drivers' daily driving distance of 46

km/day (Ernst & Young, 2010). In 2005, the Beijing Municipal Commission of Transport (BJMCT) conducted the third integrated transport survey for the city which shows the average daily driving distance in Beijing was 44 km/day (BJMCT, 2007). In the integrated transport survey for Shanghai undertaken by the municipal government in 2009, the average daily driving distance was 39 km/day (Shanghai Municipal Government, 2011). From these surveys, it can be found that the daily driving distance in China generally ranges from 45 km to 55 km, which is well below the current EVs' range per charge.

Despite EVs' capacity to supply the majority of travel demands, few consumers would accept EVs that compete with ICE vehicles with a much longer driving range. However, EVs could still be preferred in some markets. For example, given the low cost of electricity, urban commuters, who have a regular driving and parking profile, would take their regular commuting travels using EVs. Similarly, those families, which already have an ICE vehicle, might choose EVs for their short distance trips and drive ICE vehicles for longer travels. Alternatively, the plug-in hybrid electric vehicles (PHEVs) could overcome the low battery range and charging infrastructure shortage. PHEVs integrate an electric power-train system with a conventional ICE to offer both fuel and electric driving modes. For example, with the help of the on-board generator, the total range of Chevy Volt can reach over 640 km, as well as achieving a grid independent operation using conventional petrol fuel.

The driving profile of EV users would also determine their charging activities and correspondently have impacts on the power grid. The peak time charging would not only increase load burden of the power grid, but also generate more carbon emissions than off-peak time charging due to the power grid's different carbon intensities at different times. For example in the United Kingdom, drivers who charge their EVs at the peak times would generate more than twice the CO_2 emissions than those who charged vehicles at the off-peak times (Royal Academy of Engineering, 2009). When it comes to the capacity of electric power grid, there are two distinct aspects that need to be addressed: providing adequate low-carbon electricity for marginal demand from EVs and ensuring the supply when the charging demand occurs at the peak time. The EV charging impacts on the power grid is dependent on both the daily driving profile and the base load of the power grid. The EV charging demand could be regarded as a marginal load on the power grid. When a charging activity is undertaken during the off-peak period of the base load, the marginal load could be readily accommodated by the current capacity of the power grid. Otherwise (the marginal load happens at the peak time), an extra grid capacity is needed. Furthermore, with the introduction of more renewable electricity in the power system, the difference between high and low carbon intensity will be even larger. In some cases (such as hot summer or cold winter time) the incremental generation, which has to be brought online to meet the marginal charging demand, could only be supplied by coal-fired plants. In fact, both daily base load curve and daily driving profile usually follow their regular patterns, which are largely determined by the people's activities. Figure 11 presents a typical Beijing's

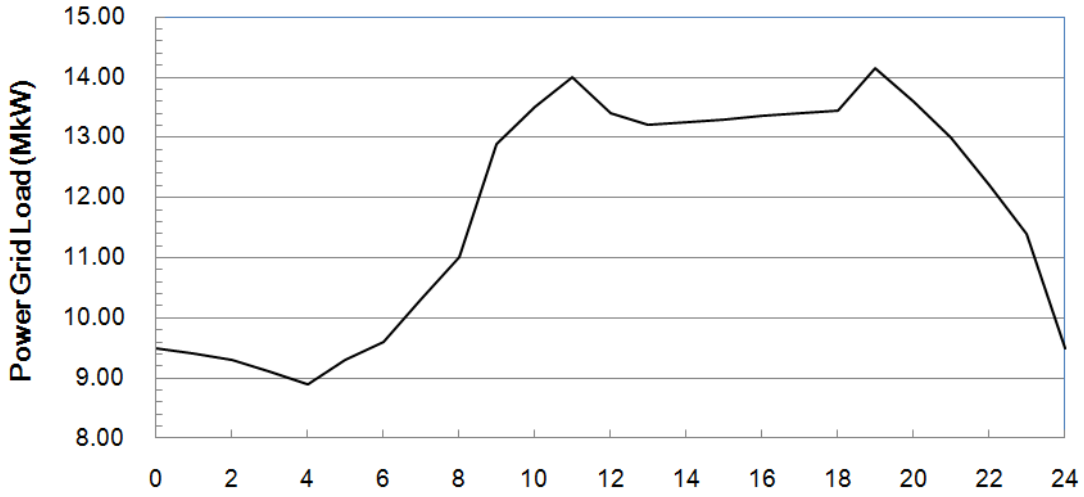
daily power base load in summer seasons (Wei, et al, 2010). It shows that the daily electricity load varies significantly to the time and there are two peak-time periods:

1) 1100 hrs (14 GW), when the power demand from the workplace reaches a high level, and;

2) 1900 hrs (14.2 GW), when the main contribution comes from the air condition load at homes.

In contrast, the daily load trough is only 8.9 GW occurring at 0400 hrs. The trough load only accounts for 63% of peak demand, which means the power plants have to suspend part of its generation capacity during the off-peak time and restart the capacity during the peak time. The frequent switches between on and off inevitably lowers the energy conversion efficiency which is uneconomic and produces more carbon emissions.

Figure 11 Summer Daily Electric Power Load in Beijing



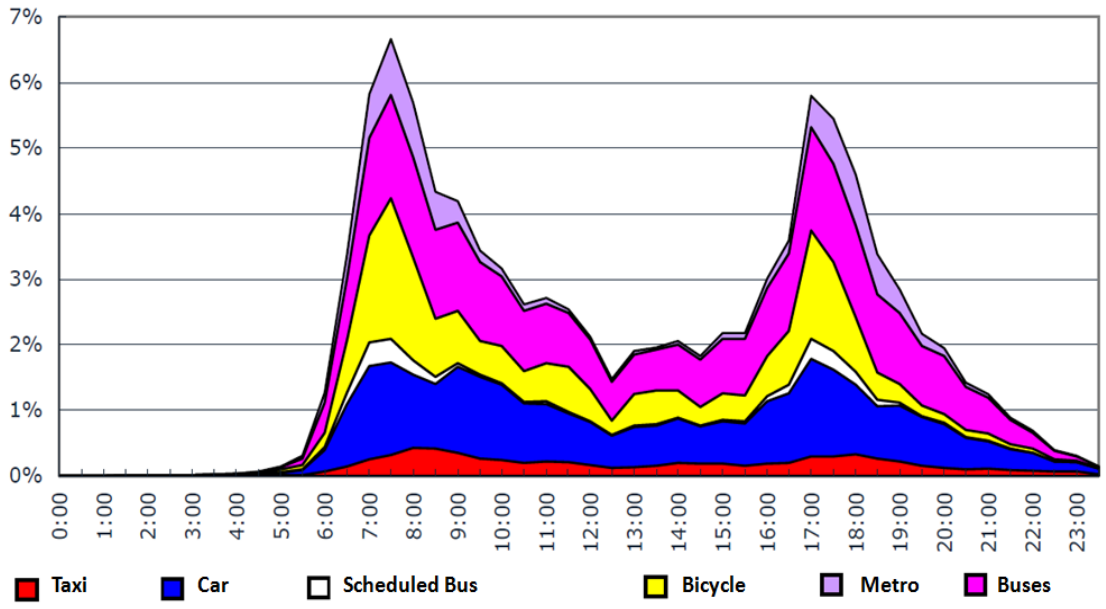
Source: Wei, et al, 2010

On the other hand, the daily profile of car traffic flow in Beijing is presented in Figure 11, where two peaks can be clearly observed:

1) 0600 to 0900 – morning peak period;
2) 1600 to 2100 – afternoon peak period.

For most vehicles, on-road running time only accounts for a small portion of a day. According to the traffic flow profile in Figure 12, the correspondent parking time profile can be estimated. It can be inferred that the low-speed charging would happen during the car parking period, and therefore it could be assumed that the potential time of low-speed charging would range from 0900 to 1600 and 2100 to next day 0600.

Figure 12 Daily Traffic Flow Distributions by Different Modes in Beijing



Source: Beijing 3rd Integrated Transport Survey, 2007

According to the grid's base load profile showed in Figure 11, the potential charging activities could happen during the peak period of the grid's base load. For instance, the morning parking period starts from 0900 while the morning peak of the power grid is at 1100. Therefore, charging activities in the morning at 1100 could lead to an extra demand for the power grid's capacity. The similar charging and power load profiles could be observed in many cities. According to the current driving behaviour, the development of EV fleet could have a significant influence on the power grid operation. To cope with the marginal charging demand, the charging time management and power grid upgrade are needed.

Because the parking time of a vehicle is usually far longer than its operation time, EV charging could be made during the parking period when the base load is low. It is important to induce a grid-friendly charging behaviour. The potential charging behaviour could be shifted by introducing the "time-of-use" electricity rate, implementing charging time management, or an appropriate charging infrastructure deployment, so that to encourage more off-peak charging. This concept is similar to a flexible electricity rate: low off-peak electricity price and high peak price to smooth the overall load profile. For EVs, the charging demand profile is largely dependent on the travel profile and the charging infrastructure chosen by the EV users. Compared with charging infrastructure upgrade, the price signal would be a straightforward and cost-efficient measure that schedules consumers' charging pattern to match the availability of low-carbon electricity.

In sum, the market acceptance of EVs would be largely determined by people's current daily driving profile. Given relatively low driving range and low electricity price, EVs would be an appropriate travel mode for drivers with short and regular travel patterns. Those families, which already have a conventional petrol car, would be also likely to take EVs for their short distance urban travel. It also shows that based on the current driving profile, the estimated charging activities could be taken during the peak period of the power grid, which causes extra load burden on the grid. To accommodate the marginal charging demand as well as balance the peak and off-peak of the power grid, charging time management and appropriate charging infrastructure deployment are needed.

2.3.3 Charging Infrastructure

One of the remarkable differences between ICE vehicles and EVs is that EVs can be charged by a variety of power outlets, such as roadside charging posts, battery swap stations or fast charging stations functioning as conventional refuelling stations (see Table 4). Fast charging stations have been initially recommended for EVs as they share similarities with petrol refuelling stations. However, there are a number of concerns about fast charging stations, including the high infrastructure cost and the long charging time. Currently, the maximum recommended charging rate of Li-ion battery is 1C, which means it needs at least one hour to fully charge the battery. When

the charging rate is further increased, charging energy efficiency will be lower and charging safety becomes another issue. Moreover, the high charging rates also require a large instantaneous power supply from the power grid causing additional fluctuations in the electric power system. A typical petrol refuelling station has 10 pumps to deliver fuel. For a fast charging station with 10 power outlets, the total charging load could reach 2 MW to 4 MW. The high voltage supply (11 kV) is needed to provide the charging service. The development of fast charging stations also depends on a unified interface between power supply and the battery. With the standardization of charging interface, vehicles can avoid board charging equipment, which significantly reduces the vehicle weight and associated energy consumption. The standardization of interface also improves the charging efficiency and facilitates the battery management.

Table 4 EV Charging Infrastructure

	Operating Power	**Charging Duration and Time**	**Location**	**Target User**	**Construction Cost**	**Operating Cost**
Charging Post	AC 5kW/post	6-10 hours; daytime and night	Parking Lots/ Communities	Private Car	20,000RMB /post	Low
Charging Station	DC 200-400kW/ charger	10-30 minutes; daytime	Motorways/ Major Roads	Bus, Taxi and Private Car	3-5million RMB/station (land exclusive)	High
Battery Swap Station	Null	3 minutes; night	Motorways/ Communities	Bus, Taxi and Private Car	20 million RMB/station (land exclusive)	Low

To address the long charging time, the battery swap strategy has been suggested (Liu, 2011; Liu, 2012). At a battery swap station, the depleted battery is switched off and

replaced by a fully charged one. The depleted batteries are then delivered to a collective charging station for the off-peak period charging. Through the battery swap, the whole charging process could take less than 5 minutes, which is comparable to a petrol refuelling process. Because charging activities actually happen at a collective charging station, rather than at a swap stations, the charging time can be scheduled based on the real-time electricity price or the load condition of the power grid, which would substantially reduce the negative impacts of charging demand on the electric power system. However, this strategy further requires battery standardization. A swap system would have to cope with diverse types of batteries with different sizes and charging specifications, which further increases the costs of the infrastructure. Due to the high capital expenditure, it is expected that battery swap stations alone cannot fully accommodate the charging demand from EVs, and they will probably be distributed around suburban areas or along motorways serving long distance journeys.

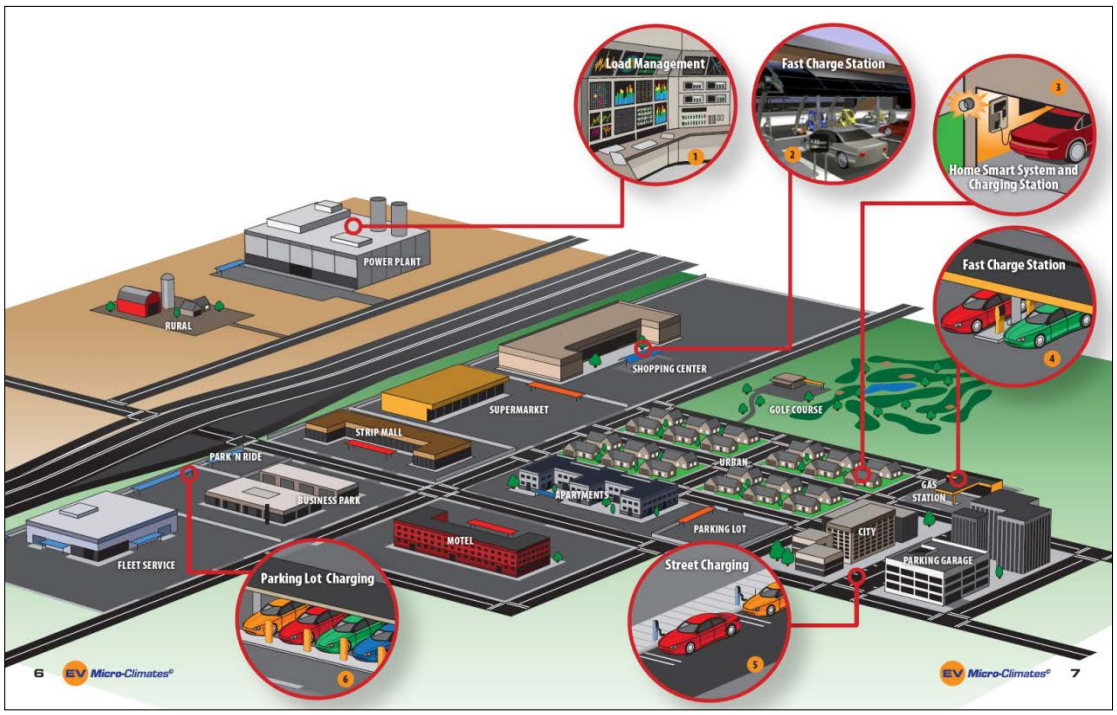
The development of battery swap stations also closely relates to the commercial strategies for battery ownership and operation. As the battery could take 50% of the cost of an EV, the separation of batteries from EVs can largely reduce the purchase costs for consumers. On the other hand, operators have to compensate the battery costs for customers initially. Although they could reimburse the initial investment through a service contract with customers, the payback period is expected to be long due to the high cost of both batteries and swap infrastructures.

Charging posts are the most inexpensive charging infrastructure, and they offer the cheapest costs for construction and maintenance. Some EV manufacturers also provide charging posts along with the vehicle for EV customers. With a high charging flexibility, charging posts could be deployed in public car parks and residential communities. Small charging facilities have appeared in China since early 2000s, providing charging services for electric bicycles. These facilities are usually distributed around public transport interchanges and operated by roadside new-stands and retailers. Given the low capital and operation cost, these charging facilities have successfully accommodated the increasing demand of electric bicycle fleet in China. In more recent years, some local authorities have begun to deploy charging posts for EVs in cooperation with the utility companies. These charging posts are mainly used to serve sanitation, postal or public transport vehicles and they are usually located in public-exclusive fast charging stations or battery swap stations. China' State Grid company plans to extend these charging posts to public car parks and residential communities. The estimated cost for each post is about RMB 20,000 (State Grid, 2009) and the installation cost could be lowered via collective construction (in workplace and community car parks). Although the widespread construction of charging posts leads to charging time management difficulties, the load of individual charging posts is low, and this causes less load pressure on the power grid than fast charging stations do. For EV drivers, who have private garages, a charging post could be installed at their homes and provide daily charging convenience. However, most urban residents in China live in apartments without a dedicated car parking space.

Instead of parking in garages, they usually park their vehicles in community car parks that are usually located underground. This offers an opportunity for collective charging infrastructure deployment, though it also involves various stakeholders, including local municipal administrative authorities and property management companies, and this could significantly complicate the installation procedure.

For on-street charging posts or public charging posts, a charging service management scheme is needed. Every charging post user should be registered with the local charging service network, and every post should be equipped a smart-card reader and be able to link to a central control system that validates the charging account and starts the charging process. In addition, the public charging posts require extra protection from weather influences (rain and snow) and man-made sabotage. The charging service operators should be responsible for providing and maintaining these infrastructures, and they also need to coordinate the upstream electric power supply and downstream street charging posts, parking lot charging posts, home charging posts, charging stations to offer an integrated service via load management systems (see Figure 13).

Figure 13 Charging Infrastructure and Distribution



Source: EV transportal, 2011

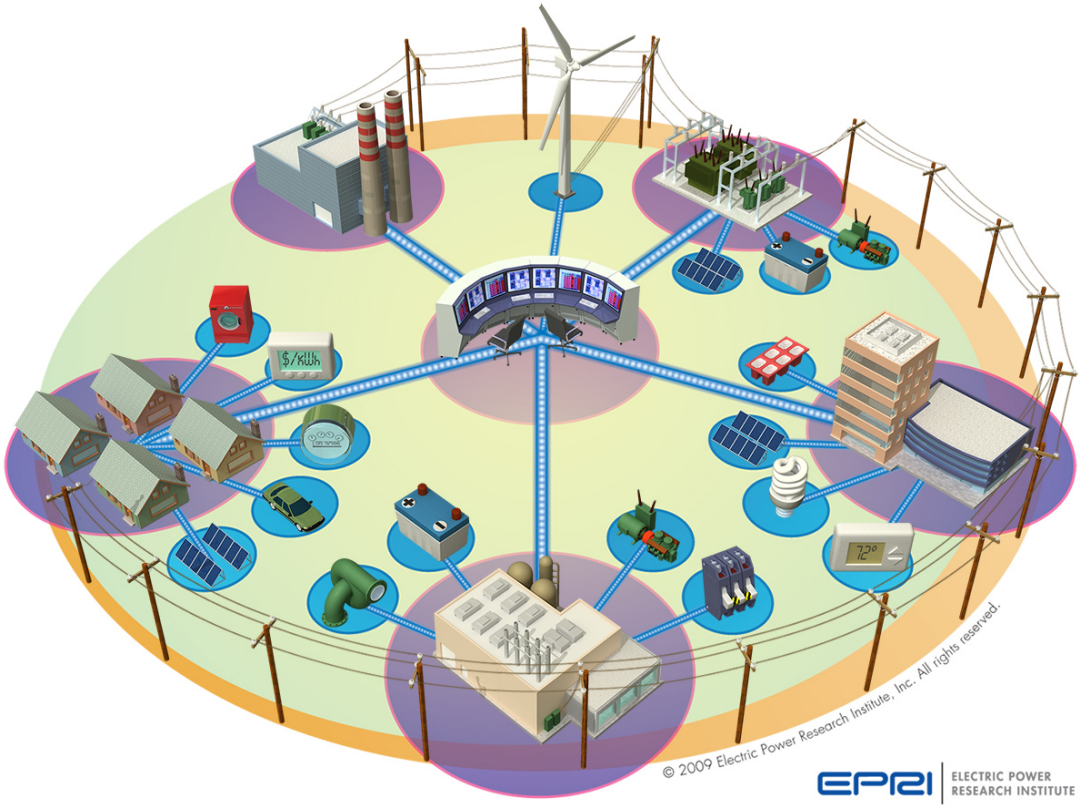
In sum, the supply of charging infrastructure is a key prerequisite for EV development. A ubiquitous and convenient charging infrastructure network can largely facilitate the charging activities and as a consequence, significantly improve the carbon emission saving potential. This is central for PEVs, as the refuelling methods and the provision of the charging infrastructure directly determine the customers' purchase decision. Moreover, the operator should provide the appropriate infrastructure based on their charging features (power and cost) and local charging demand. The location should fully consider convenience, minimum grid impact and cost. Therefore, the current travel behaviour, residential and public parking conditions and the local power grid capacity should all be investigated before deploying the charging infrastructure.

Furthermore, the charging service operator needs a well-designed business operation model to link EV manufactures, utilities and customers.

With the help of the electricity storage capacity, EVs are expected to facilitate the renewable energy integration to the current energy mix. Due to the intermittent nature of solar, wind and hydro power, they are difficult to integrate into the conventional power grid (IEA, 2011). However, a vast number of PEV batteries could offer a considerable storage capacity and supply the power grid when the power demand is high. Therefore, a "smart grid" is needed to achieve a bi-directional power transition between EVs and the power grid. "Smart grid" is usually reserved for an electric system that provides real-time information for both electricity provider and consumers of energy. The system enables suppliers to adjust and remotely control the electricity prices according to peak and off-peak times (Sun, Ge et al. 2011). A smart grid is also designed to share the supply capacity and demands between the different power sources and outlets. Implementing a smart grid that integrates EVs and renewable energy involves a number of industrial sectors, including power generators and distributors, car park operators, car makers, battery manufacturers, IT companies and local authorities (Peterson, Whitacre et al. 2010). Moreover, a smart grid system that integrates a large number of EVs introduces new commercial issues to the energy market (Guille and Gross 2009); (Wu, Liu et al. 2009). The bi-directional power transmission enables the EV users with storage capacity to become private electricity retailers, which further encourages the competition in the electric power market. This

power transmission from vehicle to the grid has been described as V2G (see Figure 14). Currently, the environmental and economic benefits of V2G are still under investigation and a number of R&D projects are conducted in the United States (University of Delaware), UK (University of Warwick) and China (SGCC).

Figure 14 Electric Power Research Institute (EPRI) Smart Grid Configurations



Source: EPRI, 2009

2.3.4 Economic Impacts and Cost Reduction

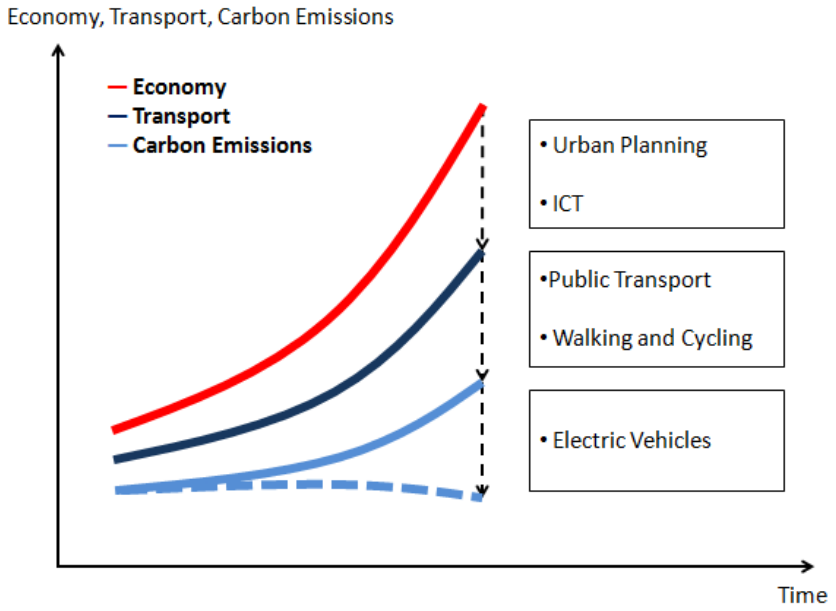
Traditionally, economic and transport activities and transport carbon emissions are strongly correlated (Banister and Stead, 2002). Economic activities can raise the

demand for transport, and in the meanwhile the increase of transport demand promotes the economic growth but increases carbon emissions. Although some historical data show that the economic growth usually coincides with the transport demand increase, there is no economic law binding them together. In fact, the growth in transport demand can be harmful to both the economy and the environment. Banister and Berechman (2001) acknowledge the link between transport growth and economic growth, but also suggest 'indeed there is strong efficiency and environmental arguments for breaking the link' (Banister and Berechman: 2001). As a derived demand of economic activities, excessive transport would have negative social and environmental impacts. In order to promote the economic growth with fewer adverse impacts from transport demand increase, there needs to be a decoupling of the economic growth, transport activities and transport carbon emissions. A wide range of measures have been proposed to decouple the economic growth and transport growth, including increased efficiency, urban planning and ICT development, all of which aim to offer the communication convenience reducing the need for travel.

As one of the key negative impacts of road transport, vehicle emissions have long seen as one target to decouple from transport activities. Traditionally, public transport and smart travel schemes (for example, car club and car sharing schemes) have been regarded as cost-effective measures and widely adopted, particularly in congested urban areas. With the growing adoption of renewable resources and low carbon combustion technologies, EVs have been increasingly recommended as a means to

reduce the transport carbon emissions. Compared with other measures, the large scale application of alternative fuel vehicle fuels is expected to fundamentally relieve the transport reliance on petroleum fuels and to further mitigate the growth of associated carbon emissions. By introducing low carbon feedstock and improving energy generation efficiency in the upstream stage, alternative fuel vehicles could even achieve the carbon reduction goal while meeting the equivalent or increased transport demand. Figure 15 presents the decoupling relationship among economic growth, transport demand and carbon emissions.

Figure 15 Decoupling Economic Growth, Transport Demand and Carbon Emissions



The massive market adoption of EVs relies on significant cost reductions. As introduced in Section 2.2, EVs currently are much more expensive than ICE vehicles

due to the high cost of battery, whereas the operation cost of EVs could be significant lower. If the unleaded petrol price is Euro 1.6 per litre (Department of Energy and Climate Change 2011), the cost per mile for a vehicle with 10 litre/100 km fuel consumption is Euro 0.16 per kilometre driven. For 20,000 km of annual driving distance, the fuel cost would be about Euro 3,000. On the other hand, assuming that the electricity price is Euro 0.2 per kilowatt and the typical energy efficiency is 20 kWh per 100 km, the fuel cost per kilometre EV driven is Euro 0.04. For the same annual driving distance of 20,000 km, the annual fuel cost for the EV is only about Euro 800. Therefore, the operation cost of an EV would be nearly 75% less than that for an ICE vehicle. In addition to the operating cost, the cost of an EV excluding the battery, could be actually somehow lower than that of an equivalent ICE vehicle, given that the EV does not have an engine, and the transmission system could also be downsized due to a simpler power-train system than an ICE counterpart.

With the fast R&D progress, the battery cost of EVs could be largely reduced in the foreseeable future. However, the high battery cost is currently still the major barrier for EVs' market penetration. Currently, the cost of a 25 kWh lithium-ion battery is about Euro 12,000 (Sankey Paul 2010). Using the annual cost saving of Euro 3,200, the payback period of an EV would be about 4 years, which could be even longer in countries where the petrol price is much lower, for example, in the United States and China. But in a lifecycle perceptive, EVs' high up front capital cost could be reimbursed over the vehicle's lifecycle.

In the United States, the cost target of United States Advanced Battery Consortium is USD 500 per kWh (Delucchi and Lipman 2001) . For a PHEV with 60 km electric range, the battery cost would be USD 6000. For an example of General Motor (GM) Volt, the battery capacity is expected to be 16 kWh costing about USD 8,000 per vehicle. According to GM's marketing publicity, the battery will operate from 30% to 80% SOC[15]. Assuming the energy economy of a lithium ion battery is 8 km per kWh, GM Volt can only provide approximately 64 km all-electric range. The battery's high cost is basically driven by expensive cell materials including lithium (Li), manganese (Mg), cobalt (Co), nickel (Ni), graphite and electrolyte chemicals, as well as the cost of packaging, manufacturing and electronics.

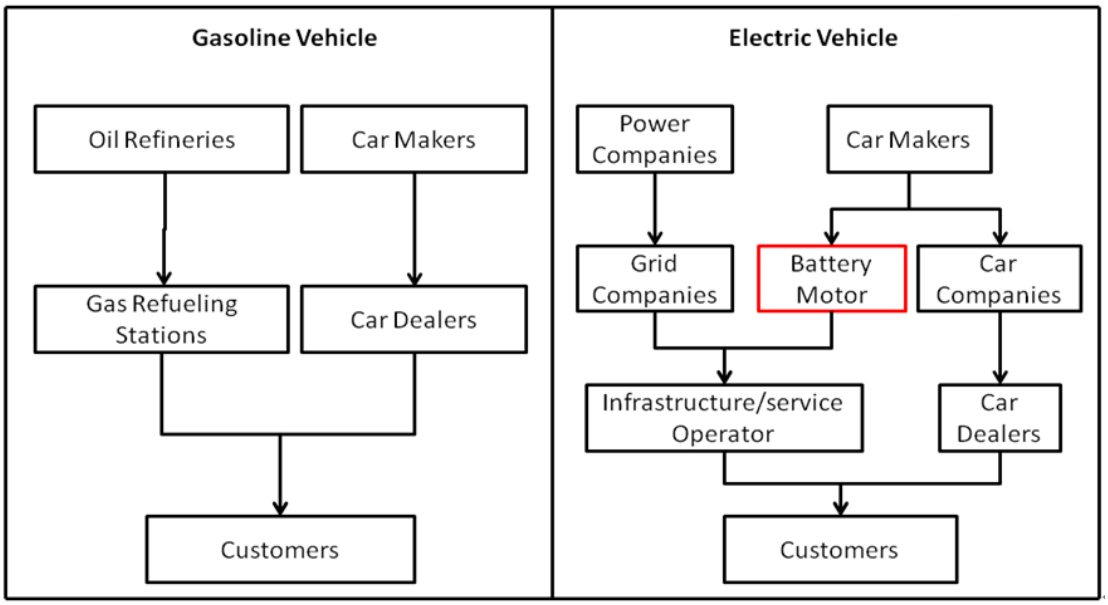
To reduce the high battery cost for consumers, some companies, such as Better Place, intend to develop a charging service business model, where the charging operator owns the battery (Better Place, 2011). This business operation model is similar to a mobile phone contract where customers get a service contract along with a free mobile phone from the service provider. This model immediately benefits the EV buyers who are able to own their vehicles and avoid the expensive battery cost. Better Place offers EV batteries and sells driving distance to customers, which helps

[15] The ability to operate over a larger charge window is also important. Certain competing chemistries are limited to operations within 30%-70% charge windows in order to maximize life expectancy, whereas other competitors, like LMO and LTO and phosphate batteries are able to use 90% of their storage capacity, where the battery operation range is from 10% to 90%.

customers purchase an EV at much lower price comparable to an ICE vehicle. The depleted batteries are removed from EVs and managed by a charge service operator (Batter Place), who is responsible for the electric energy supply and battery operation/maintenance service.

Compared with conventional car industry, the conventional car makers tend to focus on vehicle manufacture. As an intermediate body between utilities/car manufacturers and customers, the battery operator who has direct links to the upstream and downstream sectors could play a key role in the EV market (see Figure 16). Given the remarkable reduction of up-front cost and the governmental incentives to EVs, the public acceptance of EVs could be substantially promoted through this strategy.

Figure 16 The Comparison between ICE Vehicle and EV Markets



Furthermore, the international oil price drastically fluctuates over time. The

introduction of EVs, which tends to largely reduce the energy reliance on oil import, can stabilize the China's economy. There were totally 63 million civilian vehicles in China in 2009 (National Bureau of Statistics, 2010). The fast growth in the vehicle stock stimulates the demand of fossil fuels and not only causes pressures on environmental conservation and energy security, but also on China's economic stability and the country's geopolitical relationship with surrounding countries. It estimates that domestic oil production would only meet two thirds of the country's demand which means China would need 600 million tons of crude oil imported from other countries by 2020 (Goodman, 2005). The increasing oil import would leave China vulnerable to global energy market fluctuations and more susceptible to international oil conflicts.

To guarantee a secure oil supply and to mitigate its foreign oil dependence, domestic oil reserve facilities are under construction in coastal Zhejiang, Shandong and Liaoning provinces. China has also projected to build a national oil stockpile by 2020 with a total capacity amounting to 90 days imported oil. The international crude oil trade is also a primary contributor to global economic imbalance. In recent years, the China's government has also attempted to diversify the oil supply and establish oil imports from central Asia, Africa and Russia, as well as expand offshore drilling in South China Sea, instead of relying on oil imports from Middle East countries. In 2010, China imported 239.3 million tons of oil which amounted to an increase of 17.51% over the volumes imported in 2009 (CNPC, 2011). Angola has surpassed

Saudi Arabia and become China's biggest oversea oil supplier. The high international oil price and fast increase of oil import could largely increase the country's trade deficit. The high reliance on imported oil exposes the county's economy to unemployment and economic downturns stemming from foreign oil supply interruptions, and it can impose political and economical conflicts with other countries. In contrast, electric energy can be generated from a variety of feedstock sources which are widely distributed around the world. The introduction of EVs would therefore reduce the transport sector's reliance on petroleum-based fuels and eliminate the consequent economic and political concerns over oil trade.

In sum, the development of EVs is currently still largely constrained by the high costs of battery. Although EVs can achieve net energy consumption saving and carbon emissions reduction, their success still relies on their cost. To improve the market acceptance of EVs, some innovative business operation models have therefore been proposed to reduce their high upfront costs. To estimate the market potential of these business operation models, Chapter 9 takes a case study in Shanghai to forecast the cost profile for EV users and the charging operator under battery leasing and vehicle leasing models. In the national perspective, EVs could largely mitigate the road transport's petroleum consumption and hence reduce the international energy trade deficit. The reduction of import oil will not only provide more employment opportunities for the country, but also help protect the domestic economy from global energy market fluctuations.

This section has discussed a range of key determinants for EV development in China, covering energy security and environmental concerns, charging infrastructure, driving profile and economic benefits. It has found that EVs could significantly reduce the carbon emissions and the petroleum fuel consumption from the road transport sector. With growing adoption of renewable sources in power plants, EVs could have larger potential to achieve environmental benefits. However, according to the current battery technologies, EVs are still less competitive than ICE vehicles in terms of overall performance and cost. Some specific concerns are discussed about calculating the lifecycle energy consumption, the carbon emissions, and the costs and benefits of EVs compared with other alternative fuel vehicles based on the energy mix and the current driving profile in China; the charging infrastructure deployment strategy that could facilitate grid-friendly charging activities, and the innovative business operation models that could stimulates the market diffusion of EVs.

2.4 Alterative Vehicle Fuel Technologies

In addition to EVs, a variety of alternative fuel and advanced ICE vehicle technologies have also been suggested, including high efficient ICE vehicles, natural gas vehicles, liquid petroleum gas vehicles, biomass based-fuel vehicles. To make a comparison between EVs and other alternative technologies, this section introduces petroleum (petrol, diesel, natural gas and liquid petroleum gas) and biomass-based

(bio-ethanol, bio-methanol and bio-diesel) fuels and the correspondent engine technology development status in China.

- **Petroleum Alternative Fuel Vehicles**

When it comes to the vehicle fuel consumption reduction, improving the energy efficiency of conventional ICE vehicles that are powered by petroleum fuels would be a near term cost-effective solution. The petroleum fuels, including petrol, diesel, natural gas and LPG, are taking the overwhelming majority of the current world's automotive fuel market and will keep playing the leading role in the transport fuel market over the medium term. Both petrol and diesel are mainly extracted from crude oil and the fuel production, transport and distribution system has been well established for a long period, which results in a significant low price using petroleum fuel. Modern vehicles have been perfectly adapted to petrol and diesel fuels. Alternatively, the recent extraction technology development already renders alternative feedstock (tar sands and coal) as a potential source for crude oil, though their recovery and production currently involve considerable carbon emissions. For example, the production of petrol/diesel from tar sands is currently releasing 115% to 270% of the CO_2 emissions of those from crude oil, and coal-source petrol/diesel (gas-to-liquid) is emitting an extra of 80% CO_2 emissions than crude oil (King, 2007).

To alleviate the negative environmental effects of petrol and diesel fuels, a series of alternative fuels have been proposed to substitute conventional ICE vehicles. Before

2000, the most commonly used alternative fuels for vehicles were liquid petroleum gas (LPG) and natural gas (Ferguson, 2001). Although LPG and natural gas are not produced from renewable feedstock, their combustion emission levels are much lower than those of petrol and diesel.

The main component of LPG is propane (C_3H_8) which is a saturated paraffinic hydrocarbon and blended with butane (C_4H_{10}) or ethane (C_2H_6). LPG can be obtained as a by-product from the lighter hydrocarbon fractions produced during the crude oil refining and from heavy components of natural gas. LPG is stored as a compressed liquid and can be injected into the intake manifold or directly into the cylinder of a vehicle's engine. There are already a number of vehicle manufacturers that currently sell LPG fuelled vehicles in the market, primarily light and medium duty vehicles, including pick - up trucks and vans (Ferguson, 2001). LPG has only about 75% energy density of petrol (by volume). Further displacement of about 5% to 7% intake air by the LPG leads to a lower volumetric fuel efficiency (Pulkrabek, 2004), and the engine power of LPG vehicles can also be reduced due to the evaporative cooling effects (Demirbas, 2002).

Natural gas, on the other hand, is gaseous petroleum fuel, consisting primarily of methane (CH_4). Natural gas is extracted from oil fields, natural gas field or coal beds. It is primarily composed of CH_4 (60% - 98%) with additional compounds such as nitrogen (N_2), CO_2, ethane, and propane. According to the IPCC global warming

potential (GWP) index, the global warming potential of methane is ten times that of CO_2 (IPCC, 2006). CH_4 is stored as compressed natural gas (CNG) at pressure of 2900 to 3200 psi and as liquid natural gas (LNG) at pressure of about 3.6 psi with the temperature around -160^{o}C. Natural gas-based fuel vehicles have been used since 1950s and the power-train conversion for natural gas fuel are available for both spark and compression ignition engines. Because of the lower amount of carbon component in natural gas-based fuels, less CO_2 is generated and very little solid particulate matter emitted (Pulkrabek, 2004). Research and Development (R&D) work has also investigated the bi-fuel vehicles that can operate with natural gas and petrol or natural gas and diesel (Aslam, et, al, 2005). A number of heavy duty diesel engine manufacturers are also producing dedicated natural gas heavy duty engines (Graham, et, al, 2008). Similar to LPG, natural gas has a disadvantage in that it needs large pressurized fuel storage tank with high cost and safety concerns. The issue of the slow refuelling process of natural gas also needs to be addressed (Willson, 1992).

- **Biomass-based vehicle fuels**

The adoption of biomass-based fuel, namely biomass-made methanol, ethanol and biodiesel, in transport sector has been taken into the agenda particularly in some large agricultural countries, including Brazil and the United States. The energy density of biomass-based fuel is much higher than that of natural gas and LNG (though still lower than that of petrol/diesel), and biomass-based fuels could also be used by retrofitted ICEs, which means biomass-based fuels face smaller challenges in fuelling

transport than electricity does (King, 2007). The biomass based-fuels are currently mainly produced from common crops, such as sugar and corn, which are widely distributed around the world. The key advantages of biomass-based fuel vehicles include its oil consumption and the GHG emissions saving potential. In addition, their carbon emissions during fuel combustion (vehicle operation) could be counterbalanced by carbon absorption during the growth of energy feedstock (crops).

Among the various vehicle biomass-based fuels, bio-methanol and bio-ethanol have received relatively high attention (ANL, 2006). In addition to petroleum fuels, methanol (CH_3OH) can be produced from herbaceous biomass, farmed trees, corn stover[16] and forest residue. Methanol is toxic and ingestion can cause blindness and death (Health Protection Agency, 2007). Methanol has been used as a vehicular fuel as early as 1900s and it can also be used for diesel engines and fuel cells. Ethanol (C_2H_5OH) can be produced from corn, herbaceous or woody biomass through fermentation or gasification. Its properties and combustion characteristics are similar to those of methanol, but ethanol is non toxic at low concentrations. Ethanol can be blended with petrol as a vehicle fuel such as E10 - a mixture of 10% ethanol and 90% petrol by volume, and E85 - a mixture of 15% ethanol and 85% petrol by volume. E10 can reduce the petrol consumption without engine modification (Kim and Dale, 2006). In Brazil, about 50% vehicles use ethanol fuel (primarily E90) produced from sugar cane (Yacobucci, 2007). However, large-scale, efficient biomass farming for ethanol

[16] Corn stover is the residue of maize plants left in a field after harvest, such as stalk, leaves, husk and cob.

production has yet to be demonstrated.

In the WTP process from biomass feedstock to ethanol, ethanol production in ethanol plants is the largest fossil-energy-consuming and emission emitting stage (Wang, et al, 1998). Various ethanol producing resources involve different technological challenges and produce different co-products. For example, technologies that convert corn to ethanol, such as dry and wet milling technologies, have maturely developed, while technologies that convert cellulosic biomass, such as woody and herbaceous, to second generation ethanol, are still under progress (Campbell, Lobell et al. 2009). Wet milling plants produce ethanol from corn starch while producing high-fructose corn syrup, glucose, gluten feed, and gluten meal as co-products (Yu and Tao 2009). Dry milling plants are designed mainly for ethanol production and they are much smaller than wet milling plants. Ethanol is produced from corn starch, and other constituents of the corn kernel are used to produce distillers' dried grains and solubles (DDGS[17]) (Kim and Dale 2008).

The amount of emissions involved in the production of corn, woody biomass and herbaceous biomass are determined by the amount of process fuels, particularly diesel and electricity, and the use of agricultural chemicals, such as fertilizer (including nitrogen, phosphoric - P_2O_5 and potassic - K_2O fertilizers), herbicides, and insecticides (Shapouri et al, 1995). Because of agricultural research development in

[17] DDGS: Distiller's dried grains and solubles are the byproduct of the cereal distillation process and used as fodder for livestock.

genetic engineering and precision farming, the amount of energy and chemicals used per bushel of corn produced may continue to decrease in the foreseeable future (Shapouri, 1997). In addition, transporting corn and other biomass feedstock from farms to biomass-based fuel plants also causes emissions. In the United States, heavy trucks are the most common biomass transport mode (farms to plants) with payloads ranging from 6.8 tons to 13.5 tons. The fuel economy of these loaded trucks will also influence the biomass-based fuel life cycle emission levels (Wang et al, 1997b).

In contrast to corn-ethanol plants, at the cellulosic ethanol plants, the un-fermentable biomass components, primarily lignin, can be used to generate steam and electricity (Wooley, 1998). While the combustion of lignin produces CO_2 emissions, these emissions are neutralized by the photosynthesis during biomass growth. The electricity generated in cellulosic ethanol plants can be delivered to the power grid to offset generation by coal-fired power plants. Emission credits for the generated electricity are calculated by taking into account the amount of electricity generated by the cellulosic ethanol plant and deducting the emissions associated with the estimated amount of electricity that would otherwise have been generated by other power plants that use fossil fuels. Therefore, the emission credits that consider the carbon naturalization are a key factor in the cellulosic ethanol lifecycle assessment. Another key issue for biomass-based fuel lifecycle assessment is the CO_2 emissions generated from potential land use changes as a result of biomass farming. With the increasing demand for bio-fuels, the current land now idle or used as pastureland is expected to

farm biomass. In the study in the United States (Delucchi, 1998), converting every acre of idled cropland or pastureland to plant biomass would cause 204,000 g CO_2 per annum due to the carbon release from the soil.

Even though biomass-based fuels are currently considered as a probable alternative to fossil fuels, some studies show that the production of ethanol would consume more energy during feedstock growing, planting, harvesting, fermenting and delivery stages than that in fossil fuels' recovery and processing stages. This weakens the major motive to use the biomass-based fuel as an alternative vehicle fuel (Ferguson, 2001). Furthermore, although several countries have introduced targets for biomass-fuel expansion and the production has increased sharply in recent years, some analysts warned this could cause potential food crisis (Mitchell, 2008; Schneph, 2008; Schmidhuber, 2006 and Collins, 2008). These studies concur that the diversion of the corn crop to bio-fuels is a strong demand force on food prices. The rapid increase of food price could be severe concern particularly for developing countries. It may also need to reconsider the optimism regarding bio-fuels and take a more cautious developing approach. Therefore, the mass production and consequent emission savings of biomass-based fuels largely depend on the use of the second generation biomass-based fuel from dedicated non-food biomass fields, which has less impact on the food industry.

In addition to the methanol and ethanol which can be applied as alternative fuels for

spark ignition engines, a number of alternative fuels with low combustion emissions in compression ignition (CI) engines can also be produced from renewable sources, such as biodiesel, dimethyl ether (DME) and Fischer – Tropsch (FT) diesel (Wang, 1997). Methyl or ethyl esters that are produced from vegetable oils and animal fats are usually named biodiesel which is an attractive alternative fuel to reduce emissions from compression ignition (CI) engines. Because biodiesel is produced from renewable sources, it reduces diesel consumption in ICE vehicles. Biodiesel can be produced through an esterification process from natural vegetable oils including soy oil, cotton oil, and rape oil or cooked oil and animal fats (EERE, 2006). In Europe, biodiesel is mainly produced from rapeseed, while in the United States it is mainly produced from soybeans (Wang, 1998), where the soybean-to-biodiesel cycle consists of soybean farming, soybean transportation to soy oil plants, soy oil production, esterification of soy oil to biodiesel, transportation of biodiesel to bulk terminals (where it is blended with diesel), distribution of biodiesel blend to refuelling stations and vehicular combustion of the biodiesel blend. Biodiesel has been proposed for compression ignition (CI) engines to improve fuel efficiency and reduce vehicular NOx and PM emissions, and as a renewable fuel, biodiesel also helps reduce oil consumption. However, the production cost of biodiesel is prohibitively expensive, mainly because of the high cost of feedstock resources (soybean in particular). The CO_2 emission from biodiesel combustion during vehicle operation is generally similar to the conventional ICE vehicles. Like other biomass-based fuels, a significant CO_2 emission reduction can be achieved through carbon absorption from atmosphere

during the growth of feedstock plants.

DME is an oxygenated fuel and can be produced from woody biomass and herbaceous biomass via gasification process. DME is a promising fuel in compression ignition (CI) engines and owing to its high cetane number, which greater than 55 compared to 40–53 of diesel, and this means that DME is able to improve the performance stability of conventional diesel engine (Hansen et al, 1995). DME has physical properties similar to LPG and the use of DME in diesel engines can also reduce NO_x and PM emissions (Blinger, et, al, 1996). However, the volumetric energy density of DME is only half of that of diesel fuel and DME would deteriorate elastomeric materials such as rubber and plastics, though it is non-corrosive to metals (Arcoumanis, Bae et al. 2008).

The Fischer-Tropsch (FT) process is a catalyzed chemical reaction in which synthesis gas is converted into liquid hydrocarbons. The combination of biomass gasification and FT synthesis is a potential solution to produce renewable vehicle fuels. Different types of biomass resources (such as woody and herbaceous materials and agricultural and forest residues) can be used as a feedstock to produce FT diesel (FTD). FTD is similar to crude oil distilled diesel and can be used by ICE vehicles without engine or refuelling infrastructure modifications. Due to the higher cetane number (leading to the better auto-ignition quality and lower aromatic content and lower NO_x and PM emissions), FTD is a favourable option for substituting conventional vehicle fuels.

However, both DME and FTD currently have technological and economic barriers and would unlikely be applied in transport sector substantially in the near term.

From the discussion above, it can be found that biomass-based fuels usually can be obtained from a wide range of feedstock resources and can effectively reduce the lifecycle CO_2 emission when the carbon absorption of biomass growth is taken into account, though some biomass-based fuels produce a limited volume of GHG savings. However, they are relatively low energy density compared to petroleum, which means a higher volume of fuel must be carried and combusted to generate the equivalent energy to power the vehicle. In addition, the current biomass-fuels are generally produced from agricultural products. Therefore, they potentially compete with food sources and are not cost competitive compared with existing fossil fuels. More importantly, excess use of these biomass based-fuels could threaten the food supplies and biodiversity. Although the second or third generation biomass-based fuels can largely reduce the carbon emissions with less food feedstock concerns, their mass production for automotive use still needs further R&D efforts. Finally, methanol and ethanol are more corrosive on copper, brass, aluminium, rubber and many plastics which cause more difficulties to design and manufacturing of engines. Biomass based-fuels also have cold weather starting difficulties due to the low vapour pressure and evaporation at low temperatures. The high hydrocarbon emission of methanol and ethanol fuels is also a significant issue that needs to be resolved.

- **Fuel Combustion Technologies**

There are two types of natural gas vehicles (NGVs) in the current market: dedicated NGVs which are designed to operate on natural gas only, and bi-fuel vehicles which can use petrol and diesel when natural gas is unavailable (Hoekstra, et al, 1995). Although NGVs are not commercially produced at large numbers, normal conventional petrol and diesel vehicles can be retrofitted for compressed natural gas. In theory, compressed natural gas vehicles (CNGVs) could be more energy efficient because natural gas has a higher octane number than petrol, therefore natural gas engines can be designed with a higher compression ratio (Brinkman, 2005). However, on-board compressed natural gas cylinders cause an additional weight penalty which can amount to between 100 kg and 200 kg. In addition, CNGVs have lower volumetric energy efficiency than petrol. Therefore, current CNGVs have a fuel economy penalty of 5% to 7% compared with conventional petrol vehicles (Brinkman, 2005). According to the tests conducted by ANL, the fuel economy of CNGVs can be 10% to 20% lower than conventional petrol vehicles. The extra weight penalty is expected to be offset by the potential engine efficiency gain for CNGVs which could achieve a same or better fuel economy than those of comparable petrol vehicles. With regarding to the criteria air pollutant emissions, CNGVs can reduce 60% to 80% VOC with significant emission reductions for N_2O and CO. However, CH_4 emission from CNGVs operation can be over 10 times higher than that from the conventional petrol vehicles mainly due to incomplete combustion of the natural gas in the engine. The CO_2 emissions from CNGVs are nearly 20% less than that of conventional petrol

vehicles (Wang & Huang, 1999).

Similar to natural gas vehicles, almost all ICE vehicles can be converted to LPG vehicles (LPGVs). Although there is a large number of LPGVs in the automobile market, their fuel economy and emissions have not been well investigated. Currently, most LPGVs on the road were converted from ICE vehicles and usually have a higher emissions level after conversions (Wang, 1999). The original equipment manufacturer (OEM) LPGVs and dedicated LPGVs are expected to have an improved fuel economy in future. According to tests conducted by EPA (U.S. Environmental Protection Agency), the VOCs exhaust from LPGVs is 15% to 35% lower than that from conventional ICE vehicles. However, the combustion of LPG will generate about 50% CO and NOx more emissions than that from conventional ICE vehicles while the CO_2 emissions are about 10% lower.

The petrol with low-blended methanol or ethanol such as M10 or E10 can be directly used by conventional petrol vehicles, although their emissions reductions are limited. The high blended fuels (over 15% concentration of biomass based-fuel) usually require power train system modification. Although the high-blended biomass based-fuel vehicles achieve a better environmental benefit, they also cause some practical challenges. For example, because high-blended biomass based-fuel is much less volatile than petrol, it could be harder to start some engines especially when the engine is cold during the winter (King, 2006).

In the early 1990s, automakers began to offer methanol flexible fuel vehicles (FFVs) (CleanCities 2008). However, FFVs recently seem to be a plausible AFV option due to the limited methanol refuelling infrastructure and cold start problems with M100. Although little fuel economy and emission testing data available, it is assumed a greater fuel economy and emissions benefits for M100 dedicated vehicle than for M85 FFVs (Wang, et al, 1998). The Battelle Memorial Institute (1995) tested the fuel economy and emissions by use of M85 FFVs. The results show that the fuel economy of FFVs with M85 is slightly lower (-1.4%) than the conventional petrol vehicles. On the other hand, the CH_4 emission can be reduced at a significant level over 50%. The VOC and CO emissions were also reduced around 50% with the only exception of N_2O, which is about double of the emission volume of conventional petrol vehicles. The CO_2 emission from FFVs with M85 is about 18% lower than that of the baseline petrol vehicles (Wang, et al, 1998).

Compared with methanol, FFVs with E85 are currently widely available in the automobile market and have been introduced by many car makers such as Ford, General Motors, Daimler Chrysler, Mercedes Benz, NISSAN and Toyota. According to current trends, the number of FFVs with E85 are expected to grow and with the development of ethanol refuelling infrastructure, dedicated ethanol vehicles using high-ethanol blends (E90) – may be introduced and are expected to bring greater fuel economy and emission benefits than E85 FFVs in future. The National Renewable

Energy Laboratory (NREL) (Wang, 1999) tests showed that the fuel economy of FFVs with E85 differs in different vehicle types. For instance, Ford 3.0 L Taurus FFV has the fuel economy over 10% higher MPGeg (mile per gallon equivalent gasoline) than that of a typical ICE vehicle. The emissions of VOCs, CO and NOx are reduced by 14%, 7% and 7% respectively. The CO_2 emission of FFV with E85 is approximately 15% lower than conventional ICE vehicles. More than 1.2 billion gallons of ethanol are consumed per year in the United States in the form of low blending ethanol with petrol (E10) (Wang, et al, 1997). Little fuel economy (petrol-equivalent) difference can be found between petrol and E10 and the carbon emission reduction of E10 is thus limited. Furthermore, due to the higher Reid Vapour Pressure (RVP) of E10 than petrol, there is about 10% more evaporative fuel emissions by E10 than petrol. For other criteria emissions, FFVs with E10 can significantly reduce CO and VOC emissions.

For conventional petrol vehicles, diesel vehicles, natural gas vehicles and biomass based-fuel combustion engine vehicles, all have the similar power train architecture which consists of an ICE, a multi-speed manual/automatic or continuously variable transmission (CVT) and a torque converter.

Significant technological progresses have also been made for compressed ignition, direct injection (CIDI) diesel engines over last 20 years. CIDI engines can achieve a 35% improvement in fuel economy relative to conventional petrol vehicles. The fuel

economy of petrol ICE vehicles has also been improved, such as Toyota's spark-ignition, direct-injection (SIDI) technology, whose SIDI cars have a fuel economy improvement of 30% relative to conventional ICE vehicles (Automotive Engineering, 1997). However, in spite of improved fuel efficiency and tailpipe emissions, direct-injection engines usually have high NO_x emissions.

According to the EPA tests (Wang, 1999), the fuel economy of conventional diesel vehicles is 10% higher than conventional ICE vehicles running on petrol. In addition to diesel, DME, FTD and biodiesel can also be combusted in CIDI engines. DME has a high cetane number ranging from 55 to 60 compared to that of diesel and contains no sulphur and aromatics. Moreover, the adoption of DME can reduce NO_x and particulate matter (PM) emissions drastically though it emits slightly more VOCs and CO emissions. Experiments also show that the majority of hydrocarbon (HC) emissions from DME combustion consist of unburned DME and methane (CH_4) (Mikkelsen, et al, 1996) thus largely increase CH_4 emissions. The CO_2 emissions from DME combustion can be 10% lower than the use of conventional diesel. There is no DME production for transport use at present in China and DME could be a long-term alternative vehicle fuel option in future.

FTD has a high cetane number and contains virtually no sulphur and aromatics, hence it is regarded as an ideal fuel for CIDI engines with significant potential in lowering NO_x and PM emissions (Lapuerta, Armas et al. 2010). However, few studies have

been made for FTD fuel economy and emissions. According to the tests made by Graines, et al (1998), FTD achieves a 25% reduction in NO_x emissions relative to diesel. CO_2 emission from FTD can be slightly lower than that for conventional diesel engines (Wang, et al, 2006).

- **Alternative Fuel Vehicle Technologies in China**

Chinese Universities and research institutes, including Tsinghua University, Beijing University of Technology, Tongji University and China Academy of Science, have conducted a number of research projects that investigate the implications of potential alternative fuel vehicle development in China. For example, Yi et al (2005) made an energy consumption and emissions estimate for corn-based ethanol E10, E30, soybean based-biodiesel BD10 (a blend of 10% biodiesel and 90% petroleum distilled diesel in volume) and BD30. In contrast to the US DOE's studies, they found ethanol cannot effectively reduce GHG emissions in the WTW perspective due to the high cultivating energy use (fertilizer, pesticide and irrigating diesel and electricity). Hu et al (2006) further conducted an emissions assessment for biodiesel produced from soybean and oil seeds. Zhang (2003) also produced a lifecycle assessment for cassava-based ethanol with a cost analysis. Wu et al (2005) focused on natural gas based-fuels, mainly due to the plentiful natural gas resources in Sichuan Province. They concluded that cassava and natural gas based vehicle fuels are promising options for China in terms of both environmental and economic benefits, despite the limited production capacity. Zhang, et al (2005) concentrated on coal-based vehicle fuels and

demonstrated that the coal-methanol has a large potential in China. Zhang et al (2006) investigated coal-based methane/DME (Dimethyl Ether)/Diesel pathways and further indicated the DME benefit in fuel economy improvement. Furthermore, Xiao et al (2005) made a quantitative energy consumption and emissions comparison between a variety of conventional and advanced clean coal-based electricity generation technologies. According to their findings, a combination of raw coal washing, supercritical power generation and the flue gas desulphurization (FGD) has a large potential in overall emission reductions. Feng, et al (2003) concentrated on hydrogen fuel cell technologies and concluded that the most environmentally friendly pathway for producing vehicle fuel hydrogen is central production of hydrogen along with the use of pipeline to move the gaseous hydrogen to refuelling stations. Kreucher et al (1998) conducted a research on the development potential of coal-based methane and coal-based electricity in Shanxi province in China.

In conclusion, natural gas and LPG vehicles could play a significant role to substitute the petrol and diesel fuels. However, due to the limited resources, they can only meet a minority of automotive fuel demand and are more appropriate for regions with abundant feedstock sources (south-west provinces). With regard to biomass-based fuels, the large scale adoption of biomass-based fuels will inevitably cause a land and water competition for food production in China. In addition, their potential carbon emissions savings are expected to be insignificant due to the high energy intensity of the farming industry. For hydrogen fuels, they are facing high cost barriers in China,

similar to other countries and are seen as a long term option. In contrast, China has vast reserves of coal. With the rapid development of clean coal combustion and carbon capture and storage (CCS) technologies, EVs could reduce road transport dependence on fossil fuel, as well as mitigate carbon emissions. Given the recent years' fast growth of renewable energy use in China's electricity mix, further carbon reduction could be achieved by EVs.

2.5 Low Carbon Transport Strategies

In addition to the introduction low carbon alternative fuel vehicles, a number of strategies have been suggested to mitigate carbon emissions from the transport sector, including implementing pricing signals, promoting public transport, walking and cycling, improving urban planning, shifting travel behaviour and developing information and communications technologies (ICT). Although the primary purpose of many strategies is to control the transport demand growth and ease traffic congestion, particularly in urban areas, they usually also have an evident effect on energy use and carbon emissions savings with relatively lower costs.

Public Transport

Public transport is considered a conventional and effective measure to reduce transport energy use and vehicle emissions. In recent years, the extensive public transport network integrating regular bus and Mass Rapid Transit (MRT) has

developed at a remarkable rate in many Chinese cities. In Beijing, for example, only two metro lines have been built from 1980 to 2000, whereas 12 new metro lines were built and put into operation from 2001 to 2011. The total length of metro line increased from 53.5 km in the 1990s to 336 km in 2010 (Beijing Municipal Bureau of Statistics, 2011). In Shanghai, there was no metro until the 1990s. There are (2011) 12 metro lines and the total length is expected to reach 970 km by 2020 (Netease, 2007). In many cities, the Bus Rapid Transit (BRT) has been introduced as a cost-efficient measure to cope with the rapid increase of travel demand. For instance, Jinan local government has invested RMB 54.5 million and launched the city's first two BRT lines in 2008, with additional three lines in 2009 served by 165 BRT vehicles (ChinaBRT, 2011).

Walking and Cycling

Walking and cycling offer the most carbon-efficient means of travel for short distance trips. However, compared with the fast development of motorized transport, walking and cycling facilities and space are being severely squeezed in China. To encourage walking and cycling, some local authorities are now introducing public bicycle programs and pedestrian corridor networks. For example, in Hangzhou the local authority launched the "Public Bicycle Program", which provides 17,342 public bicycles and 800 service points across the city offering bicycle borrowing service for free. However, the progress of these programs is slow due to their low profitability (Beijing Evening News, 2011). In the case of Beijing, the average annual loss for a

service point with 40 public bicycles is more than RMB 100,000 due to high labour and land costs. The insufficiency of cycling infrastructure and coordination between different operators further reduces the public acceptance of this program.

City Planning

Efficient urban planning can also reduce travel demand, and hence mitigate energy use and carbon emissions. The decentralized development pattern that formulates relative distributed urban centres could effectively reduce the need for travel while offering a high quality of life. However, with the fast urbanization and the limited space in cities' central areas, more and more urban residents are moving to the outskirts encouraging growth in the suburban residential population. The increasing spatial separation between working and accommodation further promotes the growth of travel demand. To tackle the trend of urban sprawl, the Transit Oriented Development (TOD) was suggested to tackle the rapid growth of travel demand (David 2008). TOD aims to create compact communities around rapid transit systems or other public transport modes, and thus reduce people's dependence on car mobility. In addition, appropriate urban planning with improved walking and cycling consideration can encourage the travel mode shift to non-motorized travel. A well-connected interchange network would also encourage more park & ride and public transport.

Travel Behaviour

Selecting low carbon transport modes or adopting low carbon driving behaviour can reduce associated carbon emissions. Energy (fuel) efficiency significantly varies among various transport modes (see Table 5) due to their diverse carbon intensities. Because of the high passenger load capacity, public transport modes usually have relatively low energy intensities. A successful promotion of public transport (rail transport in particular) could significantly lower the fuel consumption in the perceptive of per passenger-distance travelled. On the other hand, the on-road vehicle fuel economy also differs under different driving behaviours (eco-driving) and conditions. The typical fuel efficient driving techniques include maintaining proper tire pressures, minimizing vehicle carriage weight and keeping at fuel-efficient vehicle speeds. The adoption of eco-driving behaviour relies on extensive public education and its effect is usually connected to the fuel price.

Table 5 Energy Intensities of Transport Modes

	Load Factor	**Energy Intensities**	
	persons/vehicle	Million Joules per vehicle-mile	Million Joules per passenger-mile
Car	1.55	5.78562	3.73259
Personal Trucks	1.84	7.1107	3.864465
Motorcycles	1.16	2.72612	2.5953
Buses (Transit)	9.2	41.3138	4.47531
Air	99.3	296.17437	2.98143
Rail	25.8	66916	2594

Source: United States Department of Energy, 2009

Information and Communication Technologies (ICT)

The fast developing internet has already profoundly changed people life style and has also significantly changed the travel behaviour The advanced communication technology can reduce the demand for the transport and mobility services, and has therefore been regarded as an effective measure to decouple the transport growth from the economic growth (see Section 2.3.4). Some crucial ICT applications that make a deep impact on people's travel demand include: telecommuting, e-business (or e-commerce) and e-services. All these applications have shown a large potential in reducing travel by ICT-based online activities. In China, the e-business is growing at an unprecedented rate in recent years. The proportion of online retail sales to gross retail sales and consumer goods reached 2.1% in 2009, which has resulted in an increase of 78% over the figure in 2008 (National Statistics Bureau, 2010). The penetration of ICT in the modern society is expected to continue, and this could further change people's demand for travel.

Figure 17 Energy and Carbon Mitigation Strategies in Transport Sector

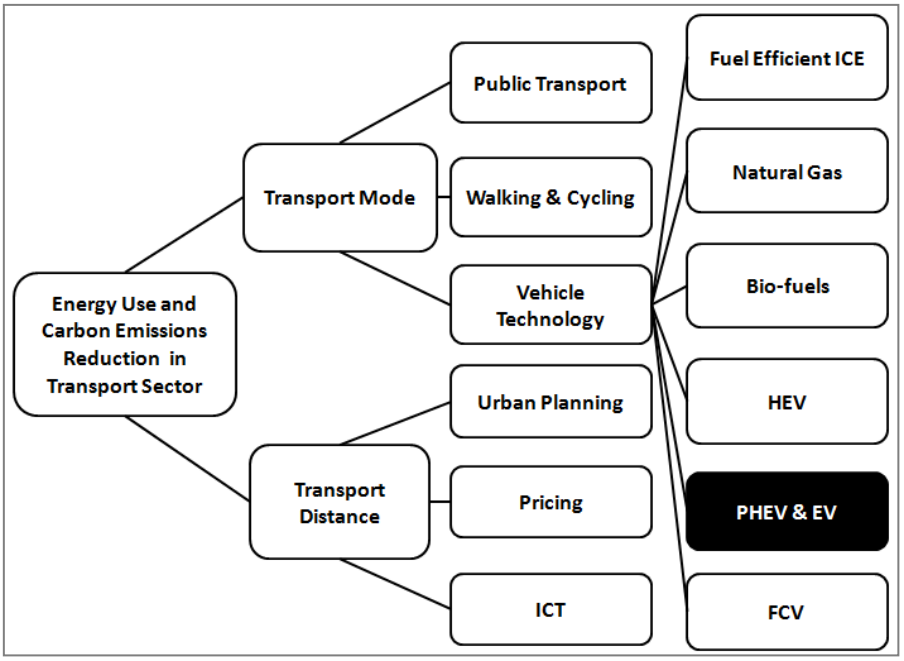


Figure 17 summarizes a range of typical measures to reduce transport energy use and carbon emissions. In general, the reduction could be made through mode shift to low carbon transport or reducing our transport demand in terms of travelled distance. Each strategy contains specific measures. For example, for the "Vehicle Technology" category, the potential options contain biomass based-fuel vehicles, natural gas ICE vehicles, HEVs, EVs, FCVs or high efficient petroleum ICE vehicles. Although there are a wide range of strategies can be implemented to reduce the carbon emissions from road transport sector, this thesis focuses on future potential of alternative fuel vehicle application, particularly EVs and the implications for China. This thesis therefore takes a study of EV potential in terms of the energy and environmental benefits as well as economic implications and provides recommendations for their future development in China. Chapter 5 compares various AFV options in terms of their lifecycle energy consumption and GHG emissions, and it conducted a

break-even analysis to predict their pay-back periods relative to ICE vehicles. Chapter 6 investigates the PHEV's energy use and GHG emissions saving potential, based on the energy mix and typical driving behaviour in China. Chapter 7 compares three charging infrastructures for PHEVs and PEVs, and takes a case study city to explore their geographical distribution impacts on the power grid. Chapter 8 conducted a vehicle population projection for EVs in Shanghai and made a quantitative analysis for potential business operation models that tend to reduce carbon emissions.

2.6 Interview Results

To investigate the current development status of EVs in China, the research takes a number of interviews with experts in new energy vehicle and energy industries. This section presents some outcomes from the interviews.

Interviewee 1 - Chief Analyst in China Automotive Development Consultancy Company

Interviewee 1 is a chief analyst in China Automotive Development Consultancy Company and an expert in automobile market and policies. He has been involved in China's automotive market and policy research for over 30 years.

In the interview, he expressed his opinions on future alternative fuel vehicles (including EVs and other alternative fuel vehicle technologies) in China. He reckons

that different vehicle fuel technologies would share the future China's automobile's market, and in particular high fuel efficient ICE vehicles, biomass-based fuel vehicles and hybrid electric vehicles would make most impact in the private car market in the medium term. He believes EVs should identify their breakthrough point in the market instead of competing with conventional ICE vehicles in the general market. For example, as some HEVs (particularly for PHEVs) are able to run purely on electricity for short distance travels (despite the limited range), they are the ideal solution in urban areas where the daily commuting trips take the majority of transport, and thus able to effectively alleviate vehicles' carbon emissions. However, both the government and automobile industry currently still have concerns over EV development: the car manufacturers are concerned that the introduction of low performance EVs would have a negative influence on their market image. In many cases, Chinese car manufacturers would rather be concentrating on improving ICE vehicles' driving performance (for example, improving the power and torque of vehicle engine) to facilitate their ICE vehicles competition in the conventional automobile market. This also partly reflects the Chinese customers' attitudes, as they prefer high performance vehicles rather than environmental friendly models.

He holds the opinion that ICE vehicles would dominate China's automobile market to 2050 and that biomass-based fuel vehicles could be the ideal option for China as the production of biomass-based fuels could offer additional income for farmers. He insists that the development of EVs should not purely rely on the battery technology

breakthrough. Instead, both government and car industry should play a more active role to raise the public awareness of alternative fuel vehicles and accelerate their market penetration.

In addition, he believes the batteries that BYD uses in their F3DM and F6DM are $LiFePO_4$ batteries (instead of the K_2FeO_4 or $BaFeO_4$ that were widely reported). He supposes the significant cost reduction of BYD batteries should be attributed to the to the renowned BYD's ICE vehicle supply chain management techniques that remarkably reduce the costs during the manufacturing and assembly processes. In summary, he recommended a multi-pathway development for China's new energy vehicle industry. Different cities and regions should develop their own solutions to introduce alternative fuel vehicles in terms of the local geographical and economical characteristics. As an example in Sichuan province which holds a vast of the natural gas reverse, CNG vehicles or LNG vehicles would be the ideal solutions.

He also provided some recently published HEV research papers from Tsinghua University focusing on the lifecycle assessment of energy assumption of the HEV pathway; and some HEV market analysis reports from China Association of Automobile Manufacturers (CAAM) focusing on the Chinese car market forecasts, as well as customers' choice analysis and government policies.

Interviewee 2 – Professor in Tsinghua University

Interviewee 2 is a professor in energy policy research from Tsinghua University. In 2008, she led the first comprehensive lifecycle assessment research for alternative fuel vehicles in China. Recently, she participated in the “Sino-Danish Renewable Energy Development” project in National Development and Reform Commission (NDRC).

In the interview, she introduced the previous research on alternative fuel vehicle lifecycle assessment by Tsinghua University and corresponding research methods and their lifecycle assessment data. She also offered her views on Chinese alternative vehicle fuels development pathways, opportunities/challenges and required political/financial incentives. The main opinion of her is: in addition to the energy and emissions assessment for new energy vehicles, some other practical issues currently play a more important role in the success of EVs, including cost reduction and the charging infrastructure establishment for EVs. For example, the market diffusion of EVs and PHEVs is largely impeded by the shortage of charging infrastructure, high battery costs and the absence of a well-established used battery market. Without addressing these key practical issues properly, it could be difficult for these vehicles to really penetrate into the automobile market, despite their apparent environmental benefits.

She agrees that the Chinese government shows its preference for HEV and EV pathways. With regarding to EVs in particular, she stressed the importance of feedstock supply reliability for electricity. Different selections of energy feedstock for

power plant during the power grid's peak and off-peak loads will largely influence the lifecycle energy consumption and emissions assessment for EVs. The adoption of renewable energy for China's current power plants is a perquisite for EV development. For the battery cost and capacity, she believes the current cost of EV is relatively high as compared with other alternative fuel vehicles due to the extremely high costs of the battery. She agrees with Interview 1's opinion that significant cost reductions have been achieved for some EV models in the market, such as BYD F3DM and e6. However, the massive introduction of EVs in the private sector still relies on continuous R&D effort to further improve battery range and to cut the cost. She particularly stressed the current charging infrastructure shortage in China, which has been one of the emergent issues that need to be addressed.

With regarding to the research methodologies, she suggested that the internet questionnaire could be an appropriate survey method. The questionnaire should be brief and simply structured. She is particularly interested in the questions relating to Chinese customer's acceptable pay-back period for alternative fuelled vehicles, and this is a core interest in Tsinghua University's research. For the data collection of energy efficiency in Chinese energy industry, she recommended the "Lifecycle Assessment for Alternative Fuel Vehicles" (Book) that has been collectively published by Tsinghua University and NDRC in 2008.

Interviewee 3 – Professor in China Academy of Social Science (CASS)

Interviewee 3 is a senior researcher in Industrial Economics Research Institute in China Academy of Social Science. He is an expert in Chinese automobile industry and consumer markets and he has been working in NISSAN Automobile Research Centre in Tokyo.

He stressed the need for political and economic interventions to promote new energy vehicles in China. Identical with Interviewee 2's opinion, he believed the most important emergent issue for new energy vehicles in China is to promote their awareness among the public and to ensure their acceptance, and this is not only dependent on the battery technological breakthrough. Political incentives for infrastructure and facility provision are urgently required. With regard to the research methodology, he suggested that the current research projects of the Chinese Environment Protection Agency and institutes could be helpful. These have been carrying out a series of transport environment research programs (including lifecycle analysis for vehicle emissions and energy use) and their research findings could be more objective and reliable than the research made by car industry.

He reckoned it is difficult to exactly predict future alternative fuel vehicle development in China, due to many uncertainties in the technological, political and market sectors. For instance, he mentioned that "although the development of fuel cell vehicles needs to overcome the hydrogen storage and transport barrier, they could be an essential competitor in car market due to the compatibility of a wide range of fuels,

including hydrogen, methanol, ethanol, petrol and diesel". He stressed that scenario setting would be essential for alternative fuel vehicle research. For data collection, he recommended that the Ministry of Industry and Information Technology (MIIT) released and updated the fuel economies of all car models currently available in the China's automobile market.

Interview 4 – Senior Researcher in China Academy of Social Science (CASS)

Interviewee 4 is the director in Energy Economics Research Office of CASS and a senior researcher in energy economics and China's energy industry reform.

During the course of interview, she stressed the importance of upstream energy (electricity) production in the lifecycle assessment for EVs, as this could have a greater impact on the final outcome than choosing different EV models in the analysis. She asserted that the current generation capacity of China's power industry is developing fast; in contrast, the electricity distribution and storage required further development. In the middle and west part of China, a number of renewable energy projects (solar and wind plants) have been proposed in recent years. Although they provide a considerable generation capacity from renewable energy, the large generation capacity and relatively limited power transmission provision has caused a significant electricity generation waste. The central government even ceased the new approval of similar projects in the regions in 2007 to 2008. She recommended that a better "plug-in" of the new energy produced energy to the main power grid is a key

issue in China's energy industrial development, and the smart grid which has been proposed in the United States could be the trend. The upgraded power grid can seamlessly integrate electricity generation, transmission, distribution and user-consumption segments. Moreover, she provided the access to CASS database for China's historical energy industry statistics and also recommended the "China Energy Industrial Reform" which has been recently published by the Energy Economics Research Office.

Interviewee 5 – Vice President of Better Place

Interviewee 5 is responsible for Better Place's global media relations and industrial analyst relations. The interview was undertaken during the 2011 European Electric Vehicle Conference in Brussels.

During the interview, he explained Better Place's mileage-contract service for EV drivers and answered my questions about charging fee collection systems. He also introduced the company's pilot projects in Demark and Japan, as well as a primary research project in the United States. According to the United States scenario, one million electric vehicles without charging management are expected to cause $750 million expenditure on charging electricity. The variable electricity pricing could influence the charging behaviour and thus reduce the cost, though the scale of cost saving is limited (10%). In contrast, a charging service operator with central battery charging management could cut the charging cost by 50%, while reducing the

incremental grid infrastructure cost as compared with the un-managed charging scenario. He admitted that the proposed business operation model relies on a full coordination between electricity generators and providers, charging service operator and EV consumers. The standardization of batteries and charging interfaces has been also a major barrier to the introduction of mileage-contract services and battery swap in the private car sector. However, some regions with relative a high petrol price and high renewable electricity share could be appropriate for the implementation of EV pilot programs.

Interviewee 6 – Researcher in China National Offshore Oil Corporation

Interviewee 6 is an expert in EV business operation models and battery charging (swap) infrastructure. He is also one of advisors for the national standard design of EV charging infrastructure.

He insisted that EV must provide both lower cost and more convenience to consumers to compete ICE vehicles in the private car market. In the future, the high EV purchase cost could be reduced by innovative business operating models, though a widely distributed charging infrastructure network requires large capital investment and perhaps needs substantial subsidies from the government. He estimated that the average initial cost of China National Off-Shore Oil Corporation's (CNOOC) battery charging and swap stations would be RMB 3 million each (excluding land cost), and the daily service capacity ranges from 200 to 300 vehicles. The proposed monthly

battery leasing rate is RMB 150 to RMB 200. He agreed that the company's business model relies on the a well-established used battery market and estimates the power grid companies would have a large demand for used batteries to develop the grid's storage capacity.

Chapter 3 Research Aims and Objectives

From the discussion in Chapter 2, it can be seen that the success of EVs depends on a series of determinants. Although the battery and vehicle technological breakthrough usually attracts more academic attention, some other key determinants are also crucial for EV development in China. Although some of the key determinants have been studied over a lengthy period, they have been not fully assessed within the Chinese situation in terms of China's energy mix, people's driving behaviour, and the economic and political conditions. For instance, the large potential for petroleum fuel savings and carbon emissions reduction are the two main motivations for promoting EVs. However, given the high carbon intensity of the power grid (highly reliant on coal) in China, the lifecycle energy and emission performance of EVs still needs thorough assessment. Moreover, Chinese drivers also have distinctive driving profile (daily travel distance and driving time) that is different to European and American drivers, and this could be a significant factor for EVs' market diffusion. In addition, the current load profile of the power grid, which is determined by the economic and social activities, will also be a key factor in building an appropriate charging infrastructure network for EVs. With regard to the commercialization of EVs, the

market diffusion is always hampered by the high battery cost. Apart from subsidies, some innovative business operation models have also been proposed to reduce the high cost. Although they are likely to directly cut the EV purchase cost for EV users, their life time cost-benefit for both EV users and the charging service provider is still uncertain in China. This research builds a network map that summarizes the factors determining EV development in China (see Appendix 7).

However, instead of covering all aspects, this thesis focuses on four key aspects of EV development in China:

1. The energy consumption and carbon emissions of EVs based on the China's energy mix;

2. The expected EV driving profile (including daily driving distance and driving time) in China and its impact on the energy use and carbon emissions;

3. The deployment strategy of charging infrastructure for the preliminary EV market in China based on the people's driving behaviour and power grid capacity.

4. The business operation models that could reduce the EV purchase cost and accelerate the EV market diffusion at an early stage.

3.1 Energy Consumption and GHG Emissions

As discussed in Section 2.3.1, although EVs can offer substantial carbon saving and air quality benefits during the vehicle operation stage, their overall environmental performance is also dependent on the upstream process and it is essential to make a lifecycle assessment of EV energy use and emissions, as well as the whole industry chain associated with EVs.

An evaluation of vehicles' energy and carbon emissions needs to be taken in a lifecycle respective that consists of the "Well to Pump (WTP)" and "Pump to Wheel (PTW)" stages. Although there have been numerous previous energy and emissions life cycle studies on EVs, the current vehicle life cycle research in China still has a series of shortcomings on both stages. For the WTP stage, the main problems include:

1. Some critical energy production data used in previous research were based on data from foreign countries or generated by simulation software, and this cannot fully reflect the situation of the Chinese energy industry.

2. Previous life cycle assessments in China mainly focused on one single energy pathway and ignored a number of secondary pathways. These involve the production of various process fuels and the calculation of many by-products embedded within the main life cycle pathway. Some previous research referred to some assumptions made for the secondary cycles in other countries (Zhang, et al,

2007). Their consequent conclusions could therefore significantly deviate from China's reality by the accumulated errors, particularly for fuel production pathways involving combined cycle processes, for example, the Integrated Gasification Combined Cycle (IGCC) or the Natural Gas Combined Cycle (NGCC).

3. Some life cycle models do not include the circular calculations that exist in the production of vehicle fuels, particularly for the electric energy pathway for EVs, where the upstream iterations to produce process fuels (for example, electricity or natural gas) were usually ignored.

The PTW assessment is also a key stage in the lifecycle analysis for EVs, particularly for plug-in hybrid electric vehicles (PHEV) that consist of both an ICE and a battery. The driving behaviour (daily travel distance in particular) directly determines the electric utility factor[18] (UF) of the vehicle, which determines the petroleum fuel consumption as well as the operating cost. This dissertation, therefore, investigates the energy and emission profiles of electric vehicles based on the observed driving behaviour in Chinese cities via onsite, internet-based surveys and the latest published commuting travel statistics. The internet-based survey was carried out in cooperation with an internet company during the period from 24 February to 26 March 2010. The onsite survey focused on the investigation of residential and public parking conditions

[18] Utility factor represents the percentage of a PHEV's electricity consumption over its entire energy consumption during vehicle operation.

(distribution, capacity, occupancy and price) in current Chinese cities.

3.2 Driving Profile

The driving profile (daily driving distance and driving time in particular) will largely influence the market acceptance of EVs. Because the electric range of EVs is currently still lower than the range of ICE vehicles running on petrol or diesel, or on PHEVs that combine both batteries and an ICE to provide both electric and fuel operation modes. For short distance travel, electricity is used to power the vehicle with zero tailpipe emissions, while petrol or diesel is used for long distance travel when the battery is depleted. As introduced in Section 2.3.2, there have been studies in the United States for the energy and carbon emission saving potential for PHEVs based on the country's daily driving profile. However, peoples' driving profile in China could be significantly different to that in the United States (in terms of both daily driving distance and driving time), which results in the distinctive battery requirement and power grid impacts in China.

Although the driving profile of EVs is a crucial factor determining both EVs' market acceptance and charging infrastructure deployment, this issue has not been fully studied in China. This thesis therefore aims to investigate the energy consumption and carbon emissions of PHEVs based on the observed driving profile in China and to evaluate the correspondent charging impacts on the power grid according to the

predicted daily charging time. Chapter 6 forecasts the utility factor of a prototype PHEV based on the daily driving distance in China through an online survey. Chapter 7 and Chapter 8 estimate charging activities' impacts on the power grid based on the driving profile in case study cities.

3.3 Charging Infrastructure Deployment

A well-established charging infrastructure network can effectively lower the range requirement for EV batteries. In contrast to ICE vehicles, EVs could be charged via power outlets distributed in residential areas, public parking and charging stations. The battery swap further increases the flexibility and complexity of EV infrastructure deployment. On the other hand, the provision of the charging infrastructure would affect customers' driving behaviour and charging impact on the power grid. The research of charging infrastructure development is a relatively new arena and there are still some insufficiencies in previous studies, namely:

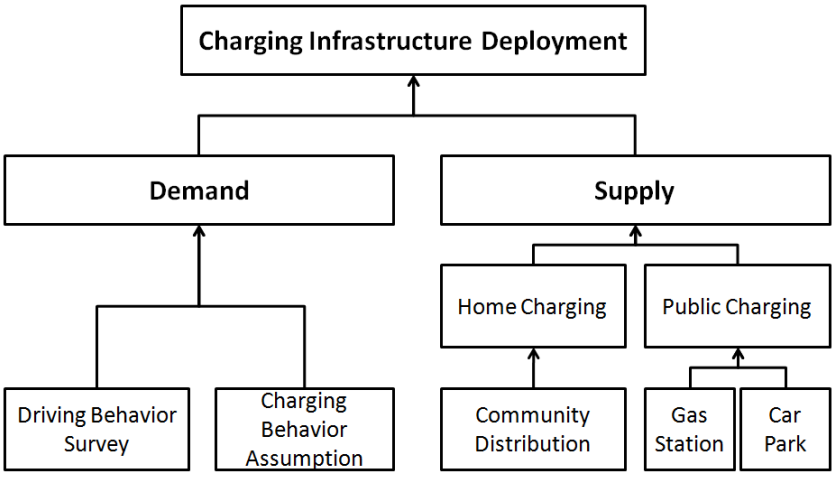
1. Previous charging infrastructure research mainly focuses on public infrastructure, including public charging spots, charging stations or battery swap stations. It has been observed that different cities have proposed distinct deployment strategies for charging infrastructure, for example as in London, where the primary charging spots have been mainly allocated to workplaces, whereas in Beijing, more charging stations, providing fast charging services, are being constructed than

charging posts Few studies have been made on the relationship between home charging and public charging, and their roles within a whole charging network.

2. Previous studies on refuelling infrastructure distribution usually use demographic, social-economic or traffic flow data to forecast EV charging demand (associated with assumptions on EV market penetration). However, the charging infrastructure needs also to be designed according to the available parking space and local power grid conditions. To produce a reliable and practical infrastructure development plan, both charging demand and supply capacity (in terms of parking space and electricity energy/load availability) should be integrally considered.

Therefore, this thesis conducts an EV charging infrastructure analysis combining residential and public charging options. Through case studies in the cities of Beijing and Shanghai, this thesis aims to propose charging infrastructure deployment strategies for both cities according to their geographic (residential and working distributions) and driving behaviour characteristics (daily travel distance and travel time profiles) (See Figure 18). On the basis of a proposed charging infrastructure pattern, a comparison of various potential business operating models is also made.

Figure 18 Infrastructure Deployment Factors

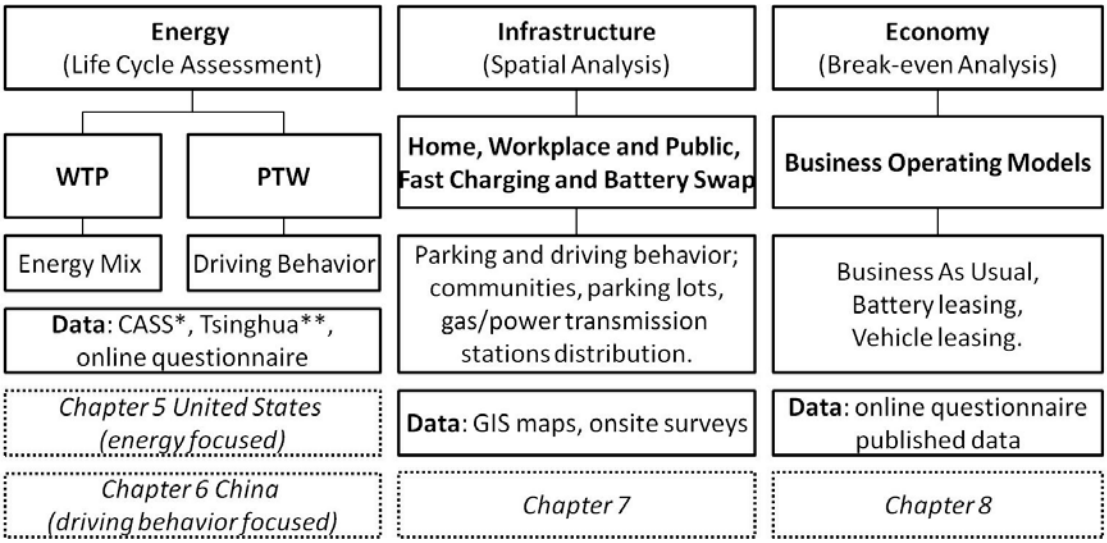


3.4 Business Operation Models

It has been discovered that the high purchase cost of EVs could be reimbursed over the lifecycle of vehicle use (Liu, 2009). However, the long payback period still significantly hinders the customers' EV acceptance. It therefore has been recommended that a service operator could own EV batteries and lease them to customers via a service contract, where EV users would only purchase an EV without a battery at a significant lower price and pay a regular contract fee to the operator. The operator in this case would be responsible for charging infrastructure and electricity provision, battery and infrastructure maintenance and battery recycle. This business model would not only promote the market attractiveness of EVs for consumers but also extend the battery life because of better battery management by the operator. A scheduled charging management by the operator would also benefit the power grid operation as the charging activities could be undertaken during grid's off-peaks, thus

lower the upgrading requirement for the power grid. Chapter 8 investigates the potential of EV business operation models in Shanghai and forecast the break-even points for EV user and the charging service operator based on daily driving profile and the estimated EV stock growth in the city. The framework of the Chapter 5 to Chapter 8 is introduced in Figure 19.

Figure 19 The Framework of Chapter 5 to Chapter 8



Note:
**CASS – China Academy of Social Science*
***Tsinghua – Tsinghua University*

Each of these aspects is focused by Chapter 5 to Chapter 8 respectively.

This thesis focuses on the cars rather than urban buses, small (delivery) vans or mopeds/motorcycles due to the considerations such as the large share of energy consumption and carbon emissions from cars, fuel (energy) economy data availability for car models. The implications of introducing EVs in public transport and other

transport modes are not covered by this study.

Chapter 4 Research Methodologies

Different research theories and methodologies have been applied in this thesis. The applied research methods can be divided into quantitative (including the lifecycle assessment for energy consumption and carbon emissions for EVs, break-even analysis for EV users and spatial optimization for charging infrastructure deployment) and qualitative methods (including interviews with experts and case studies). Chapter 4 to 7 contains the specific introduction of research methodologies. Each research method services specific research objectives in the different chapters. For example, to investigate the environmental impacts of alternative fuel vehicles, the lifecycle assessment is applied to measure the cradle to grave energy consumption and carbon emissions of various vehicle technologies; to estimate the potential market acceptance of EVs, the break-even analysis is applied to predict the cost and benefit of EV purchase. This section makes a general introduction for each theory and method.

4.1 Neoclassical Economic Theory

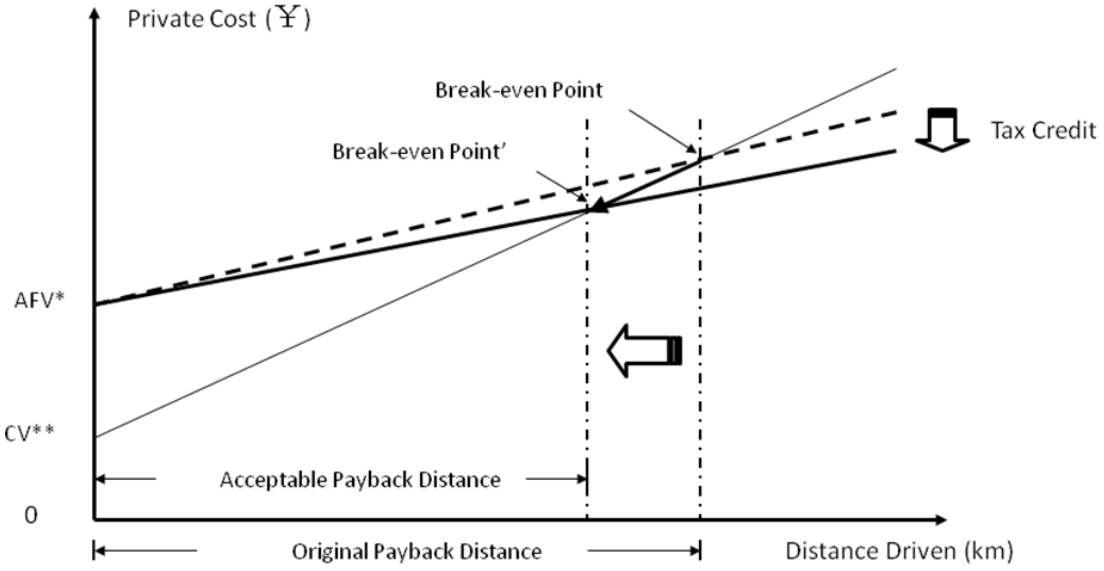
Neoclassical economics rests on several assumptions, including people's rational satisfaction, free market and full information dissemination (Weintraub, 2007). The

neoclassical economic theory currently is the mainstream in microeconomics which focuses on the determination of prices and distributions in markets through supply and demand, and it usually applies a rational choice theory where individuals make their economic decisions to maximize their utility[19]. This thesis compares different vehicle/fuel systems and business operation models through break-even analysis that simulates consumers' behaviour based on the neoclassical economic theory. In Chapter 5, various vehicle/fuel systems lead to distinctive purchase and operation costs combinations. In order to compare the market acceptance of different alternative fuel vehicles, a *break-even analysis* is conducted to calculate vehicles' lifecycle costs for consumers. In Chapter 7, the consumer's initial cost is reduced by battery leasing or vehicle leasing programs. With the lower initial cost and the comparable operating cost to petrol vehicles, innovative business operation models could effectively encourage the EV purchase.

In order to identify the 'acceptable' payback period of EVs for typical Chinese private motorists, an online survey is conducted. Once a 'maximum' payback period is identified, the viability of different vehicle/fuel systems can be assessed. A series of policy packages (vehicle purchase subsidies and fuel tax credits) to reduce the payback period of alternative vehicle fuel technologies have also been simulated. An example of the effects of a tax credit is illustrated in Figure 20.

[19] In economics, utility is referred to the total satisfaction received by a consumer from consuming a good or service.

Figure 20 Policy Effects on Payback Distances



**AFV: Alternative fuel vehicle;*

***CV: Conventional ICE vehicle.*

To estimate the EV stock growth in Shanghai, Chapter 7 adopts the *Bass diffusion model*. Bass diffusion model was a market forecast model developed by Frank Bass in 1969 to describe the market penetration process of new products (Bass, 1969). The model has successfully forecast the market penetration of a variety of products ranging from colour TVs, air conditioner and CD players, and it has now been widely applied in market and management studies. The model simulates the new product adoption process as an interaction between current users (innovators) and potential users (imitators). The algorithm of Bass diffusion model can be expressed as Equation 1:

Equation 1:

Where:

S(t): accumulated adopters;

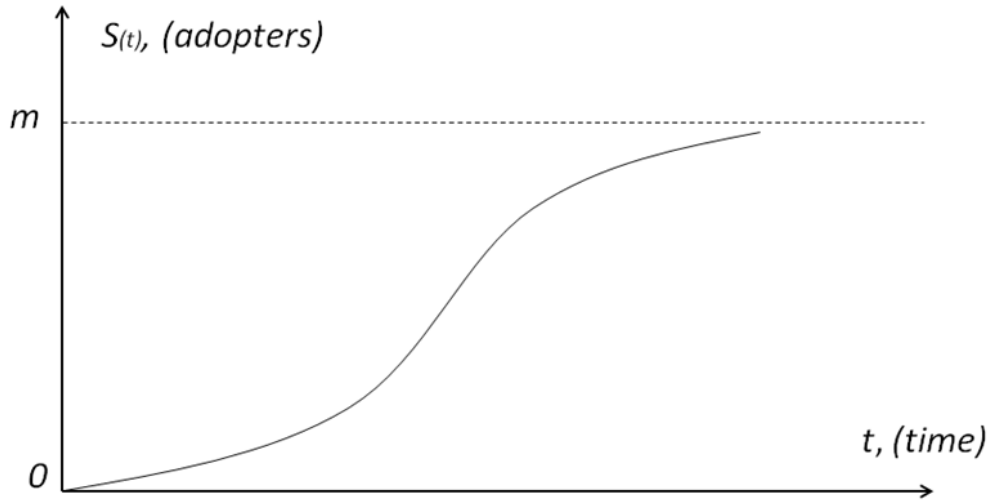
f(t): the rate of change of new adopters;

m: maximum market potential;

p: the coefficient of innovation;

q: the coefficient of imitation.

Figure 21 Bass Adopters Growth Curve



4.2 Environmental Economics

Environmental economics is a branch of economics that focus on environmental issues and this thesis applied a series of environmental economic concepts and research methods, including externalities, social cost of carbon (SCC), lifecycle

assessment and utility factor (UF).

According to the definition by Hanley et al (2007), "environmental economics undertakes theoretical or empirical studies of the economic effects of national or local environmental policies around the world…" and "…particular issues include the costs and benefits of alternative environmental policies to deal with air pollution, water quality, toxic substances, solid waste, and global warming". The core concept of environmental economics is market failure. A market failure refers to the case where the market does not efficiently allocate resources to produce largest social welfare. It occurs when the private interests of individuals conflicts with the environmental benefit. The notion of "externalities" is usually used in environmental economics to describe the effect of a person's decision on other persons, which are not reflected in the market price. In this thesis, the externality of alternative fuel vehicles would be potential energy consumption and carbon emission savings that are not accounted in the market. Therefore, some financial and political incentives, such as fuel tax credits and vehicle purchase subsidies, which intend to integrate environmental cost (externalities) in the market, are required.

In order to provide an integrated picture combining external and private costs, the *social cost of carbon (SCC)* is referred in Chapter 4. The SCC measures the full global cost today of emitting an additional tone of carbon now and sums the full global cost of the damage it imposes over the whole of its time in the atmosphere (Department of

the Environment, Food and Rural Affairs, DEFRA, 2007a). Importantly, 'the SCC varies depending on which emissions and concentration trajectory the world is on' (DEFRA, 2007b). In recent years there have been a number of studies attempting to estimate the SCC (Nordhaus, 1991, 1994; Cline, 1993; Fankhauser, 1994; Tol, 1999; Tol and Downing, 2000), as well as a number of reviews (Clarkson and Deyes, 2002, Tol, 2005, 2008). It should be noted that SCC is only valid from a social point of view. An individual will typically ignore all external costs. Therefore the market analysis will consider consumers' behaviour based on private costs only. After obtaining the private and external costs for vehicle/fuel systems, a break-even analysis can be made to identify the point where the costs of any two vehicle/fuel systems become convergent, and policy makers could correspondently identify the appropriate policy packages.

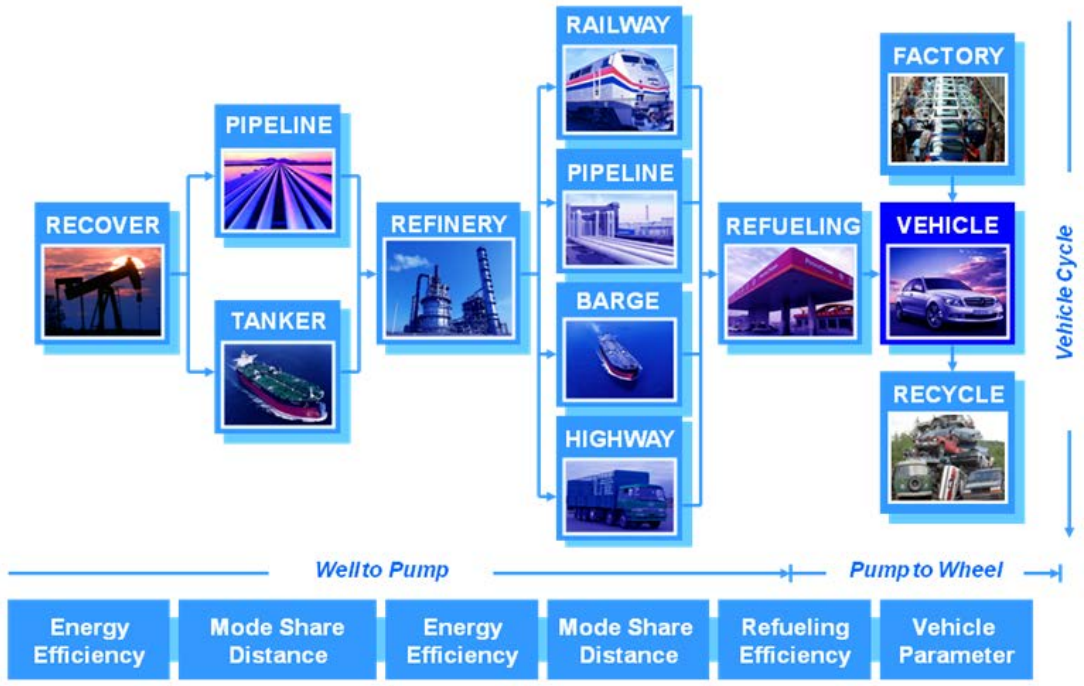
In addition to SCC, to make a comprehensive estimate for alternative fuel vehicles' environmental costs, Chapters 4 and 5 use the *lifecycle assessment* to combine the upstream (Well to Pump, WTP) and downstream (Pump to Wheel, PTW) of the fuel cycle. The potential energy and carbon emissions savings are the fundamental benefit of EVs. These savings are highly dependent on the energy resources used to generate the electricity and also on people's driving behaviour. In the WTP stage, the primary energy resources are recovered and transported to power plants, and the electricity is generated in the power plants and then transmitted to EVs' battery via the power grid, and the charging outlets distributed over the demand areas. In the PTW stage, the

electricity stored in the battery is converted to mechanical energy by a motor to propel the vehicle without fuel combustion and carbon emissions (with considerable less PTW fuel consumption for the case of PHEV).

To conduct a life cycle assessment integrating WTP and PTW stages, this research uses the GREET[20] (Greenhouse Gas, Regulated Emissions and Energy Use in Transport) model that links the upstream and downstream stages by unifying the measurement unit of energy consumption per distance travelled (BTU/km). The GREET model covers the entire life cycle flow of vehicle energy including feedstock recovery and transport; fuel production, distribution and final consumption in vehicle engines (see Figure 22). The model also involves the life cycle assessment of vehicle and battery production, maintenance and disposal. This research takes the fuel cycle assessment of electric vehicles based on China's energy mix. The energy recovery and refining data were retrieved from the latest nationwide statistics, energy reviews and research reports. Because Chapter 6 focuses on energy consumption and emissions for PHEVs, both electricity generation and petrol production pathways are reviewed.

[20] GREET is a life cycle assessment tool released by the Department of Energy of United Stages for estimating fuel cycle energy consumption and carbon emissions of alternative fuel vehicle technologies. The latest GREET version is GREET1 2011 (http://greet.es.anl.gov/).

Figure 22 Lifecycle Assessments for Alternative Fuel Vehicles



To calculate fuel-cycle energy use and emissions, GREET estimates energy use (Btu[21]) and emissions (in grams) per million Btu ($g/10^6$ Btu) of fuel throughput for a given upstream stage. The model then combines the energy use and emissions from upstream and downstream stages to calculate total energy use and emissions of a vehicle fuel. The fossil fuels that are calculated in GREET model include: petroleum, natural gas and coal; the total energy consumption covers the fossil energy use; and renewable energy use including solar energy, wind, and geothermal energy.

The total feedstock input needs to be divided into feed and fuel along different stages in the upstream process. Converting feed to a given fuel (which is usually a chemical

[21] BTU (British Thermal Unit) is a unit of energy equal to about 1055 joules.

process) may or may not produce emissions and combustion of a feedstock as a fuel certainly produces emissions. The combustion emissions can be estimated by using the amount of fuel burned and the combustion emission factors. The calculated energy consumption of all process fuels for a particular stage is then allocated to different process fuels burned during the stage. There are three cases where energy feedstock is separated between feed and fuel:

1. All the energy feedstock input is burned in producing a fuel. An example is electricity generation.

2. Some (usually a majority) of the energy feedstock input is used as feed in a conversion process to produce a fuel; the remainder, together with any other process fuels necessary for the conversion process, is burned to provide heat or steam for the process. Examples include chemical processes such as production of methanol, hydrogen, DME, and FTD from natural gas, where the total natural gas input is broken down into natural gas used as feed and natural gas used as fuel. Only the natural gas used as fuel is included in combustion emission calculations.

3. No chemical processes are involved in production (or transformation) of a fuel. Of the total energy feedstock input, a unit of energy in fuel product output requires a unit of energy in feedstock input. The difference between the energy in the feedstock input and the energy in the energy product is the amount of feed used as the process fuel. Examples include CNG and LNG production.

For example, if 10^3 Btu of process fuels is burned to deliver 10^6 Btu of fuel output from an upstream stage, GREET allocates the 10^3 Btu of process fuels into diesel, residual oil, and electricity. The process fuels that are calculated in the GREET model include: natural gas, residual oil, diesel, petrol, crude oil, LPG, coal, electricity, and biomass-fuels. As the amount of emissions attributable to fuel combustion is highly dependent on the type of fuel burned, allocating the percentages of total energy burned to different process fuels for a given stage allows GREET to calculate emissions from the stage.

The system boundary of the lifecycle assessment in this thesis covers the vehicle operation; vehicle manufacturing and recycling; fuel consumption, production and the upstream production of process fuels. The energy use and associated emissions involved in the manufacture and construction of upstream infrastructure are not included in this study.

The large amount of co-products during the production of biomass-based fuels requires appropriate allocation methods for life cycle assessment. Previous vehicle fuel lifecycle studies allocated emissions and energy use between ethanol and its co-products by using different methods for corn farming and ethanol production (Wang et al, 1997b), including weight-based method, energy content method, product displacement method, market value method and process energy approach. The

displacement method and market value methods are most often applied for life cycle assessment. The use of different allocation approaches can have significant influences on calculation result of corn ethanol fuel-cycle energy use and emissions. According to the comparison made by the Argonne National Laboratory, the corn-based fuel ethanol achieves a moderate reduction in GHG emissions, while cellulosic ethanol can achieve much greater energy and GHG benefits (Wang, 2005).

In a given fuel cycle, the upstream stages include production and transport of feedstock, production and distribution of fuel products. Upstream energy use and emissions are generated during combustion of process fuels, and during production and distribution of the fuel to vehicles. The emissions of a given upstream stage are calculated by using equation 2:

Equation 2:

Where:

EM_i: Emissions of pollutant i in g/10^6 Btu of fuel throughput from a given stage;

$EF_{i,j,k}$: Emission factor of pollutant i for process fuel j with combustion technology k (g/10^6 Btu of fuel burned);

EC: Total energy consumption for the given stage (in Btu/10^6 Btu of fuel throughput);

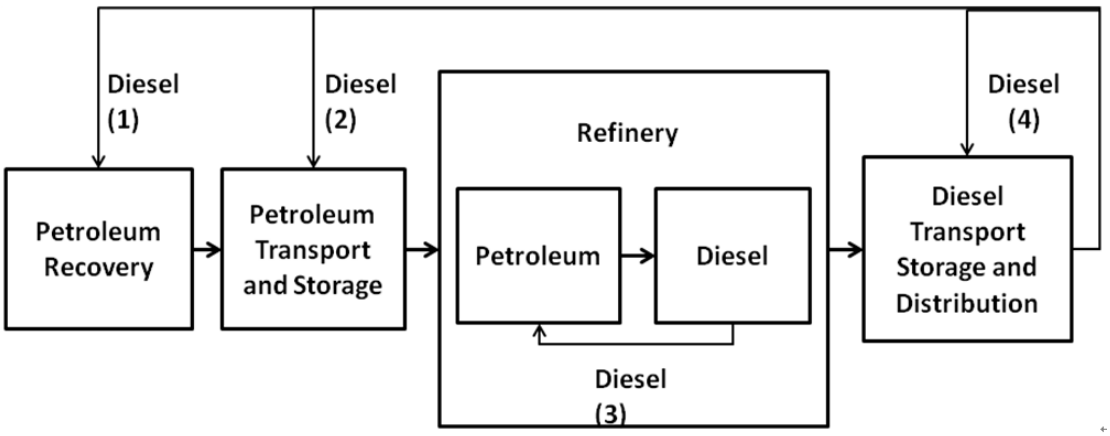
$Sharefuel_j$: Share of process fuel j out of all process fuels consumed during the stage ($jfuel_j$ = 1);

$Sharetechk_j$: Share of combustion technology k out of all combustion technologies for $fuel_j$ ($ktech_{k,j}$ = 1).

$EF_{up,i,j}$: Upstream emissions of pollutant i in g/10^6 Btu of process fuel j to produce and distribute the process fuel to the stage;

EC_j: Energy consumption of fuel j during the stage.

Figure 23 Circular Calculations of Upstream Energy Use and Emissions – Diesel Fuel



The introduction of $EF_{up,i,j}$ to the formula causes circular calculations in GREET model. The circular calculations help to deliver a full assessment of upstream energy use and emissions. For "petroleum to diesel cycle" as an example (see Figure 23), the petroleum recovery stage requires use of diesel fuel, along with other process fuels. The production of the diesel fuel (as a process fuel) involves petroleum recovery,

transport and storage, petroleum refining, diesel fuel transport, storage and distribution to oilfields, where diesel is involved with circular calculations for the associated upstream diesel fuel production. The GREET model conducts a circular calculation by means of the iteration calculation feature in Microsoft Excel. Combustion technology shares ($Sharetech_{k,j}$) for a given process fuel are determined by technology performance, technology costs, and emission regulations for stationary sources. Over time, clean-burning technologies will be likely introduced to replace the conventional combustion technologies due to increasingly strict emissions regulations.

Fuel cycle energy and emissions should be calculated to account for the effects of fuel loss. In the GREET model, the upstream energy use and emissions are calculated through:

Where:

TEM_{up}: Total upstream emissions for a given fuel cycle (in g/10^6 Btu of fuel at fuel pump);

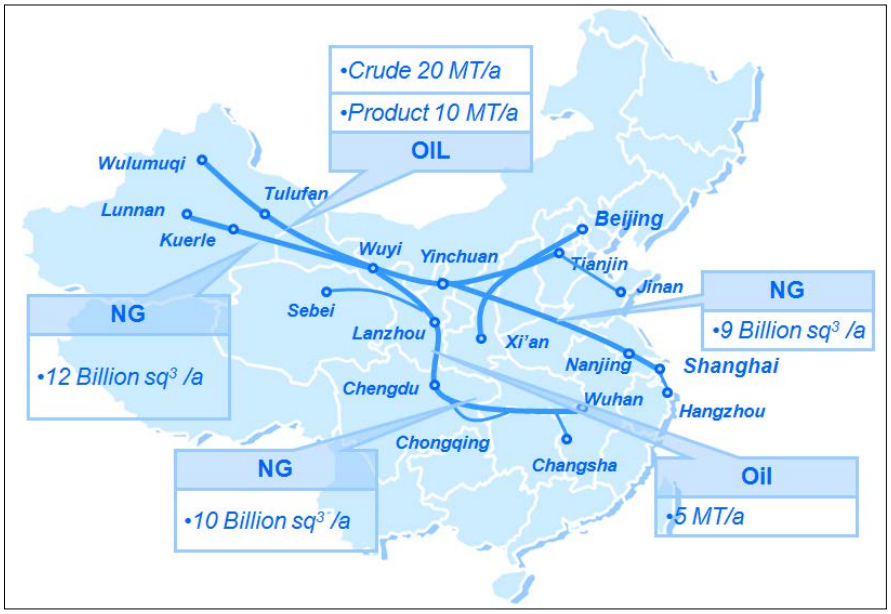
EM_i: Emissions from stage i;

K_i: Fuel loss factor for stage i to take into account fuel loss during stage i;

I: i th stage.

In China, the fossil energy recourses are mainly distributed in the western and northern parts while the consumption markets concentrate along the east coast and south regions. The spatial separation between energy sources and consumption leads to a significant amount of transport/storage/distribution (T/S/D) energy use and emissions. For the petrol fuel as an example, the T/S/D stage includes transport to bulk terminals (primarily via barges and trains in China), storage at the terminals, and distribution to refuelling stations (primarily via trucks). LPG, used primarily in industrial, commercial, and residential sectors, is transported to bulk terminals via pipelines and trains and stored there until distribution to use sites via trucks. Residual oil is used primarily in marine vessels, electric power plants, and residential and commercial heating and transported via trains, barges and pipelines. Figure 24 presents main oil and natural gas T/S/D pathways in China.

Figure 24 Oil and Natural Gas Transport and Distribution in China



Source: China Academy of Social Science, 2009

The transport and storage of liquid fuels via vessels and transmission of gaseous fuels via pipelines are subject to fuel evaporation and/or leaks (fuel loss). For a given stage, the fuel loss factor (K_i) is calculated by:

Where:

$Efficiency_i$: Energy efficiency of stage i, which is calculated as fuel output from the stage divided by total energy input to the stage (including feedstock fuel and process fuels);

$Loss_Share_i$: The share of fuel loss out of total energy inputs for stage i.

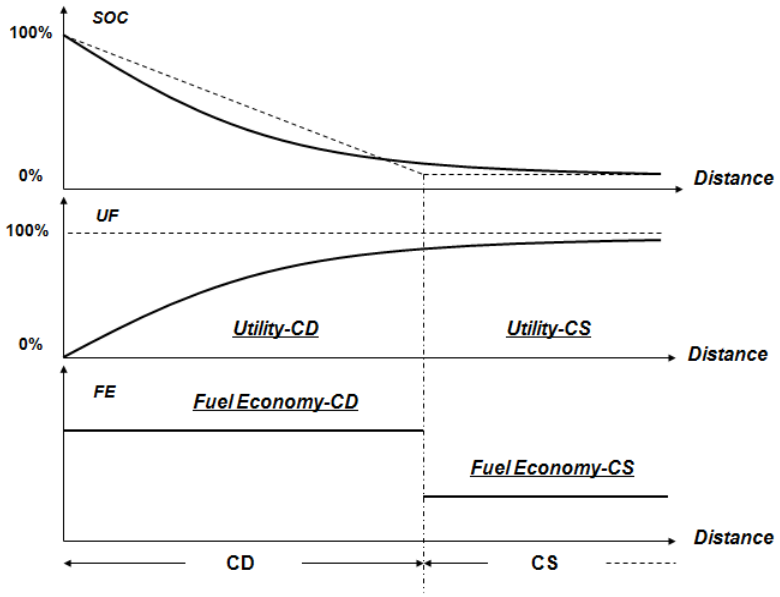
To analyze the performance of PHEVs, the amount of electricity used by the electric motors compared with the amount of fuel used by the engine is a key factor. The concept of PHEV was to charge the battery to a high state of charge (SOC[22]) (for example 90%), then the vehicle would operate in the charging depleting (CD) mode by consuming only the stored electricity until it reached a low SOC level (for example 30%). Then the PHEV would operate in charge-sustaining (CS) mode, which is similar to the operation of regular HEVs[23]. There have been a number of studies on fuel economy evaluations for PHEVs. Graham et al (2001) discussed two methods: *mileage weighted probability* (MWP) method suggested by Electric Power Research Institute and the *utility factor* (UF) method suggested by the Society of Automotive Engineers (SAE). Using the 1995 National Personal Transportation Survey (NPTS) to calculate the mileage displaced by a PHEV that is fully charged and discharged once per day, the MWP method results a lower potential for electric distance substitution than the UF method. The concept of "Utility Factor" (UF) is used to represent the percentage of a PHEV's electricity consumption over its entire energy consumption during vehicle operation (Elgowainy et al, 2009). It is therefore determined by the EV driver's driving distance between recharging activities, as well as the battery's range capacity (see Figure 25). Normally, a daily charging basis is assumed and so a daily kilometres travelled (DKT) becomes the key factor that needs to be identified via the

[22] State of Charge (SOC): the percentage of available electricity capacity to the battery's total storage capacity.

[23] Due to the high cost and low capacity batteries, a "blended" CD mode has also been recommended to reduce the size and cost for PHEVs by DOE. In the "blended" CD mode, the engine would be turned on intermittently during high power demands to increase the CD range by utilizing both electricity and petroleum fuel.

daily travel behaviour data.

Figure 25 Utility Factor Method to Calculate PHEVs' Fuel Economy



Where:

FE_{cd}: fuel economy of charging depleting mode;

FE_{cs}: fuel economy of charging sustaining mode;

i: travelled distance;

UF: PHEV utility factor.

Chapter 5 applies the UF method to use the daily driving data obtained from an online survey in China to investigate PHEVs' potential to substitute petrol fuel consumption

and to reduce the carbon emissions generated by ICE vehicles.

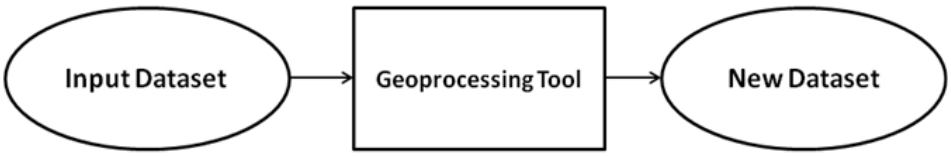
4.3 Geospatial Optimization

Geospatial optimization is a common research method in spatial analysis that uses Geographic Information System (GIS) to model the spatial interaction between GIS objects and maximize a predefined utility by dynamic simulation. The term 'GIS' is widely attributed to Roger Tomlinson and colleagues, who used the word in 1963 to describe their activities in building a digital natural resource inventory system for Canada (Tomlinson 1967, 1970). Currently, GIS is a system used to describe and characterize the earth and other geographies for the purpose of visualizing and analyzing geographically referenced information (ESRI, 2011). In a spatial analysis, an object's location directly determines the analysis result. A GIS is typically used for handling several different datasets and the information each dataset holds data about a particular feature that represents a group of realistic objects.

The spatial analysis process consists of data input, geoprocessing and producing new dataset (see Figure 26). The data in spatial analysis can be divided into vector and raster data. Each type of data requires specific spatial analysis or geospatial processing techniques. In the case of vector-based GIS, some typical processing techniques include map overlay and buffering; while for raster-based GIS, the data operations refer to image filtering or map algebra in grid cells. These techniques

involve processing one or more raster layers according to the predefined rules and produce a new map layer. GIS has been widely used in the environmental sciences and remote sensing and modern GIS analysis packages include ArcGIS, MapInfo, Manifold, TNTMips and Geomedia. In this thesis, Chapter 7 builds a charging infrastructure network via ArcGIS[24] and simulates EV users' charging behaviour using the embedded geospatial processing tools.

Figure 26 Spatial Analysis Process



The overall charging infrastructure deployment for home and external charging demands depends on a series of factors including travel behaviour, the distribution of residents and the assumed battery range. With the variation of each factor, the estimates of charging demand profile and the required charging infrastructure could be different. In Chapter 7, a charging infrastructure distribution strategy is proposed based on the estimated charging demand. The required data contains the current driving behaviour in Beijing, the charging behaviour assumption, and the current distributions of residential communities, public parking lots and petrol stations. Charging infrastructure, including home charging spots and public charging/battery

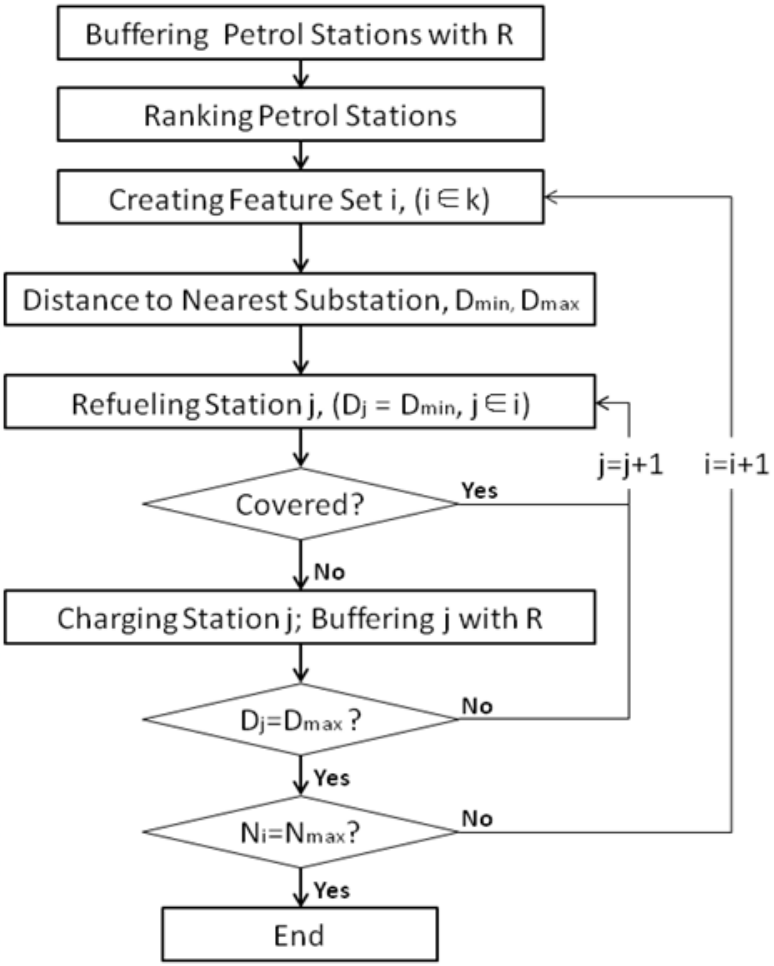
[24] ArcGIS is a GIS software produced by the Economic and Social Research Institute (ESRI). The GIS package applied in this thesis is ArcGIS 9.3.

swap stations, are assigned in residential communities, public car parks and gas stations, according to estimated regional charging demands. In order to analyze the impacts of these factors on the charging demand pattern and to propose an infrastructure deployment strategy providing cost-efficient charging services for EV drivers, the thesis selects Beijing (Chapter 7) and Shanghai (Chapter 8) as two study cities to evaluate the scale of EV charging infrastructure network serving a preliminary EV fleet, and its impacts on the current power grid. Both cities have been chosen by the National Development and Reform Commission (NDRC) as one of six pilot cities in China to implement EV purchase subsidies in the private car market, even though they have distinctive features in terms of geographical size and vehicle population.

For example in the case study city of Beijing, the variations of charging demand are measured by the petrol station distribution which is extracted from the city's GIS map. Three types of charging infrastructure, namely charging stations, battery swap stations and charging posts (in communities/homes and public parking lots), are proposed to provide charging services for private electric cars' charging demand. The GIS map provides the distribution data for communities and public parking lots, while the parking capacity data is collected from the "Transportation Administration of Beijing Municipal Commission of Transport" (BMCT, 2010), which offers the data of parking capacity in each parking lot. The places of charging/battery swap stations are selected from the current refuelling stations. Then according to the estimated charging demand,

charging infrastructure is assigned to the regional charging/swap stations, residential and public parking areas. The EV charging station deployment procedure is illustrated in Figure 27.

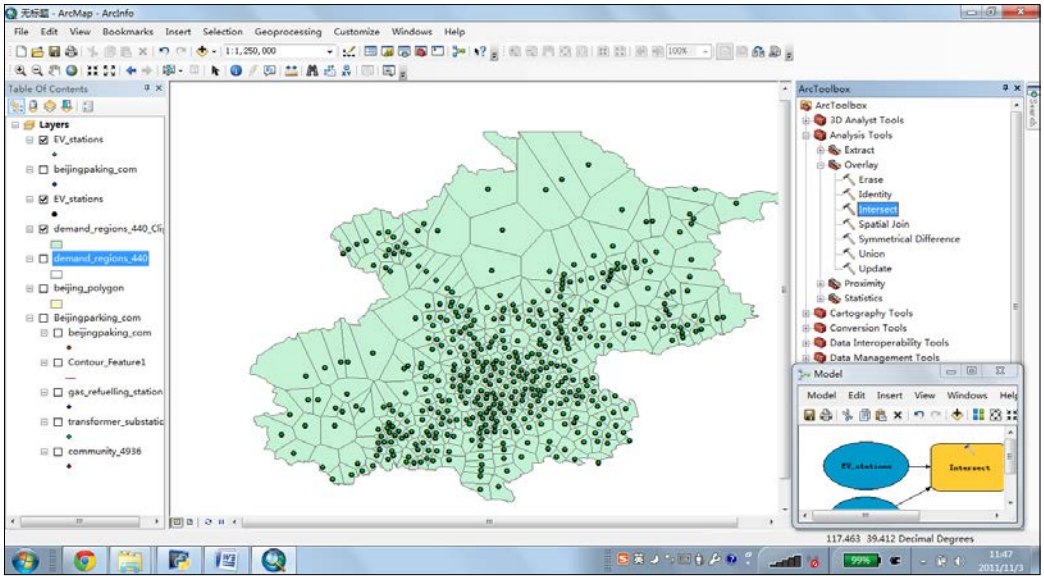
Figure 27 Flow Chart of the Identification of EV Charging Station Locations



The charging demand regions with estimated charging demands are firstly identified via distributions of current refuelling stations and power substations. Then the estimated charging demands are assigned into each region according to the region's

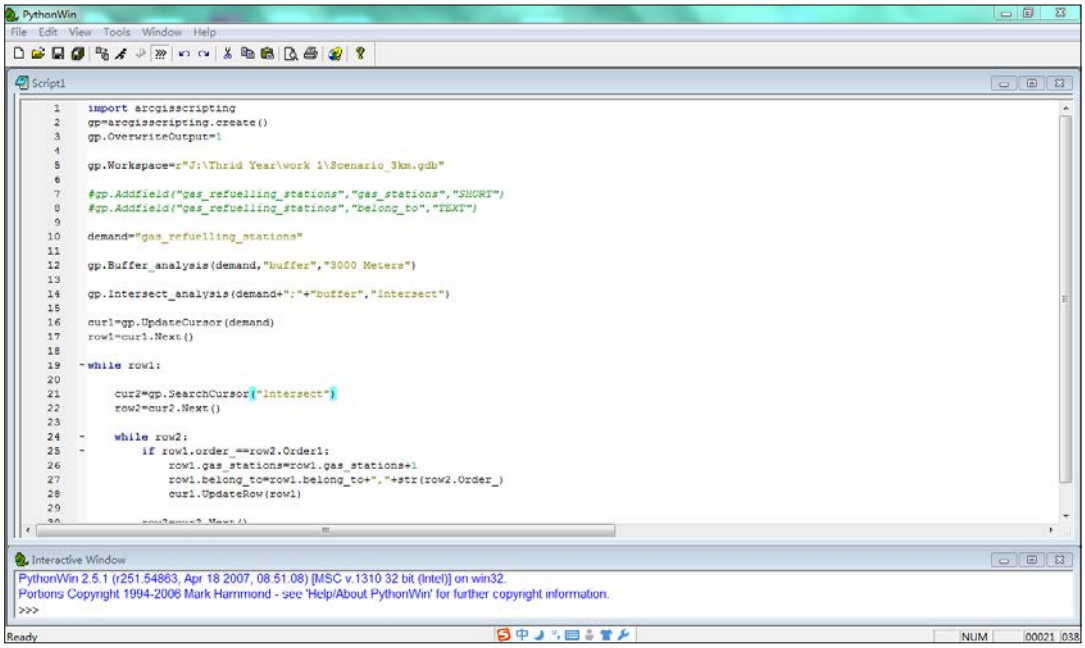
available community, workplace and public parking spaces. The charging infrastructure is deployed at a selected refuelling station according to the estimated charging demand in each demand region and the region's accessibility to the power grid (see Figure 28).

Figure 28 Regional Charging Demand Calculation using ArcGIS



There are several factors that directly influence the final infrastructure distribution, including the service radius of charging stations, and the charging energy shares between home, workplace and public charging outlets. To achieve some specific geospatial data manipulation in the distribution model and to conduct a model sensitive analysis, Chapter 7 builds a dynamic simulation model by using python script to reconstruct and integrate some GIS geospatial processing tools provided in ArcGIS 9.3 (see Figure 29).

Figure 29 GIS Charging Infrastructure Deployment with Python



In summary, the design of an EV charging infrastructure network would be more complicated than the planning for the distribution of petrol/diesel stations for ICE vehicles, as EVs involve different charging alternatives with different costs and diverse impacts on the power grid. The identification of charging methods and infrastructure also directly relates to EV business operation models, which are further discussed in Chapter 8.

4.4 **Other research methods**

As EV development involves a large number of estimates about future vehicle technologies, energy industry efficiencies and people's behaviour, the views from

experts in the relevant fields are fundamental to building future scenarios. This research conducted interviews with researchers and experts in political, academic and industrial sectors, so that the required data and information for the research could be collected. The interviews have been undertaken in different stages of the research process. Although each interview was usually taken for a specific research topic, some identical and contrary data and opinions can be found. This section provides a summary of the interviews, including a brief introduction to each interviewee and their views on the EV development in China.

Questionnaires

In order to discover people's attitudes to EVs, this thesis conducted an online survey in cooperation with Sohu website. Sohu is one of the most visited portals in China and the survey was released as a part of a new energy car promotion activity organized by the website. The online survey ran from 24 February to 26 March 2010. The questionnaire consisted of 30 questions, designed to elicit: people's attitudes to EVs in China in terms of relative prices with respect to ICE vehicles, performance expectancy and other concerns; their travel behaviour including travel mode, daily travel distance, driving speed and parking condition; personal socio-economic information including income, gender and home/work addresses. By the end of September, 2011, there are totally 469 responses. More details are attached in Appendix 9.

Onsite survey

EVs can be charged at various outlets distributed at homes, in workplace and public parking lots. Therefore, the charging behaviour and infrastructure deployment are dependent upon the current car parking environment. In Beijing, most people live in apartments and vehicles are usually parked in the parking lots in residential communities. As to workplace parking, employers and public parking lots provide the daytime parking service. For potential charging infrastructure deployment, the current parking lots' distribution and capacity are needed. The distribution data of parking lots is obtained from the 2008 Beijing Digital Map, while the public parking lots' capacity is retrieved from the Beijing Transport Management Bureau. With regard to parking capacities of residential community and workplace parking lots, this research conducted an onsite survey during August and September in 2010 in Beijing. The survey contained 8 residential community parking lots and 10 workplace parking lots. The survey items included each parking lot's parking space number, on-ground, under-ground parking space proportion, parking price, occupancy rate (daytime and night), household number (community) and construction year (see Table 6). More details are included in Appendix.

Table 6 Onsite Parking Lots Survey

Items	Distribution	Capacity	Average Capacity
Gas Stations	Yes	Literature	All gas stations share same refuelling capacity (ton/station day) **Average of cases**

Home Parking	Yes	Case Study	All communities share same parking capacity (parking seats/lot) **Average of cases**
Public parking	Yes	Literature (total public parking spaces)	**All public parking lots share same parking capacity (parking spaces).** **Average of literature statistics**
Workplace parking	Yes	Literature (total workplace parking space)	**All parking spaces - other POI.** **Average of literature statistics**
Power Provision		Case Study & Interview	

Chapter 5 Decarbonising the Road Transport Sector: Breakeven Point and Consequent Potential Consumers' Behaviour for the US Case

Jian Liu

School of Geography and the Environment and Transport Studies Unit, University of Oxford

Georgina Santos (corresponding author)

School of City and Regional Planning, Cardiff University and Transport Studies Unit, Oxford University

Key words

Low carbon transport, net present value, breakeven analysis, electric vehicles, bio-fuels, lifecycle analysis, external costs of road transport.

Abstract

A breakeven analysis of low carbon vehicle/fuel systems is conducted for the US for the year 2020, taking into consideration both private and external costs. All comparisons are made with respect to the conventional gasoline car as the baseline. Interestingly, the social cost of carbon prevailing in the literature, even at its highest end, is not high enough to justify the prioritization of low carbon vehicle/fuel technologies and the only way forward if such a track were to be chosen would be a political decision not necessarily grounded on economic principles. Nonetheless potential policies for the most financially viable alternative vehicle/fuel systems are considered.

5.1 Introduction

Transport currently accounts for 14% of total global greenhouse gas (GHG) emissions, to which road transport alone contributes 45% (HM Treasury, 2007a). In most OECD countries, transport even makes up more than 25% of all GHG emissions and the relative share is estimated to increase further in the future (Albrecht, 2000). Under the scenario of business-as-usual, road transport emissions will be doubled by 2050 and will become one of the main causes of global warming (HM Treasury, 2007b). In that case the global temperature would raise 2-3^{o}C by 2050 (Waston, 2001), which in turn, would very probably result in various negative environmental effects, such as extreme weather events, sea level rise, floods, droughts, population displacement, ecosystem destruction and malnutrition (Lee, 2007).

A number of policies and policy packages with the aim of reducing CO_2 emissions from road transport have been suggested both in the academic literature and in the real world. These range from economic instruments such as vehicle ownership and usage taxes and cap-and-trade systems, to changes in public transport provision, land use and urban design, cycling and walking facilities and new technologies which rely on low-carbon fuels.[25]

Although there are already a number of low emission vehicle technologies and alternative fuels, all with some shortcoming to one extent or other, some likely to be

[25] Santos et al. (2010a,b) provide an overview of such policies both in theory and practice.

solved in the short-term whilst others only likely to be solved in a much more distant future (three or more decades), none have yet penetrated the market massively.[26] In any case, they are all substantially more expensive to produce than the standard fossil-fuel car and therefore even if they were ready for mass use, their production costs and market prices would be very high. Except for motorists who cared so much about their personal CO_2 emissions that were prepared to incur in such higher costs, the majority would probably remain unconvinced and would need some persuasion in order to change their behaviour.[27] Caulfield et al. (2010), for example, conduct a survey of car buyers in Ireland and find that respondents do not rate GHG emissions as an important point to take into account when buying a car.

This paper aims to compare various vehicle/fuel systems in terms of their CO_2 emissions and their private and environmental costs for the US case in 2020. It also aims to assess whether there is an economic case for favouring some vehicle/fuel types and regardless of whether there is one or not, how this can be achieved by the government. Even when there is not an economic case for favouring cleaner technologies there may be a political case.

[26] Inderwildi et al. (2010) provide an excellent review of current road vehicle technology and the potential for a number of alternative vehicle/fuel technologies.

[27] If the utility a consumer derived from using alternative fuels (and caring for the environment) were high enough to make marginal benefit equal to marginal cost she would be prepared to pay a higher price for alternative fuels and vehicle technologies, subject to her budget constraint. In that sense, there may be scope for advertising and information campaigns aimed at changing consumers' preferences. Budget constraints, however, are likely to cap the potential market to only high income segments.

We use break-even analysis and complement it with the calculation of the Present Value of costs (PVC), which summarizes in just one number, the present costs of each vehicle/fuel system.

5.2 Technologies

There are a number of promising vehicle/fuel systems which are either already in the US market, at least to some extent, or will probably be in the market in the near future and the not so near future. All comparisons in this paper are made against the spark ignition internal combustion engine (ICE) conventional vehicles on gasoline (SICEG). This is taken as the baseline as gasoline cars with ICEs are by far the dominating vehicle/fuel system in any country, including the US, where they represent 90% of the car fleet (Ward, 2008). We use the average US passenger car as the benchmark.[28]

The technologies we consider are the spark ignition direct injection vehicles on gasoline (SIDIG), compression ignition ICE vehicles on diesel (CICED), which have already penetrated many markets worldwide, are more fuel efficient and produce less carbon emissions, compression ignition ICE vehicles on biodiesel (20% biodiesel and 80% diesel blend) (CICEBD), spark ignition flexible fuel ICE vehicles on E85 (15% gasoline and 85% ethanol blend) (SFFICEV), spark ignition dedicated ethanol ICE

[28] Only passenger cars are modelled.

vehicles E90 (10% gasoline and 90% ethanol blend) (SDEICEV), spark ignition ICE on compressed natural gas (SICECNG), fuel cell vehicles (FCV) on hydrogen (FCVH), on methane (FCVM) and on gasoline (FCVG), hybrid and pure electric vehicles. The electricity used by pure electric vehicles always comes from the grid but the electricity used by hybrid electric vehicles can either be sourced from the grid (grid connected) or independently (grid-independent). Thus, we have grid-connected hybrid electric vehicles (GCHEV), grid-independent hybrid electric vehicles (GIHEV), and pure electric vehicles (EV).

The main reason for including biomass-based fuel vehicles in this analysis is that biomass-based fuels are renewable resources which have the potential of alleviating energy dependence on fossil fuels. According to the US Department of Energy (US DOE), corn has and will continue to have the largest share of bio-ethanol feedstock in the US by 2050 (Argonne National Laboratory, ANL, 2008). This, however, is a fairly strong assumption, especially given the recent debate on net lifecycle CO_2 emissions savings of corn-based ethanol over conventional gasoline, with some arguing that instead of producing savings, it would double GHG emissions (Searchinger et al., 2008).

The grid-independent HEVs have been on the market for a while and due to their compatibility with current refuelling stations, they have been gradually accepted by the motoring public. Both grid-independent and grid-connected HEVs are expected to

achieve significant CO_2 emission reductions owing to their improved fuel economy, expressed as miles per gallon (MPG).[29]

Because of the technological challenges and high costs involved, the massive penetration of both pure EVs and FCVs can only be seen as long-term options. However, this study still includes them. Due to the fact that lifecycle CO_2 emissions of EVs and FCVs are concentrated during their well-to-pump process, the emissions can be relatively straightforward to collect by methods such as carbon capture and storage (CCS) and the potential for CO_2 emission reduction is large. Table 7 summarizes the vehicle/fuel systems considered in this study.

Table 7 Vehicle/fuel systems considered in this study

Vehicle	**Energy**	**Acronym**
Spark ignition ICE conventional vehicle	Gasoline	SICEG
Spark ignition direct injection vehicle	Gasoline	SIDIG
Compression ignition ICE vehicle	Diesel	CICED
Spark ignition ICE on compressed natural gas	Compressed natural gas	SICECNG
Spark ignition flexible fuel ICE vehicle	E85 (85% ethanol and 15% gasoline)	SFFICEV
Spark ignition dedicated ethanol ICE vehicles	E90 (10% gasoline and 90% ethanol blend)	SDEICEV
Compression ignition ICE vehicle	Biodiesel (20% biodiesel and 80% diesel blend)	CICEBD
Grid independent hybrid electric vehicle	Gasoline and electricity	GIHEV
Grid connected hybrid electric vehicle	Gasoline and electricity	GCHEV
Pure electric vehicle	Electricity	EV

[29] In this paper, gallon refers to a US gallon, which is different from a UK gallon (1 US gallon = 0.833 UK gallon = 3.7854 litres).

Fuel cell vehicle	Hydrogen	FCVH
Fuel cell vehicle	Methane	FCVM
Fuel cell vehicle	Gasoline	FCVG

Note: Both GIHEVs and GCHEVs in this study are assumed to run on a combination of electricity and gasoline.

5.3 The GREET Model

To fully evaluate energy and emission impacts of alternative vehicle technologies and fuels, the whole fuel cycle from well to wheel (WTW) and the whole vehicle cycle need to be considered. In this study, CO_2 emissions are estimated for each vehicle/fuel system using the 'Greenhouse Gas, Regulated Emissions and Energy Use in Transport' (GREET) Model, which is essentially a lifecycle emission assessment model from the US DOE, that covers the fuel lifecycle of feedstock recovery and transport; fuel production, distribution and final consumption in vehicle engines. The version used here is GREET 1.8b, which models energy consumption and emissions of typical passenger cars in the US under the assumption that all other factors (vehicle performance, range, maximum speed, engine size, etc) for different vehicle/fuel systems are of a comparable level and all gasoline (for ICE or blended in bio-fuels) is 'standard US conventional reformulated gasoline'. For vehicle lifecycle of production, maintenance and disposal however, we do not use GREET but we use Weiss et al.

(2000).[30]

The lifecycle assessment in GREET contains two parts: the well-to-pump (WTP) process and the pump-to-wheel (PTW) process. The WTP process is further subdivided into feedstock recovery from wells or fields, transport to refineries and storage for use; fuel production, transport to storage terminals and distribution to refuelling stations. For the feedstock recovery and fuel production, GREET applies the "process fuel" method, which estimates emissions based on the process fuel consumption.

Wang (1999, pp.19-20) summarizes GREET's calculation procedure as follows. To obtain 10^6 BTU fuel feedstock out of well, the total required process fuel is given by Equation 3:

$$\text{Process fuels} = \left[\frac{1}{\text{efficiency}_{\text{crude recovery}}} - 1 \right] \text{x} \, 10^6 \, \text{BTU} \qquad (1)$$

where $\text{efficiency}_{\text{crude recovery}}$ = energy output/energy input. For instance, according to estimates produced by the ANL (2007a), recovering 10^6 BTU fuel feedstock requires 20,400 BTU process fuels, which comprise 204 BTU crude oil, 204 BTU residual oil, 3,057 BTU diesel, 408 BTU gasoline, 12,635 BTU natural gas and 3,872 BTU electricity. As 20,400 BTU fuel are consumed during the recovery process, the fuel

[30] The latest version of GREET also models vehicle lifecycle emissions.

feedstock that needs to be recovered in the first place is much more, coming to a total of 1,020,400 BTU. This is to cover the process fuel consumption and energy loss during the whole pathway. However, to recover 1,020,400 BTU feedstock, additional process fuel $\left(20{,}400\,\text{BTU}\times\frac{20{,}400}{10^6}\right)$ is required again. GREET in this case applies a circular calculation until the difference between successive results is less than 0.001 BTU.

The obtained process fuels are integrated by GREET with emission factors (provided by the US DOE and embedded in the default parameters that GREET uses) to estimate CO_2 emissions. The WTP processes of all alternative vehicle fuels are estimated in the same way. The energy efficiency data plays a significant role in the lifecycle assessment. GREET 1.8b uses estimates of fuel efficiency produced by the ANL, in the context of the US energy industry. Since this study uses GREET 1.8b, it automatically adopts the ANL estimates as well.

For the PTW process, GREET adopts the vehicle operation simulation results from the MOBILE6 model[31] for benchmark ICE gasoline vehicles and the Environmental Protection Agency's (EPA) fuel economy predictions for alternative vehicle/fuel systems.

[31] The MOBILE6, produced by the US Environmental Protection Agency National Vehicle and Fuel Emissions Laboratory, is an emission factor model for predicting grams per mile emissions of hydrocarbons, carbon monoxide, nitrogen oxides, carbon dioxide, particulate matter, and toxics from cars, trucks, and motorcycles under various conditions.

5.4 Lifecycle CO_2 Emission Assessment for US 2020

5.4.1 Fuel Lifecycle Assessment

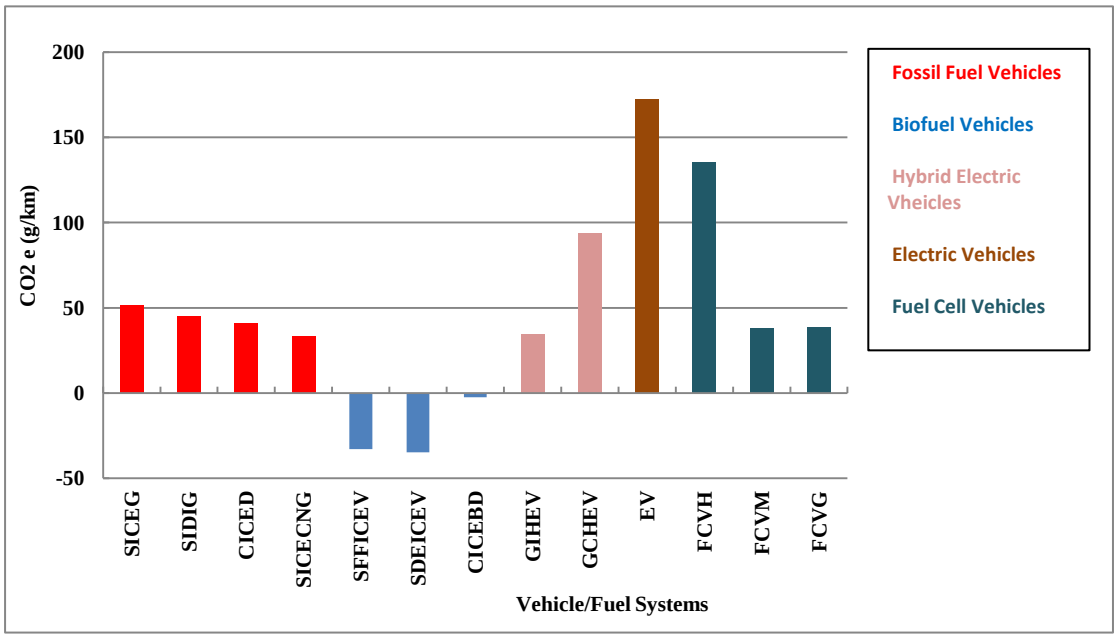
All GREET 1.8b outputs are expressed in grams of CO_2e emitted per mile for a typical passenger car within each of the categories listed in Table 7.

The results are described below.

5.4.1.1 WTP Process

Figure 30 shows the WTP results (see Appendix 1).

Figure 30 Well to Pump CO2e Emissions in the US for 2020 (estimated using GREET 1.8b)



From Figure 30, it can be observed that EV has the highest WTP CO_2e emissions among all vehicle/fuel systems. This is mainly due to the electricity generation pathways simulated by the GREET model, which assumes that 48.6% and 24.3% of electricity for transport use are generated from coal-fired power plants and natural gas-fired power plants, respectively. Both types of power plants burn a large amount of fossil fuel while generating electricity. Low carbon technologies, such as nuclear, water and wind, have a combined share of only 25.1% of electricity generation used for transport. On the other hand, the feedstock recovery and fuel refinery of fossil fuels only involves the combustion of a small amount of process fuels. The combustion of fossil fuel products, which produces considerable emissions, only occurs during vehicle operation.

Because GREET 1.8b accounts for carbon absorption during biomass growing, the WTP net carbon emissions from bio-fuels are very low and for corn-ethanol and biodiesel, they are actually negative. Thus, WTP CO_2e emissions for SFFICEV, SDEICEV and CICEBD are all negative on Figure 30.

For GCHEVs, the WTP carbon emissions are highly dependent on the share of electricity and gasoline. In order to simplify the assessment, GREET 1.8b assumes a 2:1 ICE mode and electric mode for GCHEVs in terms of the vehicle travelled mileage. An interesting finding is that the WTP emissions of GCHEVs are significantly higher than those from conventional gasoline, owing to the high WTP emissions from electricity generation. For GIHEVs, the WTP carbon emissions are about 25% lower than those for baseline SICEGs. This is not surprising given that the electricity in GIHEVs is generated in the vehicle itself[32] and the demand for gasoline by these vehicles is much lower than the demand for gasoline by SICEGs.

The WTP CO_2e emissions from SICECNG are around 30% lower than those from the baseline SICEG. Also, as it can be seen from Figure 30, WTP CO_2e emissions from SIDIG and CICED are only marginally lower than those from baseline SICEG.

[32] There are a number of technologies to achieve this, including regenerative braking, which converts the vehicle's kinetic energy into battery-replenishing electric energy, and motor electricity generation, which consists in the internal combustion engine generating electricity by spinning an electrical generator.

Finally, WTP CO_2e emissions from fuel cell vehicles vary. Those from FCVH are relatively high, and only lower than those from EV. The reason for this is that the production of hydrogen entails high CO_2e emissions, under the assumption of a 100% natural gas feedstock share for hydrogen production, which involves a steam methane reforming process. This steam methane reforming process causes extra emissions.

WTP CO_2e emissions from FCVM and FCVG are around 30% lower than those from baseline SICEG and 71% lower than those from FCVH. This is because the fuel production of methane and gasoline involve a significant lower volume of process energy consumption than the production of hydrogen.

5.4.1.2 PTW Process

For the PTW assessment, GREET 1.8b relies on the modelling results of benchmarking SICEG's emissions through EPA's vehicle emission modelling software, MOBILE6, and their "emission changing ratio" for various alternative fuel vehicles.

Figure 31 shows the PTW CO_2e emissions for the different fuel/vehicle technologies listed on Table 7.

Figure 31 Pump to Wheel CO2e Emissions in the US for 2020 (estimated using GREET 1.8b)

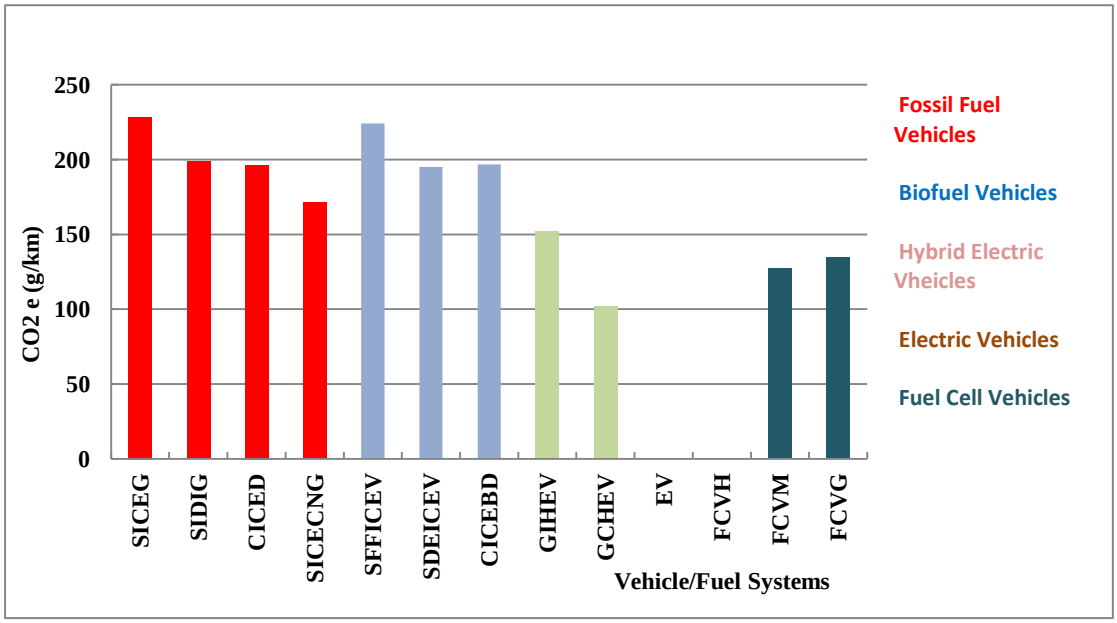


Figure 31 shows that the PTW CO_2e emissions from various vehicle/fuel systems almost follow an inverse profile to that of the WTP process. Obviously, EVs and FCVHs produce zero CO_2e emissions during vehicle operation. Just like in the WTP process, SICECNG can also effectively reduce CO_2e emissions in the PTW process. Bio-fuel vehicles have a comparable CO_2e emission level to that of fossil fuel vehicles. In particular, SFFICEV (which run on E85 produced from corn), cause PTW CO_2e emissions close to those from baseline SICEG. Both GCHEV and GIHEV cause significantly lower emissions than those from fossil fuel vehicles, mainly due to the improved MPG and electric driving.

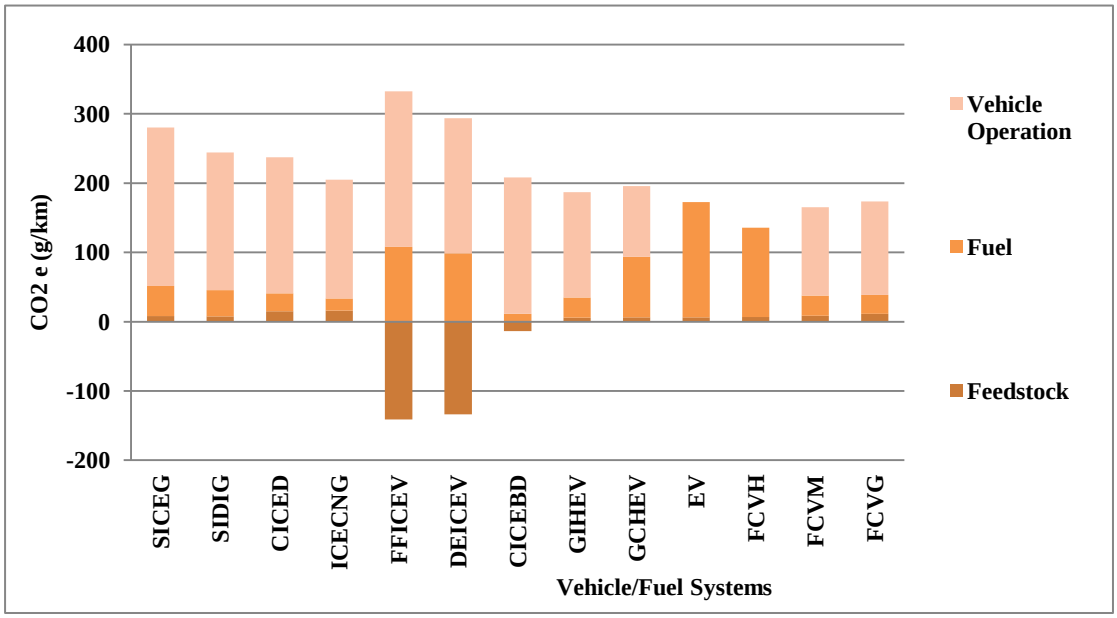
Both FCVM and FCVG produce significant CO_2e emissions during vehicle operation. In contrast with hydrogen, fuel cell vehicles running on other fuels need an additional

fuel process, which converts the fuels chemically to hydrogen, and this involves intensive CO_2e emissions. Then the cleaned up hydrogen is transmitted to a fuel cell stack which converts hydrogen electrochemically to electric power as hydrogen. Therefore, although the hydrogen reaction in a fuel cell stack only generates electric power and water, the fuel processing prior to the hydrogen reaction produces a considerable amount of CO_2e emissions, which are generally somewhere in between the emission levels of GIHEVs and GCHEVs.

5.4.1.3 WTW Assessment

After obtaining emission estimates from WTP and PTW processes, the total net CO_2e emissions of the various vehicle/fuel systems can be compared in terms of their full WTW cycle. It should be noted that the WTP emissions for a vehicle/fuel system also depend on MPG. GREET 1.8b firstly converts the WTP emissions to the unit of grams per km based on vehicle MPG and then combines the WTP and PTW results to produce the final output. Figure 32 shows the final output for each vehicle/fuel system.

Figure 32 Well to Wheel CO2e Emissions in the US for 2020 (estimated using GREET 1.8b)



Source: estimates produced by the authors using GREET 1.8b

Throughout the whole WTW cycle, the conventional SICEG produces the greatest amount of CO_2e emissions. This result is very much in line with previous LCA estimates, like for example those by Weiss et al. (2000). SIDIG, CICED and SICECNG achieve modest but welcome emission reductions, and since they are already in the market they could be considered feasible short term alternatives to SICEG.

Although biomass-based fuels produce the greatest levels of CO_2e emissions in the refinery and vehicle operation process, their carbon absorption during photosynthesis when they are being grown largely reduces their overall emission level. Thus, CO_2e emissions from SFFICEV, SDEICEV and CICEBD are approximately equal to those

from GCHEV.

GCHEVs, GIHEVs, EVs, FCVMs, FCVGs and FCVHs yield very low CO_2e emissions in the LCA. HEVs are already penetrating the market and EVs are a realistic option in the short and medium term. FCVHs, on the other hand, still face challenges related to the storage and transport of hydrogen in the vehicle.

FCVMs and FCVGs yield relatively low CO_2e emissions but they also pose problems. FCVMs rely on biomass, and there is simply not enough capacity on the planet at the moment for mass production of methane in that way. FCVGs save emissions but need gasoline, which will eventually run out.

5.4.2 Vehicle Cycle Assessment for US 2020

This paper uses the vehicle lifecycle emission assessment outputs from Weiss et al. (2000). The vehicle lifecycle consists of four stages: vehicle production and assembly, distribution, maintenance and disposal. The vehicle production assessment stage aggregates the emissions from different materials constituting a vehicle such as metals (iron, aluminium, magnesium, copper, zinc and lead), glass, plastics, and rubber. For vehicle distribution, the energy needed to transport a vehicle from the assembly line to the dealership depends on the energy intensity of the freight carrier and the transport distance. Weiss et al. (2000) assumes the average energy intensity of a heavy truck to

be 1.5 megajoules per tonne km (1.5MJ/tkm) and of railway to be 0.5MJ/tkm, and a mean transport distance for the US of 1,600 km. The energy required for distributing the vehicle is therefore 1.6 MJ/kg of vehicle mass.[33] Maintenance energy encompasses all energy that is used to replace vehicle parts or liquids throughout the entire vehicle life. As there is virtually no information available, this stage is neglected in Weiss et al. (2000). However, the associated error should be small, as energy use and emissions are likely to be significantly smaller than material production and vehicle assembly. After the vehicle finishes its life, it is shredded and its non-recyclable portion sent to a land-fill. The disposal energy in Weiss et al. (2000) is estimated to be a linear function of vehicle mass. The disposal energy is the sum of the energy needed to move the hulk from a dismantler to a shredder (0.24 MJ per kg of material over a distance of 160 km and a truck energy intensity of 1.5 MJ/tkm^2) and the shredding energy (0.37 MJ per kilogram of material).

For vehicle lifecycle emission analysis, the different vehicle types presented in Table 8 can be grouped in seven different classes, as shown on Table 8.

[33] (1.5 MJ/tkm * 1,600km + 0.5 MJ/tkm * 1,600)/2 = 1.6 MJ/kg.

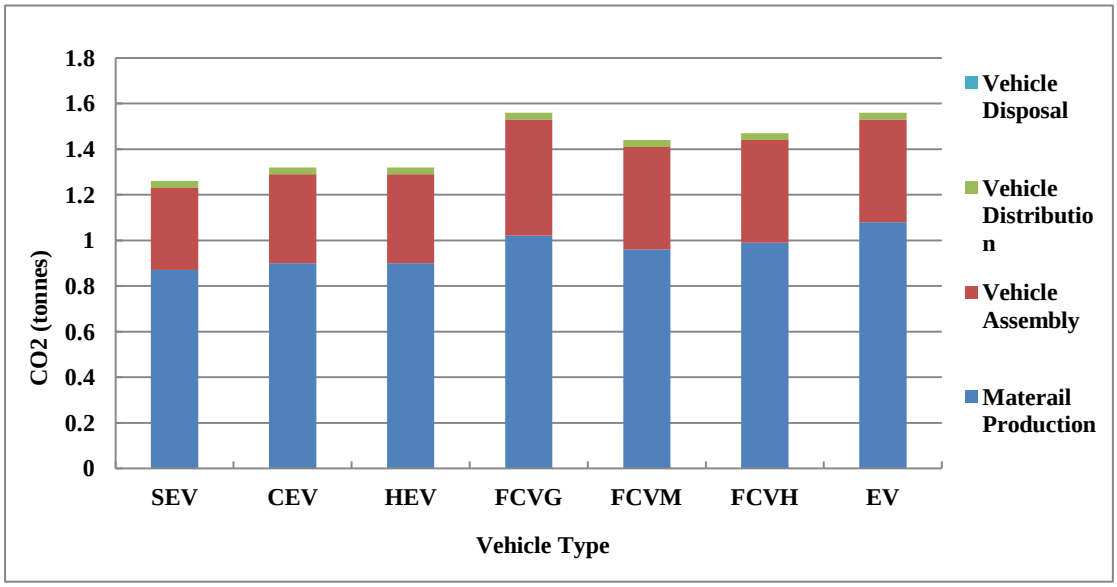
Table 8 Vehicle classes considered in this study

Classes	**Acronym**
Spark Engine Vehicles (SEV)	SICEG SICECNG SFFICEV SDEICEV
Compressed Engine Vehicles (CEV)	SIDIG CICED CICEBD
HEV	GIHEV GCHEV
EV	EV
FCVH FCVM FCVG	FCVH FCVM FCVG

In Weiss et al. (2000) the energy requirement for the production of vehicle materials and vehicle disposal are based on a recycling rate of 95% for all materials except plastics and window glass, for which the recycling rate is assumed to be 50%. The distance driven over the vehicle lifetime is assumed to be 300,000 km.

Figure 33 shows vehicle lifecycle CO_2e emissions, as estimated by Weiss et al. (2000).

Figure 33 Vehicle lifecycle CO2e Emissions in the US

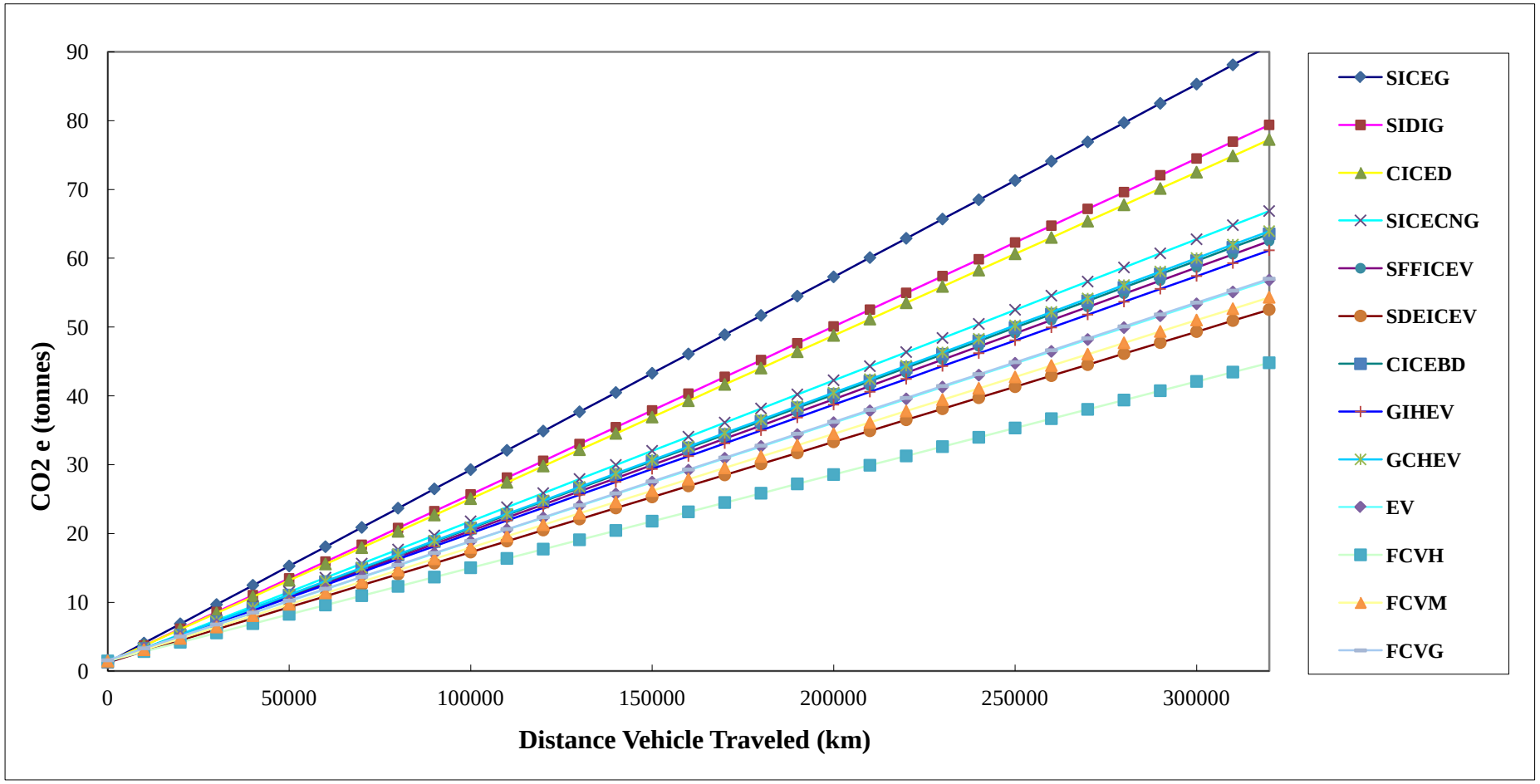


Source: Weiss et al. (2000)

As it can be seen on Figure 33, CO_2e emissions from FCGVs and EVs are the largest among all vehicle/fuel systems. The production of conventional ICE gasoline vehicles involves relatively small CO_2e emissions. HEV's CO_2**e** emissions are in between. Within a vehicle lifecycle, the production of the vehicle produces the highest emissions followed by vehicle assembly.

With the estimated fuel WTW cycle and vehicle lifecycle emissions, the integrated emission evaluation for the various vehicle/fuel systems can be made. Figure 34 shows this integrated result.

Figure 34 Integrated CO2e emissions from different vehicle/fuel systems (including both vehicle and fuel lifecycles)



Source: for vehicle lifecycle, Weiss et al (2000) and for WTW emissions, estimates produced by the authors using GREET 1.8b

Although it is difficult to see on the graph, fuel cycle CO_2e emissions are significantly greater than vehicle cycle CO_2e emissions for all vehicle/fuel systems. In all cases 10,000 km of travelled distance generates more CO_2e emissions than the production, maintenance and disposal of a vehicle, regardless of its class.

Vehicle lifecycle emissions for different vehicle types range between 1 and 2 tonnes of CO_2e. Figure 33 can be recalled to see the difference between lifecycle emissions from different vehicle technologies. The constant blue line on Figure 34 corresponds to vehicle lifecycle CO_2e emissions of SEVs. .

5.5 Break-Even Analysis

Having ranked all vehicle/fuel technologies according to their lifecycle CO_2e emissions, it is interesting to ask why the low carbon ones are not yet being chosen by producers and consumers. Not surprisingly, the answer simply boils down to their relative costs. Two further points then need to be considered. First, is there a breakeven point where consumers are indifferent between choosing cleaner cars with higher initial costs but lower operating costs and less environmentally friendly cars with lower initial costs but higher operating costs? Second, would relative costs change if the environmental damage caused by the different vehicle/fuel technologies (often not fully paid for by consumers) were taken into account? We conduct a break-even point analysis in order to determine the number of kilometres (or years, if

we assume an average annual distance driven) at which consumers would be indifferent in terms of costs between paying a higher vehicle price but lower operating costs and paying a lower vehicle price but higher operating costs.

We conduct the analysis taking into account private costs only and also private plus external costs.

5.5.1 External Costs

An external cost exists when the following two conditions prevail: (a) an activity by one agent causes a loss of welfare to another agent and (b) the loss of welfare is uncompensated (Pearce and Turner, 1990, p.61).

In order to estimate the external costs of the different vehicle/fuel systems, two pieces of information are needed. First, the total carbon emissions resulting from each vehicle/fuel system, including both the vehicle and fuel life cycle, which were presented in Section 4 above, and second, the social cost of carbon (SCC).

The SCC measures the full global cost today of emitting an additional tonne of carbon now and sums the full global cost of the damage it imposes over the whole of its time in the atmosphere (Department of the Environment, Food and Rural Affairs, DEFRA, 2007, p.1). Importantly, ‘the SCC varies depending on which emissions and

concentration trajectory the world is on' (DEFRA, 2007, p.1).

In recent years there have been a number of studies attempting to estimate the SCC (Nordhaus, 1991, 1994; Cline, 1993; Fankhauser, 1994; Tol, 1999; Tol and Downing, 2000) as well as a number of reviews (Clarkson and Deyes, 2002, Tol, 2005, 2008), including a couple of reviews by the UK government (Department of Energy and Climate Change, DECC, 2010) and by the US government (US Interagency Working Group on Social Cost of Carbon, IAWG, 2010). Estimates differ greatly: Tol (2005, 2008) finds that estimates of the SCC are driven to a large extent by the choice of the discount rate (the lower the discount rate the higher the SCC estimated) and equity weights (when a higher weight is assigned to developing countries the final aggregate impacts tend to be higher because developing countries are expected to suffer the worst impacts). He also finds that the more pessimistic estimates, which correspond to pessimistic scenarios, have not been subject to peer review.

Since this is a study for the US 2020 we use the SCC figures from IAWG (2010). As we show further down the results are not sensitive to the SCC chosen, unless we use numbers out of the range of values suggested in the literature.

Non-CO_2 emissions, such as CO, CH_4 and NO_x, are converted by GREET 1.8b to CO_2 equivalent (CO_2e) under a 100-year scale according to the IPCC suggested rates (IPCC, 2001). Once converted to CO_2e we use the same SCC to value their damage,

although this ignores other externalities, such as air pollution and health effects.

5.5.2 Private Costs

Private costs are simply the costs actually faced by consumers. They include the purchase cost, maintenance cost and operating costs of the vehicle. Federal and state taxes are excluded at the initial comparison stage because they only distort relative prices[34] and are precisely the subject of discussion in the policy recommendations section.

The different vehicle post-tax prices as well as bio-diesel and hydrogen post-tax prices for the US 2020 were taken from the VISION model[35] database spreadsheets. Since not all the vehicles considered in this study were included in the VISION spreadsheets, the data was complemented with data from Weiss et al. (2000). Petrol, diesel, natural gas, LPG, E85 and electricity prices (both for commercial and residential purposes) were taken from the US Energy Information Administration

[34] For example, if the pre-tax price of good *x* is $5 and the pre-tax price of good *y* is $10, the ratio of the prices if 0.5. That ratio changes to 0.6 if the government introduces a tax of 20% on good *x* but not on good *y*.

[35] The VISION model was developed by the Argonne National Laboratory to 'provide estimates of the potential energy use, oil use and carbon emission impacts of advanced light and heavy- duty vehicle technologies and alternative fuels through the year 2050', later extended to 2100 (http://www.transportation.anl.gov/modeling_simulation/VISION/).

(EIA), which provides official energy statistics.[36] The data on fuel taxes and subsidies (which had to be subtracted from the figures we had) was taken from the Internal Revenue Service (IRS) Form 720.[37]

Commercial and residential electricity prices are different. Charging points at work or shopping centres do and will continue to pay a commercial tariff, whereas those charging at home would pay domestic tariffs. We think that 2/3 to 1/3 domestic to commercial might make most sense as a rule of thumb for EV in the US 2020.

5.5.3 Payback periods

We plot payback periods for all the vehicle/fuel systems included in Table 7, except for the three fuel cell vehicles. Fuel cell vehicles have an initial cost which is almost two and a half times that of a conventional SICEG. For this reason it would be virtually impossible for these vehicles to be commercially viable.

Figures 35 and 36 illustrate cost trajectories, assuming an average annual distance

[36]http://www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2011&subject=3-AEO2011&table=3-AEO2011&region=1-0&cases=ref2011-d120810c

[37] http://www.irs.gov/pub/irs-pdf/f720.pdf

driven of 20,000 km[38], a discount rate of 6% and annual vehicle maintenance costs of 3% of the purchase cost, increasing 5% per year.

Figure 35 includes both private and external costs, while Figure 36 includes private costs only. As it can be seen, the figures are very similar, i.e. external costs are small relative to vehicle and operating costs.[39]

The points of intersection between lines show breakeven points. For example, the cost line for CICEBD intersects the one for GIHEV around 2012 and the one for GCHEV around 2018. In other words, whilst compression ignition ICE vehicles that run on 20% biodiesel and 80% diesel blend may be cheaper than hybrid electric vehicles to start with, within two years, the lower operating costs of grid independent hybrid electric vehicles make up for the initial vehicle price difference and within eight years, grid connected hybrid electric vehicles do the same.

As it can be seen on Figures 35 and 36, spark ignition ICE conventional vehicles running on gasoline (SICEG) constitute the undisputedly cheapest vehicle/fuel technology. The only vehicle/fuel technology that breaks even with SICEG is

[38] This is roughly the average distance driven by passenger cars in the USA. In 2009 the annual vehicle distance travelled was 16,608 km (US Department of Transportation, 2009). In 2020 this distance can reasonably be assumed to be 20,000 km.

[39] For example, the social cost of carbon emissions for a spark ignition ICE conventional vehicle running on gasoline is $126 in the first year, whereas fuel costs are $1,099 and maintenance costs are $665.

compression ignition ICE vehicles running on diesel (CICED), and it only does so after nine years (if environmental damage is included) or ten years (if only private costs are included in the calculations). If the average annual distance driven were assumed to be higher, the payback period would be shorter. For example, if average annual distance were 40,000 km, the cost line for CICED would intersect the one for SICEG in the fifth year, regardless of whether environmental costs were included in the calculations or not.[40]

The two questions we asked at the beginning of this section can now be answered. First, in most cases there is no reasonable payback period and consumers are unlikely to tilt towards other vehicle/fuel systems on the basis of costs. Second, the picture does not change much when the environmental costs of carbon emissions are included in the calculations.

The immediate conclusion from these calculations is that without tax or subsidy incentives it will be fairly difficult to persuade consumers to switch from SICEG to other more environmentally friendly vehicle/fuel technologies.[41] Another important conclusion is that a tax or subsidy computed on the basis of environmental costs will

[40] This is because the environmental cost is very small in relative terms. If it is included the breakeven point occurs slightly earlier but still within the fifth year.

[41] In economics it is standard to assume that a consumer maximises her utility function subject to a budget constraint. If one of the arguments of her utility function were ‘concern for the environment’, a consumer would probably choose a more expensive vehicle/fuel system, even one that never paid back, only because doing so would increase her marginal utility.

not be enough to change consumers' choices. Taxes or subsidies favouring cleaner vehicle/fuel system will need to be political and will have no economic grounding.

Figure 35 Break-even Point - Private and External Costs (excluding all taxes and subsidies)

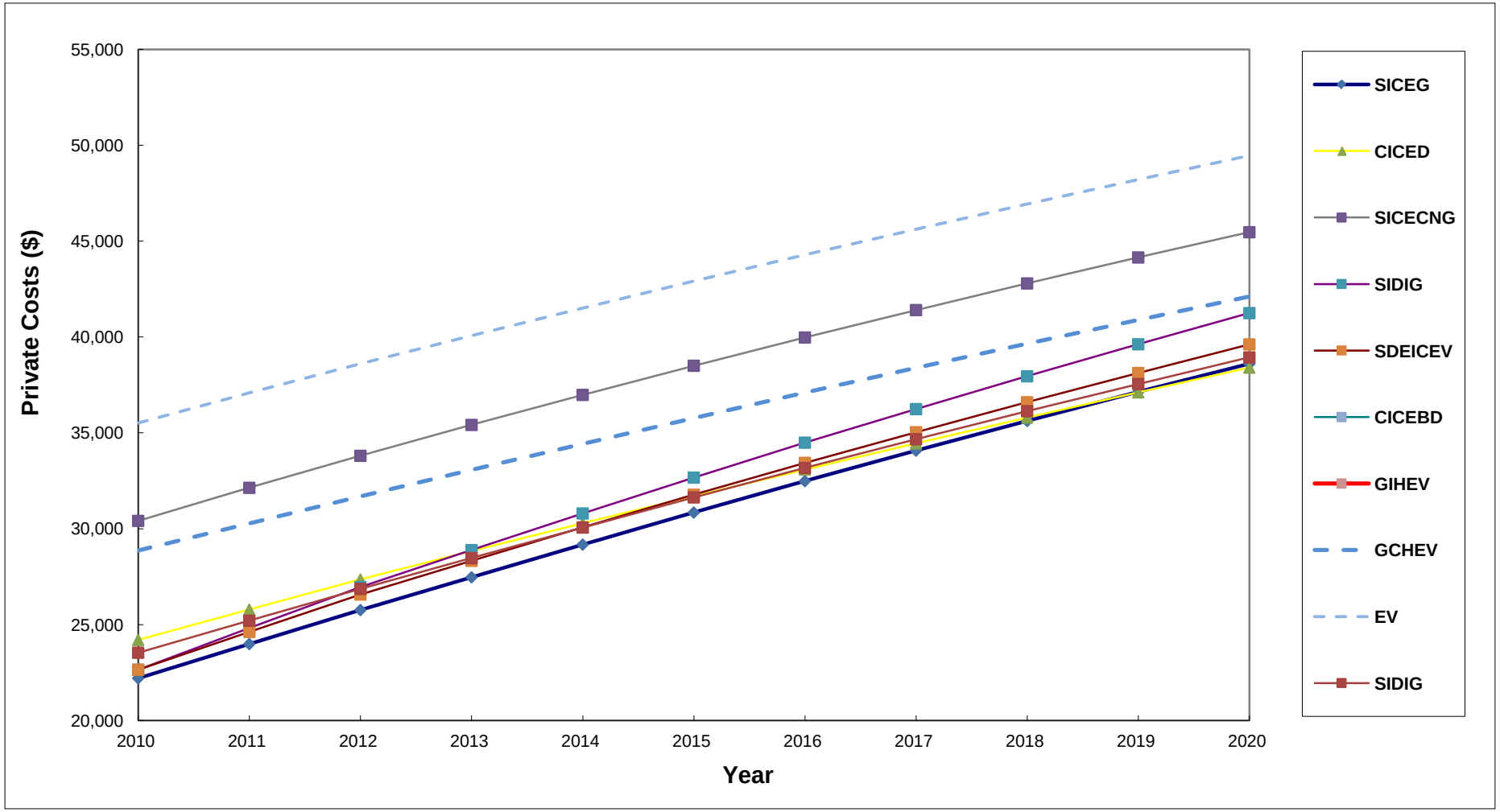
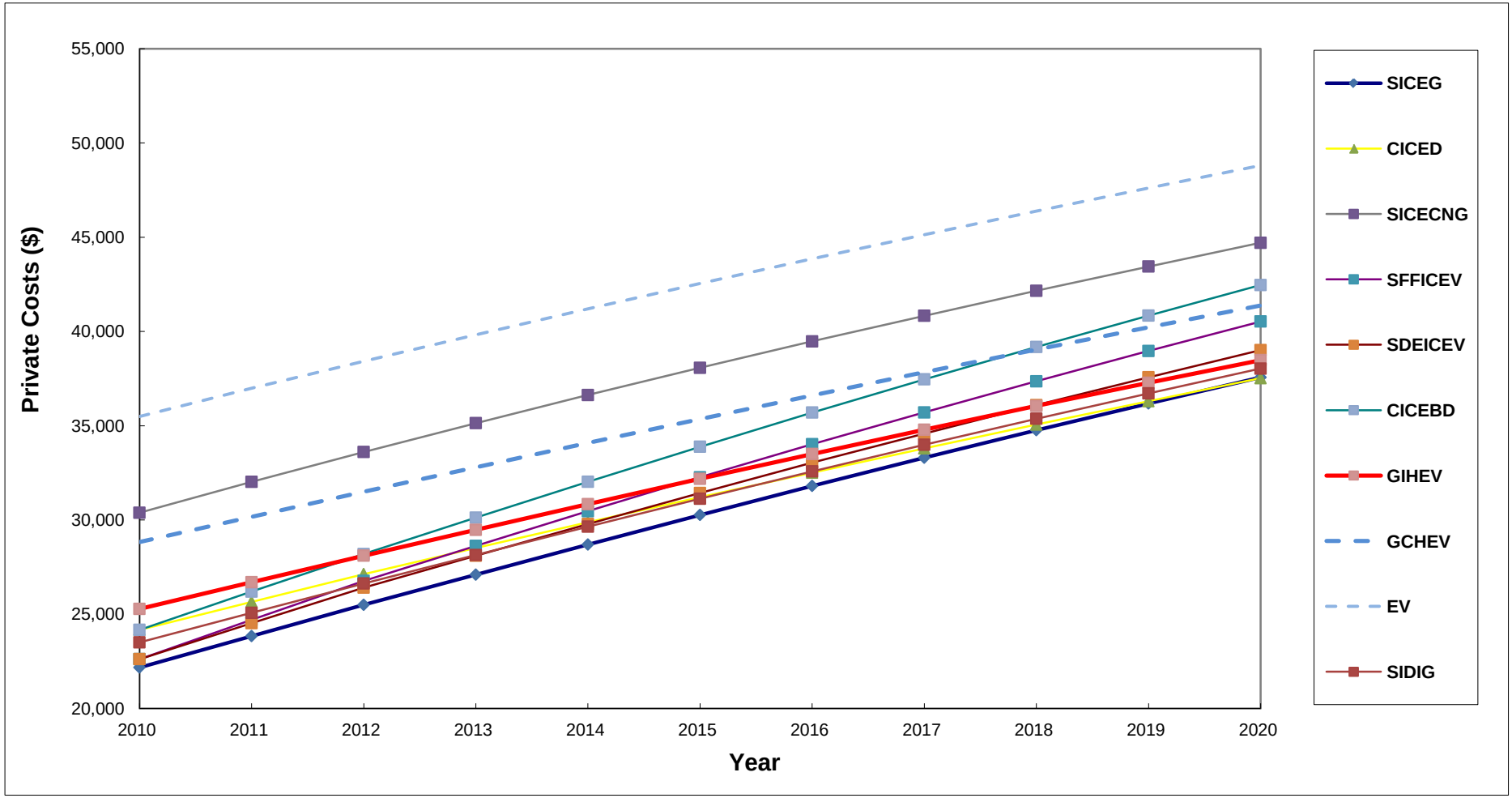


Figure 36 Break-even Point – Private Cost-Only (excluding all taxes and subsidies)



5.6 Present Value of Costs and Discussion

The breakeven analysis conducted in Section 5 considers both purchase cost and operation cost for consumers when deciding whether to purchase a more expensive but cleaner vehicle. The Present Value of costs (PVC), calculated in this section, summaryzes in just one number, the present value of all the costs, private and external, for each vehicle/fuel system over ten years. Like in the Breakeven Analysis these include: vehicle purchase, vehicle operating costs, annual depreciation and maintenance costs, and damage from carbon emissions. Like before, we use a discount rate of 6%[42]. Table 9 shows the results of these calculations. The different vehicle/fuel systems are ranked by ascending private cost, the factor most likely to influence consumers' choice in the first instance

Table 9 PVC of Alternative Vehicle/Fuel Systems

	Private costs	External costs	Private and external costs
CICED	37,520	864	38,384
SICEG	37,565	1,018	38,583
SIDIG	38,029	888	38,917
GIHEV	38,481	682	39,163
SDEICEV	39,012	585	39,597

[42] To compete with ICE vehicles in the market, the discount rate should be referred to common values used by other investments in the market. This study applied a modest discount rate of 6% which could lead to a relatively short payback period for alternative fuel vehicles. On the other hand, this study agrees that the result of break-even analysis is highly influenced by the selected discounted rate.

SFFICEV	40,532	697	41,229
GCHEV	41,374	713	42,087
CICEBD	42,462	709	43,171
SICECN	44,702	746	45,448
EV	48,802	632	49,434
FCVM	72,158	603	72,761
FCVG	74,854	634	75,488
FCVH	91,254	496	91,750

Note: All figures are in 2009 US dollars and 2010 values. The fuel cell options are presented in a lighter colour font because they are substantially more expensive, and therefore, do not seem to be financially viable in the short and medium run.

Not surprisingly, CICED has the lowest PVC and should therefore be the most chosen vehicle/fuel system in the US. In Section 5, we saw that CICED breaks even with SICEG after ten years when only private costs are considered. With the payback period being so long, many consumers choose SICEG instead, even though the PVC is higher. Not many consumers compute the PVC when purchasing a vehicle, but many do calculate its payback period.

The environmental damage produced by the carbon emissions from the different vehicle/fuel systems, depicted on the column entitled ‘External costs’ is lowest (in line with Figure 34 in Section 4) for all three types of fuel cell vehicles (running on hydrogen, methane or gasoline), spark ignition dedicated ethanol ICE vehicles E90 (SDEICEV) and electric vehicles (EV). Apart from fuel cell vehicles not being available for mass production yet, they have very high PCV due to their very high initial price, as already highlighted above, and consumers would be unlikely to choose them. It would be virtually impossible for the US government to introduce tax or subsidies to match those PVC with those of SICEG, as the difference in PCV exceeds

34,000 US dollars.

SDEICEV, on the other hand, would be more plausible. The PVC of SDEICEV is only 1,447 US dollars higher than that of SICEG, when only private costs are considered. When environmental damage is also included the difference is smaller. The problem with SDEICEV for mass penetration is that the production of ethanol can be problematic.[43] For this reason, we would not recommend this option. The external cost savings from EVs would be almost 34% over a ten-year period. The PVC is almost 1.3 times that of SICEG, which makes this an expensive option for the government to subsidize.

Other vehicle/fuel systems that would achieve savings in environmental costs of between 30% and 33% include grid-connected and grid-independent hybrid electric vehicles (GCHEV and GIHEV), compression ignition ICE vehicles running on biodiesel (CICEBD), and spark ignition flexible fuel ICE vehicles (SFFICEV). All these have PVC which are higher than the PVC for SICEG but not impossible to match with fiscal incentives. We would recommend favouring GCHEV and GIHEV rather than CICEBD and SFFICEV because of the limitations that their production would face for large scale market penetration.[44]

[43] An important barrier would be the competition for livestock feed (Ou et al, 2010, p.3952), since ethanol is produced mainly from grain and sugar crops on agricultural land (Inderwildi et al, 2010, p.18).

[44]CICEBD and SFFICEV rely on biodiesel and ethanol respectively and the problem of food

To summarize, our recommendation would be to prioritize GCHEV and GIHEV.

In Section 7 we discuss some financial incentives that could potentially help change consumers' choices in favour of GCHEV and GIHEV.

5.7 **Financial Incentives**

Taxes and subsidies affect the Budget, and this in turn can have snowballing effects on the economy. Even in the case of revenue (or expenditure) neutral taxes (or subsidies) substitution effects will have impacts throughout the economy.

In this section, we present some examples of fiscal policies that might help change consumers' decisions. We do not assess the effects that these measures would have on the US economy as a whole, nor on its social welfare. That analysis exceeds the scope of this paper. Also, all pending or proposed legislation, regulations and standards in the US, not yet currently in place, are ignored.

Since we have already concluded that there is no economic justification for favouring lower carbon vehicle/fuel systems, these measures would not be 'corrective'. They would only be intended to change payback periods (i.e. breakeven distances) and

versus fuel competition (Timilsina and Shrestha, 2011, p.2067) and the use of agricultural land remains, just like in the case of SDEICEV.

PVC.

Before we venture into proposing any policy, we present on Figure 37 the breakeven points of the different vehicle/fuel technologies, including current taxes and tax credits in the US as of 2011. These reflect all the taxes and tax credits in place in the US, which are summarized on Table 10.

Table 10 Summary of taxes and tax credits in road transport in the US as of 2011

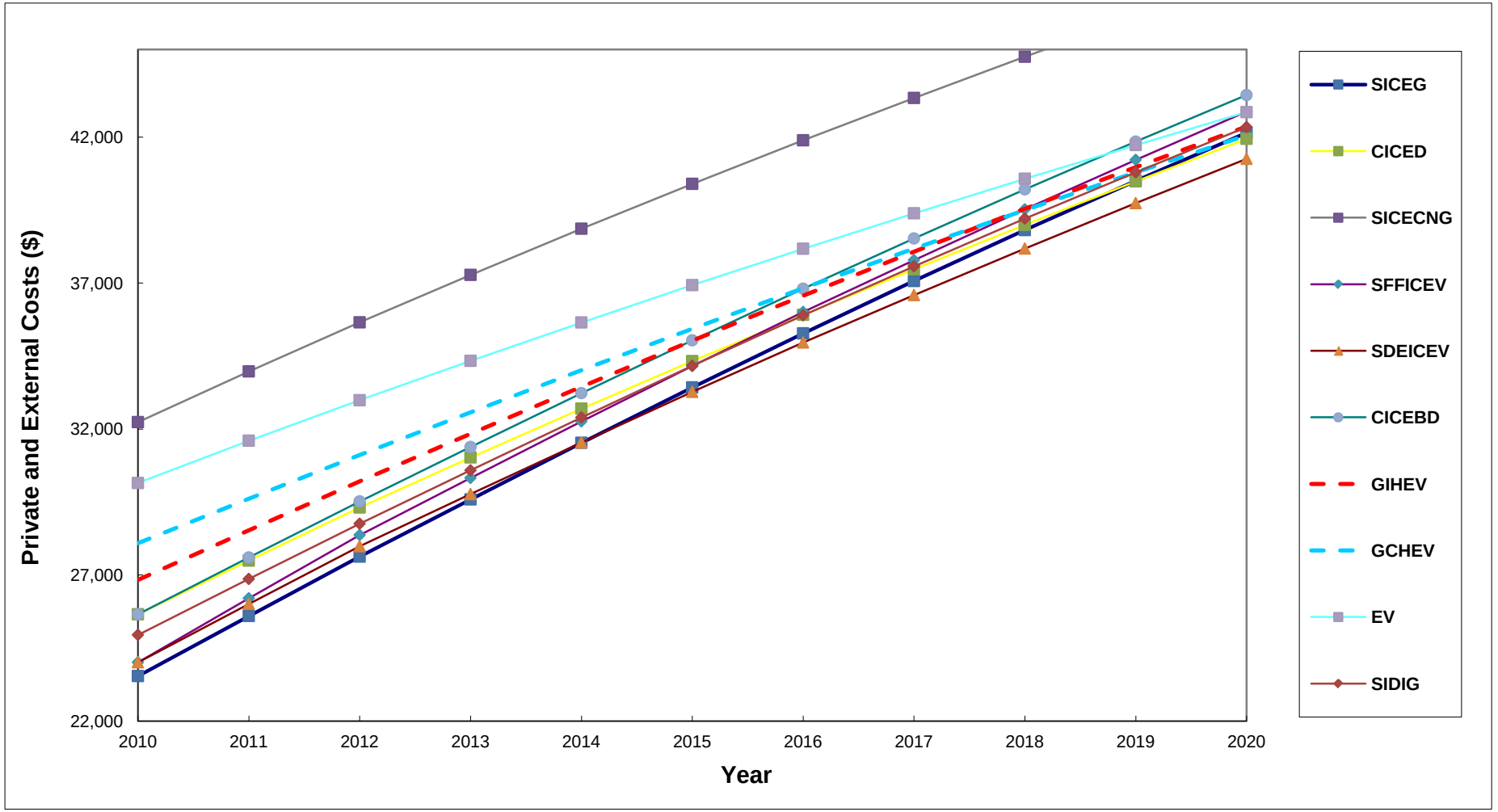
Energy and Vehicle	**Tax, tax rebate and/or subsidy**
Petrol	The average tax, which includes the federal and state taxes, is $0.47 per gallon.
Diesel	The average tax, which includes the federal and state taxes, is $0.51 per gallon.
Compressed natural gas	The average tax, which includes the federal and state taxes, is $0.42 per Gasoline Gallon Equivalent (GGE). There is also a tax credit of $0.5 per GGE.
E85 (15% gasoline and 85% ethanol blend)	The average tax, which includes the federal and state taxes, is $0.42 per GGE. There is also a tax credit of $0.45 per GGE.
E90 (10% gasoline and 90% ethanol blend)	The average tax, which includes the federal and state taxes, is $0.42 per GGE. There is also a tax credit of $0.45 per GGE.
Biodiesel (20% biodiesel and 80% diesel blend)	The average tax, which includes the federal and state taxes, is $0.51 per GGE. There is also a tax credit of $1 per GGE.
Electricity	Electricity is subject to a (state) sales tax, which is, on

	average, 6% of the pre-tax price.
Hydrogen	The average tax, which includes the federal and state taxes, is $0.42 per GGE. There is also a tax credit of $0.50 per GGE.
GCHEVs and EVs	Consumers receive federal vehicle purchase tax credits ranging from $2,500 to $7,500 ($417 per kWh) according to the battery size (from 6kWh onwards).

Source: US Department of Energy, Federal and State Incentives and Laws (http://www.afdc.energy.gov/afdc/laws/matrix/incentive) and IRS 720 form (http://www.irs.gov/pub/irs-pdf/f720.pdf)

Note: Gasoline Gallon Equivalent is essentially the amount of compressed natural gas, E85, E90 or any alternative fuel it takes to have the energy content of one gallon of gasoline.

Figure 37 Break-even Point – Private and External Costs, including current taxes and subsidies as of 2011 (including all taxes and subsidies)



The feature that stands out of Figure 37 is that the cost trajectories for SICECNG and EV have changed their relative positions when compared to Figures 35 and 36. This is thanks to the generous federal tax credit of up to $2,500 and $7,500 that GCHEVs and EVs receive, respectively. A number of intersection points have also moved forward and backward, according to the different taxes and subsidies.

Our two recommended fuel/vehicle systems, GCHEV and GIHEV, do not benefit greatly, in relative terms, from the purchase tax credits in place. This can be seen by a simple comparison of Figures 36 and 37. Although the cost trajectory for GCHEV now intersects that for SICEG vehicles, it does so at a very late stage, towards the end of the ten-year period in question and the cost trajectory for GIHEV still does not intersect that of SICEG.

Another difference is that before any policy the cost trajectory for GCHEV was always above and never intersected that of GIHEV, whereas now they do break even in 2018.

The policies currently in place in the US do not yield payback periods that encourage motorists to purchase and use our recommended vehicle/fuel technologies, GCHEV and GIHEV, as Figure 37 clearly shows. To achieve this, the options can be many. The

idea is essentially to change payback periods and relative PVCs over the lifetime of the vehicle.

Since we do not recommend the mass penetration of EVs, the tax credit that these receive could potentially be scrapped. Instead, we would recommend tax credits on both GCHEVs and GIHEVs.

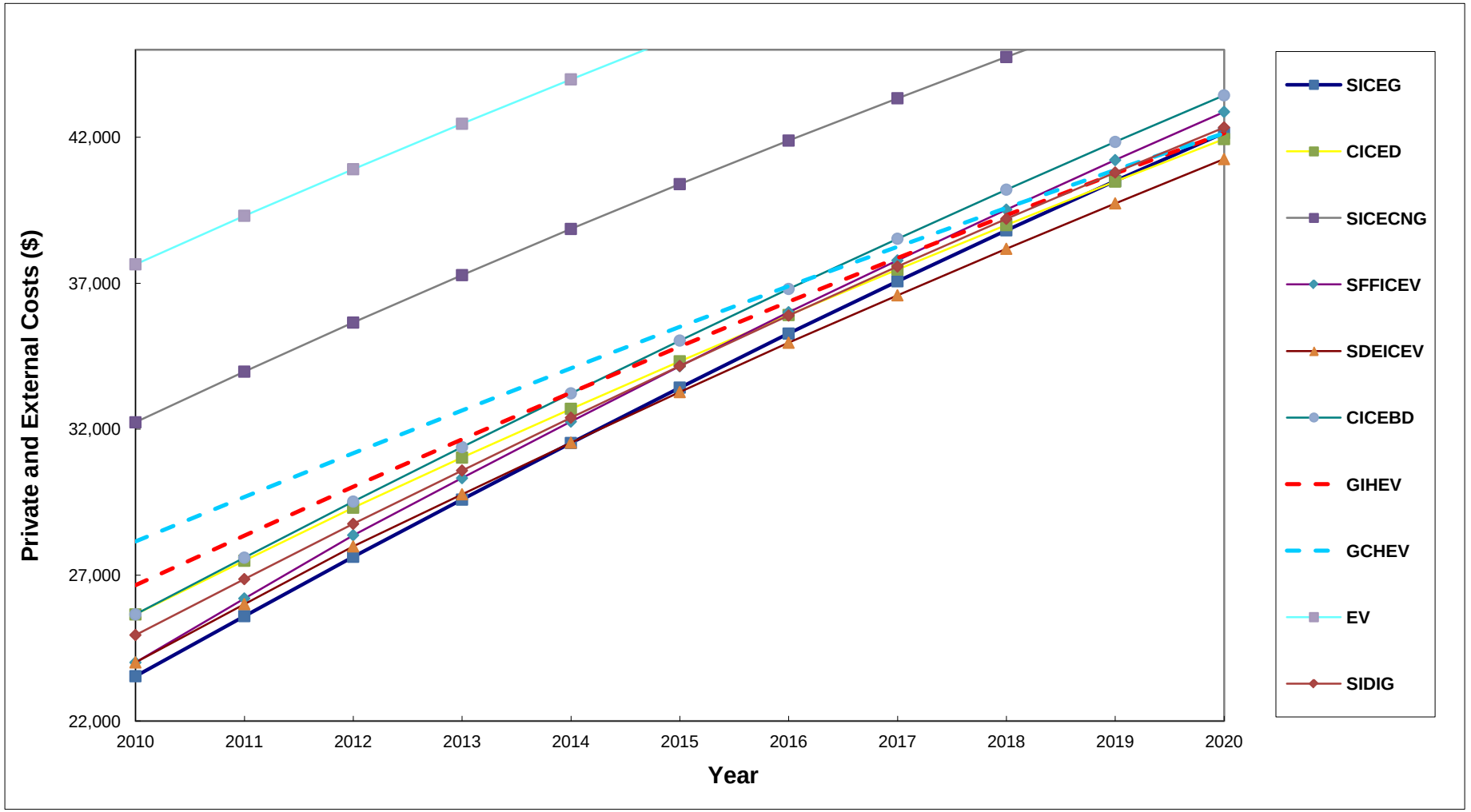
In order to make the PVC of GCHEV, GIHEV and SICEG equal, the tax credit for GCHEV would need to be \$2,434[45] and the one for GIHEV would need to increase to \$172. Except from scrapping the tax credit for EVs, all other current taxes and tax credits would stay the same. Making the PVC equal should make consumers indifferent between SICEG, GCHEV and GIHEV. Having said that, the payback periods may not be short enough for impatient or short-sighted consumers. As we saw in Section 6, not many consumers compute the PVC when purchasing a vehicle, but many calculate its payback period.

Figure 38 presents the payback periods for all vehicle/fuel technologies, assuming the tax credit on EVs is scrapped, GCHEVs receive a vehicle purchase tax credit of \$2,434, GIHEVs receive a vehicle purchase tax credit of \$172 and all other taxes and tax credits stay the same. As it can be seen, the payback periods for GCHEVs and

[45] Note that this is lower than the current tax credit of \$2,500.

GIHEVs, relative to SICEG are 10 years (by the end of the time period considered in our model).

Figure 38 Break-even Point – Private and External Costs under tax credits that equal the PVC of SICEG, GCHEV and GIHEV



Given that not many consumers will be persuaded to buy GCHEV or GIHEV unless the payback period is shorter, the tax credits could be increased. Table 11 presents alternative payback periods and the necessary tax credits to achieve them, assuming all other taxes and tax credits stay the same, except for the tax credit on EV, which is scrapped.

Table 11 Alternative vehicle purchase tax credits and payback periods

Payback period (relative to SICEG vehicles)	**Tax credit on GCHEV**	**Tax credit on GIHEV**
2 years	$5,862	$2,515
4 years	$4,859	$1,862
6 years	$3,992	$1,296

Source: Authors' own calculations

Note: All current taxes and tax credits stay the same, except for the EV tax credit which is scrapped and the GCHEV and GIHEV tax credits, which change, according to the figures on the table. We do not include external costs in the calculations for two reasons: first, consumers do not include them and most importantly, we have already showed earlier that these are negligible in any case.

Increasing the gasoline tax rather than implementing vehicle purchase tax credits would be politically suicidal and it would never be accepted by car drivers.[46] The increases needed would be ridiculously high, ranging from $2 per gallon for a 6 year payback period to $9 per gallon for a 2 year payback period for GIHEVs. Having said that, higher gasoline taxes could be combined with vehicle purchase tax credits to bring the payback period forward. Table 12 anchors the gasoline tax at $1 per gallon[47] and combines that higher tax with the vehicle purchase tax credits that would be needed to achieve payback periods of 2, 4 and 6 years.

Table 12 Alternative gasoline taxes, vehicle purchase tax credits and payback periods

Payback period (relative to SICEG vehicles)	Gasoline tax	Tax credit on GCHEV	Tax credit on GIHEV
2 years	$1	$5,686	$2,356
4 years	$1	$4,511	$1,574
6 years	$1	$3,487	$909

Source: Authors' own calculations

[46] It would not be efficient either. Although efficiency principles are not the basis for our policy proposals, we would not want to suggest policies that are highly inefficient.

[47] Although this is an arbitrary choice it may be just about politically acceptable and is also close to the efficient tax. Parry and Small (2005) suggest that the efficient gasoline tax for the US for the year 2000 was just over $1.

Note: All current taxes and tax credits stay the same, except for the EV tax credit which is scrapped and the GCHEV and GIHEV tax credits, which change, according to the figures on the table, and the gasoline tax, which increases to $1 per gallon. We do not include external costs in the calculations for two reasons: first, consumers do not include them and most importantly, we have already showed earlier that these are negligible in any case.

From a comparison between Tables 11 and 12, the subsidies required are always higher when they are not combined with a higher gasoline tax, as expected. Also, unsurprisingly, given that the GIHEVs rely on gasoline for producing electricity, the impact of the gasoline tax is greater. For a payback period of 4 years, the vehicle purchase tax credit without a gasoline tax increase is 18% higher than with a $1 per gallon tax. This increases to 43% for a payback period of 6 years.

Although it would be politically difficult to implement such an increase in gasoline taxes in the US, it could potentially help fund the vehicle purchase tax credits, which in any case, would be smaller.

Tables 11 and 12 are examples of plausible policies. Many other combinations can be thought of and before any decision was taken, a thorough general equilibrium analysis would need to be carried out. Taxes and subsidies impact not just the federal budget but they have effects throughout the economy.

Needless to say the final decision would also need to rest on evidence, perhaps from further research, on acceptable payback periods for Americans. There is some evidence that shows that consumers in the US want a payback period not longer than three years (Lee and Lovellette, 2011, p.13).

To conclude this section, we highlight the fact that if a political decision were taken to steer consumers towards GIHEVs and GCHEVs, this could be achieved through pertinent financial incentives such as taxes and subsidies. Given the values we estimated on Tables 11 and 12, with tax credits falling well within the range of current tax credits, we do not envisage our proposed policies or equivalent ones would be impossible to implement in practice.

5.8 Conclusions

This paper has conducted a breakeven analysis of low carbon vehicle/fuel technologies for the US for the year 2020, taking into consideration both private and external costs as well as calculated the present value of the costs of the different options.

Not even the highest estimates of the social cost of carbon prevailing in the literature justify the mass introduction of low or zero carbon vehicle/fuel technologies. If this were to be done, it would be a political decision rather than one based on economic principles.

Potential fiscal measures are entertained with a view of changing consumers' choices to favour green technologies. Our two recommended technologies are Grid-Connected Hybrid Electric Vehicles (GCHEVs) and Grid-Independent Hybrid Electric Vehicles (GIHEVs). Both types of vehicles are initially more expensive than spark ignition internal combustion engine (ICE) conventional vehicles on gasoline (SICEG). Their running costs, however, are much lower. In order to persuade consumers to buy GCHEVs and GIHEVs rather than SICEG vehicles we propose that the federal government scraps the current vehicle purchase tax credits on EVs and increases those on GCHEVs and introduces tax credits on the purchase of GIHEVs.

The values of the tax credits would need to be tailored according to the target payback period, which in turn, as already highlighted, depends on consumers' perceptions. Further research could help determine target payback periods.

Although we do not find an economic justification for favouring cleaner fuel/vehicle systems, we do not discard the possibility that these could be justified if the social cost of carbon were revised upwards by the academic community or more importantly, if other externalities were also taken into account, including non-GHG emissions and oil dependence. The inclusion of these in our breakeven analysis fall outside the remit of the present paper but are postulated here as future lines of research.

Finally, a general equilibrium analysis of the implications of alternative policy packages would be in order before deciding on a particular one.

Chapter 6 The PHEV Potential for Urban Transport in China: the problem of energy sources and charging behaviour

Jian Liu

School of Geography and the Environment, University of Oxford

Georgina Santos (corresponding author)

School of City and Regional Planning, Cardiff University

Key words

Plug-in Hybrid Electric Vehicles (PHEV), Lifecycle Analysis, GREET, Utility Factor, Battery Charging

Abstract

To investigate the lifecycle energy consumption and emissions of Plug-in Hybrid Electric Vehicles (PHEVs) in China in the year 2020, this paper undertakes a "Well-to-Wheel" (WTW) lifecycle energy consumption and carbon emission analysis using the latest 'Greenhouse Gases, Regulated Emissions and Energy Use in Transport' (GREET) model from the US Department of Energy. The study finds that PHEVs have substantial potential in terms of energy consumption and GHG emission reductions in China, especially if electricity were produced in a clean manner. This benefit could however deteriorate if travel distances increased, which will happen as China's car ownership rises and vehicle operating costs go down.

6.1 Introduction

In contrast with Grid Independent Hybrid Electric Vehicles (GIHEVs), which convert the vehicle's kinetic energy into battery-replenishing electric energy, or use the internal combustion engine to generate electricity by spinning an electrical generator to either recharge their batteries or to directly power the electric drive motor, Plug-in Hybrid Electric Vehicles (PHEVs) get the electricity from the grid and store it in an on-board battery. If the electricity is generated in a low-carbon way the potential for carbon emission savings is important, relative not just to conventional internal combustion engine (ICE) vehicles but also relative to GIHEVs. On top of that, PHEVs contain a dual power-train system capable of both electric drive or ICE drive alone and combined, unlike GIHEVs, which can only work on a combination of both.

The current PHEVs prototypes, such as Toyota Hymotion Prius with an A123 battery system, can provide competitive performance when compared with mid-size conventional ICE vehicles. Also, in contrast with other alternative fuel/vehicle systems, such as hydrogen fuel cell vehicles (FCVs), PHEVs have an infrastructure advantage, as they use the electricity supplied by the already existent electric power grid. Moreover, because of the reduced requirement of battery capacity, production costs (and therefore the minimum price at which manufacturers will be willing to sell PHEVs for) are not as large as those for pure electric vehicles (EVs). This would not be the case though if there were a breakthrough in battery technology which lowered pure EVs production costs substantially relative to PHEVs. However, this is unlikely

in the time frame considered in the present study.

Nevertheless, PHEVs also face many challenges. Although the batteries required are not as costly as those required by pure EVs, the capacity still needs to be high and that means higher production costs than conventional ICE cars. The battery capacity is one of the main problems that hybrid and pure electric vehicles face, as the (electric) driving range depends on the battery. Also, as already mentioned above, the reduction in carbon emissions depends on how the electricity is generated. Bradley and Frank (2009) review the potential environmental benefits of PHEVs for the US and conclude that improvements to the electricity grid can yield environmental benefits in the PHEV fleet. Finally, people's travel behaviour is an issue that is seldom mentioned but has an important role to play in carbon emission reduction, not just in the case of ICE vehicles but also in the case of PHEVs. By travel behaviour in this study we are talking about refuelling and battery charging frequency and daily distances driven, rather than mode choice.

This paper investigates PHEVs' lifecycle energy consumption and carbon emissions for the case of 2020 China using the 'Greenhouse Gas, Regulated Emissions and Energy Use in Transport' (GREET) Model, which is essentially a lifecycle emission assessment model from the US Department of Energy that covers the fuel lifecycle of feedstock recovery and transport; fuel production, distribution and final consumption

of vehicle engines.[48] The answers to a simple questionnaire conducted in China are also used to make assumptions about travel behaviour and energy consumption of PHEVs, although there are some caveats regarding their usefulness.

6.2 Methodology and Data

The overall energy consumption and carbon emissions of PHEVs are determined by two factors: energy source and electricity/petroleum consumption split. As already advanced in the Introduction, in this study the GREET model is used to estimate lifecycle energy consumption and emissions. The parameter values input into the model correspond to China, and were sourced from Chinese data bases. As is already standard practice, lifecycle is divided in two stages: Well-to-Pump (WTP) and Pump-To-Wheel (PTW).

2.1 Well-to-Pump Stage

The energy recovery and refining data input onto GREET for WTP simulation were retrieved from the latest nationwide statistics and research reports. The exact source of each piece of information is further detailed below.

Because this study focuses on the energy consumption and emissions of PHEVs, both

[48] The version used here is GREET 1.8c.0 and is downloadable for free from http://www.transportation.anl.gov/modeling_simulation/GREET/

electricity generation and gasoline production are reviewed. Other vehicle fuels such as diesel, natural gas based fuels, hydrogen and biomass-based fuels are not included, although they can also be used by the dual-power-train systems of PHEVs.

Gasoline pathway

The two key questions when modelling the gasoline pathway are how the gasoline is produced (energy feedstock[49] types) and how it is processed and transported. Since GREET in default mode uses data for the US case, all the data regarding gasoline production, process and transportation were replaced with numbers corresponding to the Chinese case. In this section a brief overview of the assumptions is presented.

2.1.1.1 Crude oil

The oil recovery efficiency has improved for all the three major oil companies in China over the last 30 years. However, given that many oil and gas fields in China are approaching their late-stage of extracting life, the efficiency improvement rate could decline gradually in the next few years. The recovery efficiency assumptions for 2020 are therefore conservative. The crude oil recovery energy efficiency gap between China and the US in this study is assumed to remain at 5%, or in other words, the crude oil recovery energy efficiency in China in 2020 is assumed to be 93%, against

[49] Feedstock is defined as energy resources for fuel/electricity products.

98% in the US (Zhang et al, 2007, p.37).

2.1.1.2 Gasoline

Since 1999, Chinese domestic gasoline production has met domestic demand. Therefore, this study only considers the refining efficiency of Chinese refineries. The two main oil companies, China National Petroleum Corporation (CNPC) and China Petroleum and Chemical Corporation (Sinopec), jointly supply 90% of the gasoline in China. Domestic fuel production energy efficiency is assumed to be 87% (Zhang et al, 2007) for 2020 for both CNPC and Sinopec, in contrast with 92% for the US[50]. Since 2020 is only ten years away from the year when this paper was written (2010) the assumption of China being able to supply all of its gasoline demand in the future seems reasonable. Given the very rapid growth of China's gasoline demand though, this assumption would be questionable further into the future.

2.1.1.3 Transport

Apart from the energy efficiency of oil recovery and gasoline production, the transport of both crude oil and gasoline also play an important role in the lifecycle. In China the distances that the fuel needs to be transported are large and this causes relatively high energy consumption and emissions during the energy transport

[50] GREET 1.8c.0 assumes a fuel production energy efficiency in the US for 2020 of 92%.

process.

Figure 39 summarizes the shares of oil sources for China, as well as the transport modes used and the average distances.

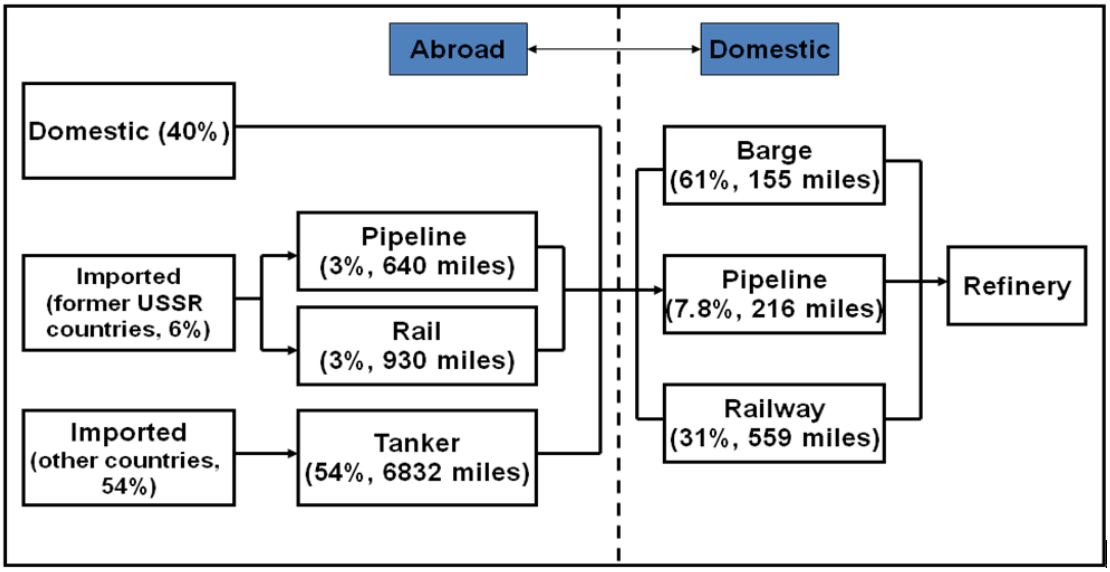
Currently, China's imported crude oil accounts for more than 40% of national demand and this figure could reach 60% to 80% by 2020 (Zhang et al, 2007, p. 36, Table 13).

The imported crude oil is largely transported by tankers (90%), except for the crude oil from former USSR countries, which is usually delivered through pipelines and rail (National Development and Reform Commission, NDRC, 2006). There is also some oil imported from Southeast Asia and Russia, which is transported by railway. Taking into account transport routes and distances from the Middle East (38.5%), Asia-Pacific (17.4%), West Africa (19%), North Africa (1.9%), Southeast Africa (2.7%), Latin America (6.7%) and Europe (0.2%), the average transport distance by tankers can be assumed to be 11,000 km.

Domestic and imported crude oil *within* China is transported by three modes: pipeline (61%), barge (7.8%) and railway (31%). According to the NDRC statistics (NDRC, 2006), the average distance that crude oil was transported in China in 2005 was 390 km. The majority of barge-based crude oil transport in China takes place along the East China Sea and the Yangzi River, and the average transport distance is between

100 and 400 km (Ministry of Communications and Transportation, MOC, 2005). Because barge fleets in China are comprised largely of small boats fuelled by residual oil, energy consumption is 2-5 times higher than in the US. The oil transported by railway has increased relatively slowly compared to the increase in crude oil demand. The average transport distance by railway ranges from 860 km to 960 km. Most trains are fuelled by diesel (61%) and electricity (39%).

Figure 39 Crude Oil Transport in China 2020



Source: estimates produced by the authors using data from Jia (2003), China Logistics Association (2005) and MOC (2005)

Since domestic gasoline meets and will continue to meet national demand in 2020, this analysis only considers the transport of gasoline within China. The main transport modes for fuel products currently are pipeline (15%), railway (50%), barge (25%) and highway (10%) (Jia, 2003). These shares are assumed the same for 2020. A

considerable amount of gasoline has to be transported long distances by railway, from the north-east and north-west to the eastern provinces. The average transport distance by train is around 800 to 1000 km (China Logistics Association, 2005).

Because the major Chinese oil refineries are located along the east coast and the Yangzi River, barge is also an important transport mode for fuel products. MOC (2005) and Jia (2003) estimate that 20% to 30% of oil products in China are transported by barge. Here an average of 25% is assumed, with an average distance of 1200 km. Finally, gasoline and diesel from oil depots to service stations are transported by road, and an average distance of 50 km is assumed. Although fuel transport via pipelines has increased in the period 2000 to 2010, its share among total transport remains minor. Assuming the share of pipeline transport continues to increase at 1.2% per year, this analysis assumes 30% of total fuel products will be transported by pipeline in China by 2020. Because pipelines currently are mainly applied for short distances the average transport distance is assumed to be 160 km. However, with the progress of new “North-to-South” and “West-to-East” energy transport projects, the distance in 2020 is assumed to be 800 km (NDRC, 2006).

Electricity Pathway

At present, China’s national grid is operated by two state-owned companies: State Grid Corporation of China (SGCC) and China Southern Power Grid (CSPG). In both cases electricity is mainly generated in coal power stations. The new generation

clean-coal technologies, such as Integrated Gas Combined Cycle (IGCC), are currently only used to produce 1.25% of overall coal-based electricity. Following coal, hydropower ranks second. The shares of natural gas, residual oil and nuclear-based electricity generation are minor. Wind and biomass-based electricity generation are at their trial phase in some provinces only, including Inner Mongolia and Tibet (China National Statistics Bureau, 2006).

According to data from the National Development and Reform Commission (NDRC) in China, the shares of capacity installation and electricity generation in China in 2020 will be as depicted in Table 13 (Zhang et al, 2007, p. 94).

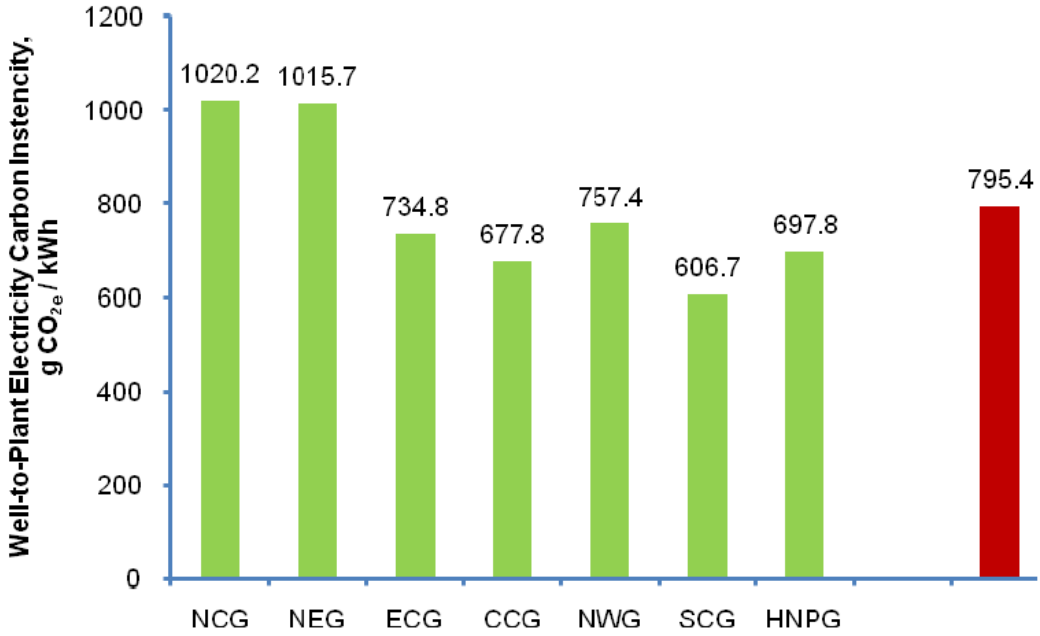
Given the NDRC's plans to implement a renewable energy program by 2020, the share of hydro, nuclear and wind power will increase, although coal will still remain the major resource in the medium term. The electricity transmission loss is predicted to be around 7% by 2020, a slight improvement compared to the 2010 level of 7.1% (Zhang et al, 2007, p. 95).

Table 13 National Grid Energy Feedstock Share in China 2020

	Coal	Oil	Natural Gas	Hydropower	Nuclear	Solar, Wind & Biomass
2007	80%	2%	2%	15%	2%	0.50%
2020 Estimated	63%	1.00%	6.80%	19%	6.70%	3.50%
2020 Slightly cleaner	40%	1%	10%	19%	20%	10%
2020 All nuclear	0%	0%	0%	0%	100%	0%

Source: International Energy Agency (2010); Zhang et al (2007, p.94)

Figure 40 Electricity Generation Carbon Intensity Values of Regional Power Grids in China



Note: NCG-North China Power Grid; NEG-Northeast China Power Grid; ECG-East China Power Grid; CCG-Central China Power Grid; NWG-Northwest China Power Grid; SCG-South Power Grid; HNPG-Hainan Power Grid

Source: Earley, et al, 2011

Pump-to-Wheel Stage

Two essential assumptions are needed for Pump-to-Wheel (PTW) simulation: the selection of a reference plug-in vehicle for modelling and the share between electricity and gasoline consumption during vehicle operation.

The reference plug-in vehicle for modelling in this study was the Toyota Hymotion Prius with an A123 battery. It was chosen because it is a promising prototype.

The share between electricity and gasoline use is determined by kilometres travelled per charge, which further relates to the vehicle's electric operation range, and the required frequency of recharging. This in turn can be linked to driving behaviour. A combination of a high-charging frequency rate and a low-driving distance per charge could offer nearly an all electric driving of PHEVs. This pattern would, for example, illustrate the driving behaviour of workers commuting short distances by car and recharging the vehicle's battery at home every night.

To address the share of electricity and gasoline consumption, the concept of "Utility Factor" (UF) has been introduced in recent PHEV fuel economy studies (Elgowainy et al, 2009) to represent the percentage of a PHEV's electricity consumption over its entire energy consumption during vehicle operation. Normally, a daily charging basis is assumed and so a Daily Kilometres Travelled (DKT) becomes the key factor that needs to be identified. For this, daily travel behaviour information is required. However, there is currently no such a nationwide level survey available for China. This study hence has conducted a non-representative simple travel and attitudinal survey. The results of this survey are used with much caution and a number of caveats highlighted when deriving conclusions.

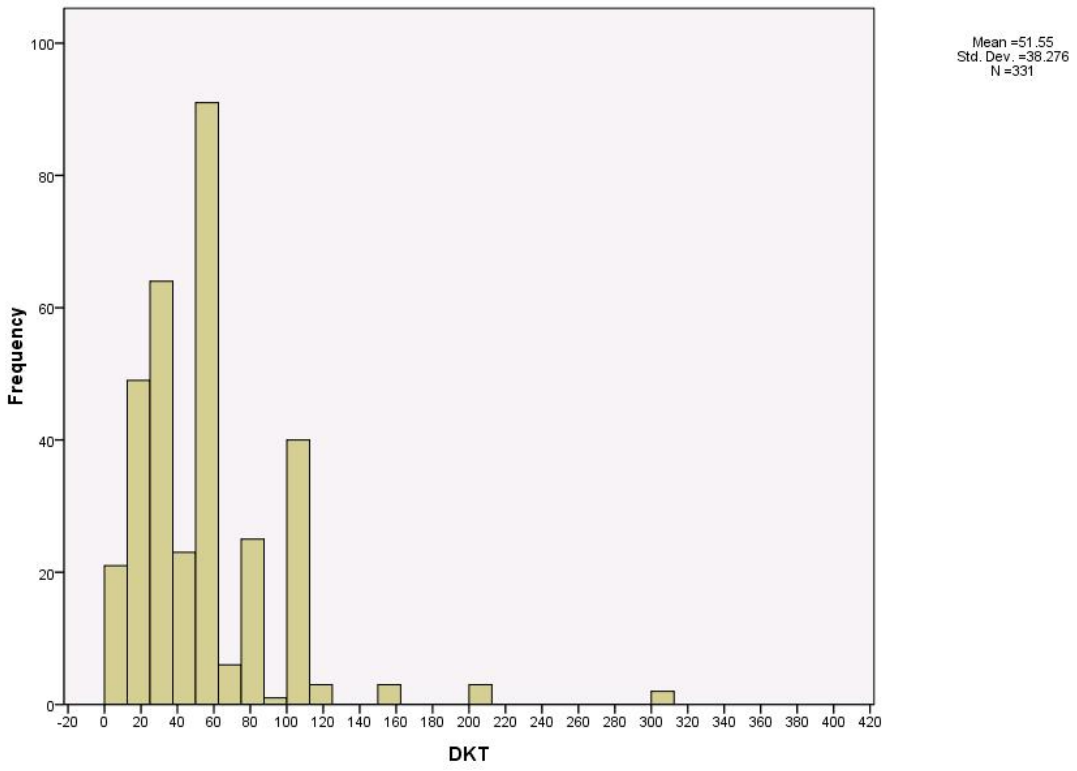
The Survey

The survey was conducted on the 'Auto.Sohu' website[51] and the results reported in this paper correspond to responses posted in the period 24 February to 26 March 2010. The survey consisted of 30 questions, designed to elicit: (1) people's attitudes to EVs and PHEVs in terms of relative prices with respect to ICE vehicles (for both the cost of the vehicle and the operation cost), performance expectancy and other concerns; (2) their travel behaviour including mode of transport used, daily distance travelled, speed and driving/parking habits, and; (3) personal socio-economic information including income, gender and home/work addresses (see Appendix 8).

Three hundred and thirty one usable responses were collected and are used in this paper. The histogram in Figure 40 illustrates the distribution of DKT across the survey's observations. The majority of daily distances for all transport modes, including bus, car, metro, cycle and walk, and trip purposes, including commuting, shopping, recreation, and also work-related trips, as well as all other trips (such as attending doctor's appointments, etc) are concentrated from 20 km to 60 km.

Figure 41 Frequency Distribution of DKT by all modes

[51]The 'Auto.Sohu' website is a Chinese website owned by a private company that specializes on the automobile reviews, information, news, surveys, data, etc. The geographical distribution of respondents is determined by the online survey (sohu automobile) outcome. This could also reflect EVs could be more preferable in these areas.
http://auto.sohu.com/20100224/n270407525.shtml



Source: Responses to the survey conducted by the authors

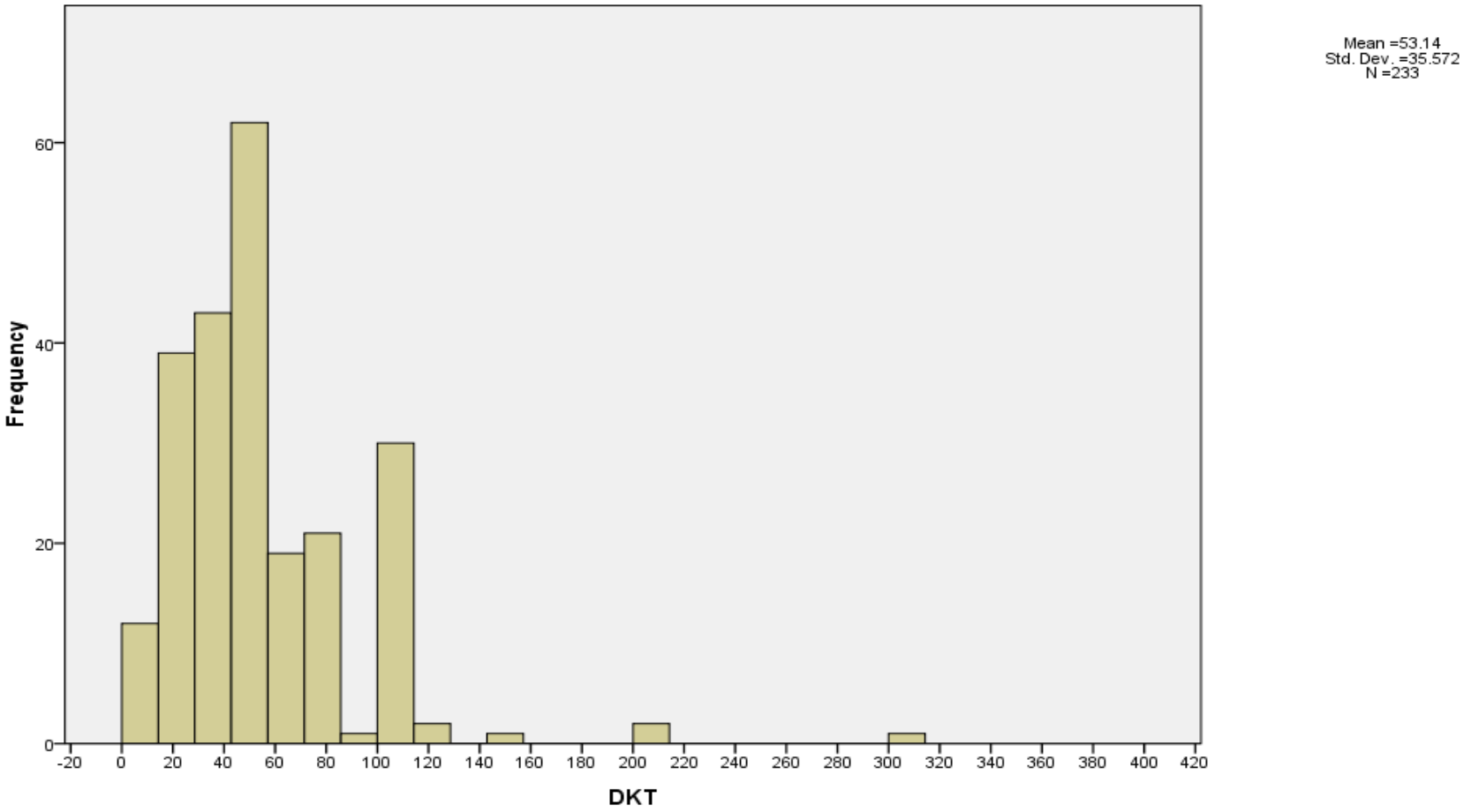
Figure 41 is a snapshot of a very small and not necessarily representative group of Chinese people. The geographical distribution of the respondents is also uneven. For example, 22% of the responses came from Beijing province, where only 1.09% of the Chinese population lives; and almost 17% of the responses came from Shanxi province, where only 2.85% of the population lives.

The histogram in Figure 42 illustrates the distribution of DKT by car across the survey's observations. All trip purposes are still included but the only transport mode considered in this case is the private car. As it can be seen, the average distance is higher, now concentrated between 25 and 70 km. The number of responses was obviously limited by the number of respondents who actually own or have access to a

car. It should be born in mind that car ownership in China is still very low, with only 36% and 2.2% of households owning a car in capital Beijing and the whole of China, respectively (National Bureau of Statistics of China, 2009, Table 15-27: Private Car Ownership 2009), in contrast with the UK, where 76% of all households have regular access to at least one car (UK Department for Transport, 2009, Table 9.15, p.166).

One important consideration in this context, which regards travel behaviour, is that the private car brings freedom of movement and convenience, and car owners tend to travel longer distances more frequently in time. We return to this point later.

Figure 42 Frequency Distribution of DKT by car



Source: Responses to the survey conducted by the authors

6.3 Data Analysis

If and when a consumer decides to buy a PHEV rather than a conventional ICE vehicle, he will typically consider a number of issues on top of the cost of the vehicle itself and the cost of operating it, including battery capacity (for instance, for how long he can drive without re-charging the battery) and maximum possible speed.[52]

In this paper it is assumed that drivers recharge the vehicle battery once a day[53]. As already explained above, if drivers were able/willing/had the necessary facilities to recharge the vehicle battery twice or three times a day, they would be able to drive longer distances on electricity.

3.1 Utility Factor

[52] Axsen and Kurani (2009) conduct an Internet-based survey of 2,373 new car-buying households in the US and find that fuel economy appears to be the most important characteristic for potential buyers of PHEVs in their sample.

[53] This assumption is common in the literature. Even the documents produced by the Society of Automotive Engineers (SAE) in the US assume that batteries are only recharged once a day (Bradley and Quinn, 2010). Axsen and Kurani (2010) evaluate different re-charging patterns and, not surprisingly, conclude that PHEV electricity use could be increased through policies supporting non-home recharging opportunities, although this increase would occur during daytime hours and would therefore potentially increase peak electricity demand.

PHEVs can run on conventional oil-based fuels and electricity from the grid. Since their storage capacity is limited, PHEV batteries can only supply electricity to drive the vehicle for a limited number of kilometres. As a result, PHEVs operate in two modes: 'a charge-depleting mode where the stored battery energy contributes to the propulsive energy consumed by driving the vehicle, and a charge-sustaining mode, where the net energy from the battery is essentially zero' (Bradley and Quinn, 2010).

The daily distance UF of a PHEV can be defined as the ratio of the number of kilometres driven under charge-depleting mode to the total number of kilometres driven:

$$UF_{distance}(R_{CD}) = \frac{\min(d, R_{CD})}{d}$$

Where d is the distance driven and R_{CD} is the charge depleting range. As Bradley and Quinn (2010, p.5400) put it, the daily distance UF of a PHEV is equal to the ratio of the charge-depleting range to the distance travelled: R_{CD}/d if $d < R_{CD}$, and 1 if $d > R_{CD}$.

Following Elgowainy et al (2009), in order to identify the UF for various PHEV models (or battery energy storage capacities), the survey observations are categorized in 12 groups in terms of DKT, as shown in Figure 42. Only the responses from car drivers are taken into account for these calculations, as DKT by other modes would

not be a good estimate of drivers' behaviour.

Figure 43 can be read as follows. The first two columns indicate the limits of the range of DKT. For example, the first range corresponds to respondents who travel between 0 and 10 km per day. The 'Frequency' column is simply the number of respondents who gave that answer. The 'Share' column is the percentage of respondents with a DKT falling in that range. The rest of the columns give the daily distance UF for different R_{CD}. Paraphrasing Bradley and Quinn (2010, p.5400), the daily distance UF is the fraction of km travelled by the sample fleet in charge depleting mode.

For example, when the R_{CD} is 10 km, drivers with DKT between 0 and 10 km will be able to drive all those km on charge depleting mode. As long as the R_{CD} is higher than the DKT the PHEV will be able to drive on charge depleting mode alone. When the R_{CD} is 50 km but the DKT are between 80 and 90, drivers will be able to drive the first 50 km on charge depleting mode but they will drive the remaining 30 to 40 km on conventional fuel. The PHEV Utility Factor on the last row indicates the percentage of total DKT by survey respondents that can be driven on electricity. If the R_{CD} is 10 km only 32.28% of DKT by all respondents can be driven on charge depleting mode, whereas if the R_{CD} is 70 km then 94.63% of DKT by all survey respondents can be done on charge depleting mode.

Figure 43 Utility Factors for PHEV with RCD of 20, 40, 60, 80, 100 and 120 km

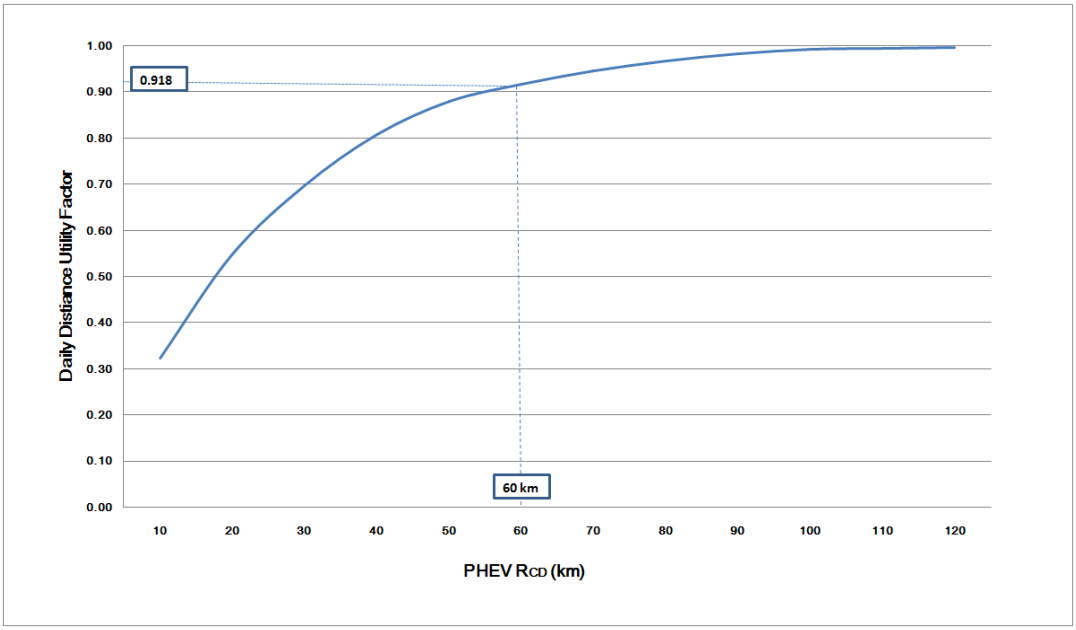
DKT (min - max, km)		Frequency	Share	20	40	60	80	100	120
0	10	12	5.15%	5.15%	5.15%	5.15%	5.15%	5.15%	5.15%
10	20	33	14.16%	14.16%	14.16%	14.16%	14.16%	14.16%	14.16%
20	30	32	13.73%	10.99%	13.73%	13.73%	13.73%	13.73%	13.73%
30	40	17	7.30%	4.17%	7.30%	7.30%	7.30%	7.30%	7.30%
40	50	59	25.32%	11.25%	22.51%	25.32%	25.32%	25.32%	25.32%
50	60	20	8.58%	3.12%	6.24%	8.58%	8.58%	8.58%	8.58%
60	70	2	0.86%	0.26%	0.53%	0.79%	0.86%	0.86%	0.86%
70	80	21	9.01%	2.40%	4.81%	7.21%	9.01%	9.01%	9.01%
80	90	1	0.43%	0.10%	0.20%	0.30%	0.40%	0.43%	0.43%
90	100	30	12.88%	2.71%	5.42%	8.13%	10.84%	12.88%	12.88%
100	110	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
110	120	2	0.86%	0.15%	0.30%	0.45%	0.60%	0.75%	0.86%
120	Max	4	1.72%	*0.21%*	*0.43%*	*0.64%*	*0.86%*	*1.07%*	*1.29%*
PHEV Utility Factor		233	100.00%	54.69%	80.78%	91.78%	96.82%	99.24%	99.57%

Source: Calculations by the authors using survey responses

Figure 44 shows the daily distance UF curve for PHEVs if these were to be driven by the survey respondents, and if the respondents did not change their DKT as a result of driving a PHEV rather than a conventional ICE vehicle.

The daily distance UF on the Y-axis represents the share of km in the total DKT by all survey respondents that could be driven in charge depletion mode if they all drove PHEV. As it can be seen from the figure, the UF of PHEVs increases at a diminishing rate with the increase of R_{CD}.

Figure 44 Utility Factors for Different RCD in our sample



Source: calculations carried out by the authors using survey responses

A PHEV with a R_{CD} of 60 km offers a UF of 0.9178. In other words, 91.78% of all DKT by all survey respondents could be driven in charge depletion mode, provided they all drove PHEVs. It would be interesting to conduct a nationwide travel survey and be able to compare the Chinese UF with the one computed by Elgowainy et al (2009) for the US, which they estimate at 64%, or the one computed by Vyas et al (2009), also for the US, which they estimate at 74.4%. Unfortunately the authors do not count with the necessary financial resources to conduct a representative household travel survey in China.

6.4 Lifecycle Assessment Results

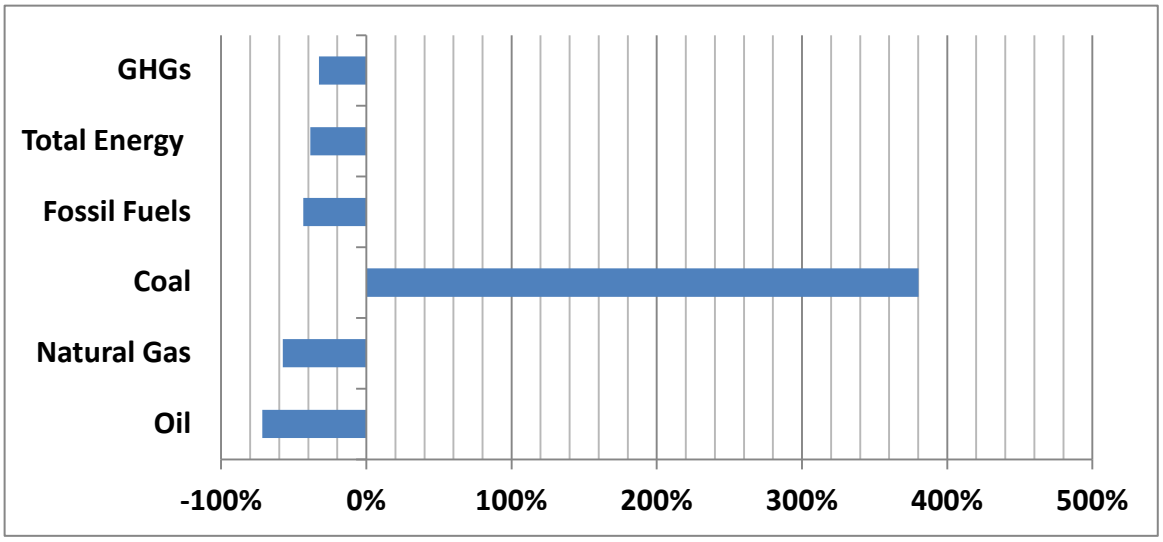
Figure 45 graphically summarizes the lifecycle energy consumption and emissions for

PHEVs with R_{CD} of 60 km relative to ICE vehicles. GHG emissions are 26% lower and total energy consumption is 34% lower. These results are not too different from those reported in Samaras and Meisterling (2008), who argue that PHEVs could reduce emissions in the US by 32%, compared to ICE vehicles.[54]

Assuming that grid electricity in China continues to be mainly generated in coal power stations, coal consumption obviously increases. One clear conclusion from these estimates, which is further discussed below, is that for PHEVs to be truly environmentally friendly and make significant improvements on energy consumption and GHG emissions, the electricity to power them needs to be generated using clean technologies. Even though energy consumption from coal (measured in BTUs) increases, energy from fossil fuels (coal, oil and natural gas put together) decreases because energy consumption from oil and natural gas (measured in BTUs) decreases.

[54] Duvall et al (2007) estimate GHG reductions in the whole of the US for the year 2050 as a result of low, medium and high market penetration of PHEVs. Although they report results under a number of different scenarios, they report them in billion metric tons of CO2e rather than percentage changes. Also their analysis concerns marginal emission reductions rather than total emission reductions. The model they use is the National Electric System Simulation Integrated Evaluator (NESSIE), developed at the Electric Power Research Institute. The NESSIE models the US electricity sector from 2010 to 2050. For all those reasons comparisons with the Chinese case in the present study are not straightforward.

Figure 45 Lifecycle Energy Consumption in BTUs and GHG Emissions in CO2e for PHEVs with RCD of 60 km relative to ICE Vehicles in China 2020 for the travel survey sample



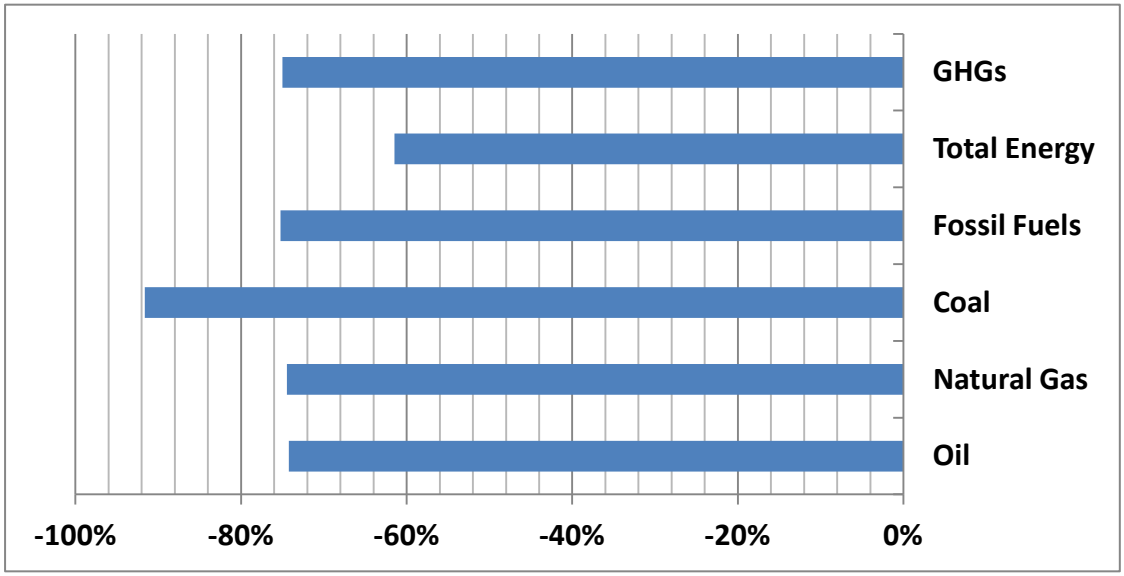
Source: estimates produced by the authors using GREET 1.8c, using parameters derived from the travel survey they conducted

Note: For the year 2020 fuel economy for PHEVs driving in charge depleting mode is assumed to be 15.14 km/l and fuel economy for ICE vehicles is assumed to be 10.8 km/l. GREET assumes PHEVs running in charge sustaining mode to have a fuel economy 40% better than that for ICE vehicles (see Appendix 1).

Although GHG emissions and energy consumption would both be reduced, it is interesting to see what the changes would be if all electricity in China were produced in nuclear power stations, rather than coal power ones. Figure 46 shows the results of this exercise, even though it is an impossible scenario. In any case, power plants are long lived investments, which also take time to be built, and ten years would not be a

long enough period of time to substantially change the shares of electricity production from different sources.

Figure 46 Lifecycle Energy Consumption in BTUs and GHG Emissions in CO2e for PHEVs with RCD of 60 km relative to ICE Vehicles in China 2020 for the travel survey sample in an all nuclear scenario



Source: estimates produced by the authors using GREET 1.8c, using parameters derived from the travel survey they conducted and assuming all electricity is generated in nuclear power stations

As it can be seen on Figure 46, if electricity were generated in a clean way the reduction in energy consumption and GHG emissions resulting from using PHEVs rather than ICE ones would be drastic. Although China could not convert to all nuclear by 2020 the exercise serves as a warning of the forgone benefits from feeding PHEVs electricity produced in coal power stations (see Appendix 2).

Table 14 Carbon Emissions (g CO2 e) of PHEVs in Six Scenarios

6 scenarios	Feedstock recovery	Fuel production	Vehicle Use	Total	Total (g/km)
0.92 2020 Mix	33	165	130	328	204
0.78 2020 Mix	33	179	115	327	203
0.69 2020 Mix	34	202	90	326	203
0.92 Nuclear	7	16	90	114	71
0.78 Nuclear	13	20	114	147	92
0.69 Nuclear	15	23	130	167	104
0.92 Slightly	26	144	90	260	162
0.78 Slightly	26	130	115	271	168
0.69 Slightly	32	126	133	291	181
0.92 IEA 2009	38	235	90	363	226
0.78 IEA 2009	37	207	115	359	223
0.69 IEA 2009	37	190	130	357	222
ICE vehicle	Feedstock reco	Fuel production	Vehicle Use	Total	Total (g/km)
Mix	43	74	348	465	289
Nuclear	38	63	347	448	278

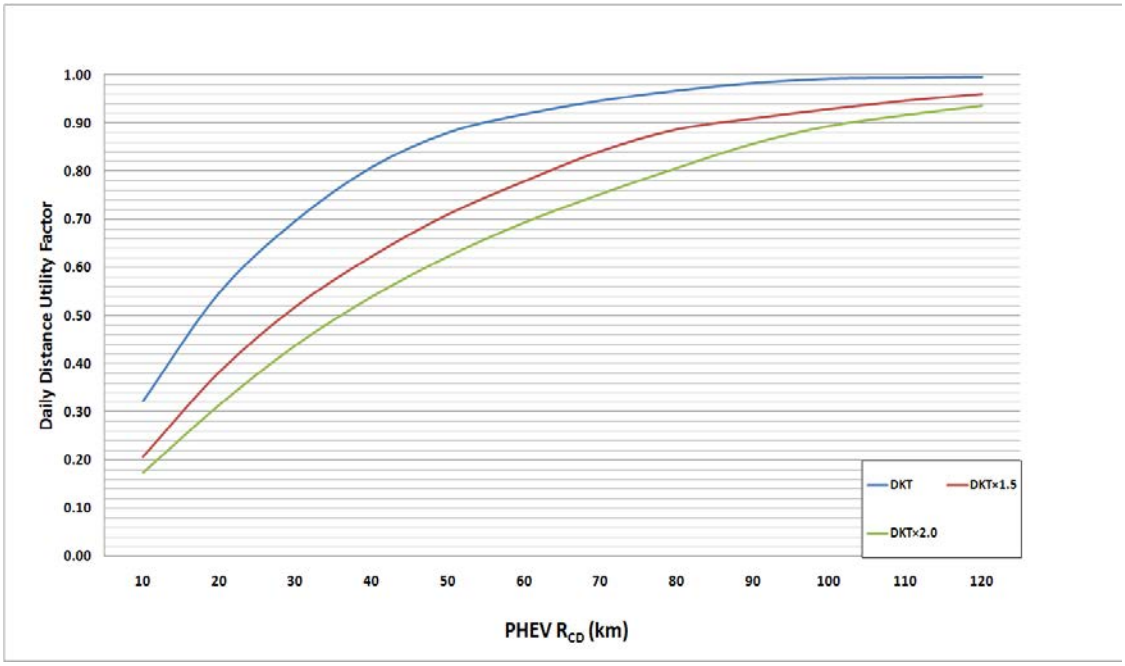
6.5 The Effects of Travel Distance Increase

The rather high daily distance UF of 91.78% for the survey respondents is simply the result of their low daily travel distances. If travel distances were larger, and this is likely to happen with both increases in car ownership and lower vehicle operating costs, the UF would be lower, and the potential for reduced energy consumption and emissions would be diminished.

Lower vehicle operating costs cause a ‘rebound effect’ and this is also a well-documented fact in the transport studies literature (Greening et al, 2000; Gorham, 2002, Portney et al, 2003; De Haan et al, 2006; Evans, 2008). In a nutshell, as costs decrease (be it fuel costs, time costs, etc) quantity and/or length of trips increase.

Figure 47 presents the daily distance UF curve for various PHEVs with R_{CD} of 10 km to 120 km for average daily distances of 53.14km, 79.71km and 106.28km, which is the average, 1.5 times and twice the average distance travelled by the drivers in the sample.

Figure 47 Daily Distance UF Curves for DKT, 1.5 DKT and 2 DKT



Source: calculations produced by the authors

6.6 Conclusions

Using the responses to a small survey conducted by the authors in China, this paper has conducted a fuel cycle energy consumption and GHG emissions assessment for PHEVs on the basis of China's electricity generation mixes in 2020.

For the surveyed sample, PHEVs have large potential for reducing gasoline consumption, compared to ICE vehicles. The potential for reducing GHG emissions could be larger if electricity in China were generated using cleaner technologies rather than coal. For example, under an all nuclear scenario the reductions would be over 20 times those under the projected electricity generation mix, where coal power stations play a central role, producing 63% of all electricity in 2020.

The potential of PHEVs for reducing gasoline consumption amongst our survey respondents is important due to their low daily travel distances. If this were found to be the pattern in the whole of China, the Chinese daily distance UF for PHEVs would be higher than that in the US. The UF of a PHEV with R_{CD} of 60 km in the survey sample is of 91.78%, which indicates a large share of charge depleting mode in PHEV total energy consumption. Although such a high UF is expected to decrease with an increase in daily travel (very likely if car ownership increases and vehicle operating costs decrease), the reductions in energy consumption and GHG emissions can still be

important, provided R_{CD} can be increased.

Chapter 7 Analysis of Charging Infrastructure Assignment for an Early Electric Car Market in Beijing

Jian Liu

Transport Studies Unit

School of Geography and the Environment

University of Oxford

Key words: electric vehicle charging infrastructure, battery swap stations, fast charging stations, charging posts, spatial assignment.

Abstract:

This paper estimates the charging demand of an early electric vehicle (EV) market in Beijing and proposes an assignment model to distribute charging infrastructure. It finds that each type of charging infrastructure has its limitation, and integration is needed to offer a reliable charging service. It also reveals that the service radius of fast charging stations directly influences the final distribution pattern and an infrastructure deployment strategy with short service radius for fast charging stations has relatively fewer disturbances on the power grid. Additionally, although the adoption of electric vehicles will cause an additional power load on the Beijing's power grid, this additional load can be accommodated by the current grid's capacity via the charging time management and the battery swap strategy.

7.1 Introduction

In 2009, China became the worlds' largest automobile producer and petrol fuel consumer (China Association of Automotive Manufacture, CAAM, 2010). According to the current growth rate, China's annual automobile production and sales are likely to exceed 25 million in 2020, with an estimate of oil consumption of over 500 million tons. China has announced strong goals for reducing CO2 emission per unit of GDP by 40% to 45% by 2020 compared with the 2005 level (State Council, 2009), and the introduction of electric vehicles (EVs) is seen as an important strategy for China's automobile industry to reduce its carbon and energy footprint. In 2009, the central government released the "Automobile Industry Development Master Plan", where new energy vehicles have been proposed as the means to achieve these targets for China's automobile industry (National Development and Reform Commission, NDRC, 2009). A series of policies to facilitate electric vehicle industrialization and commercialization were then introduced, including pilot projects (Ministry of Science and Technology, MOST et al, 2009), production standards (Ministry of Industry and Information Technology, MIIT, 2009) and purchase subsidies (NDRC et al, 2010a). A range of car manufacturers have announced their EV models and mass production plans. In some cities, EVs have already accounted for a significant share in public transport and public service vehicle fleets. In June 2010, six cities (Beijing, Shanghai, Changchun, Hefei, Shenzhen and Hangzhou) were further chosen to implement EV purchase subsidies with a maximum of RMB60,000 ($9,000) per vehicle in the

private car market (NDRC, et al, 2010b).

To meet the expected charging demand from the growing EV fleet, both utility and oil companies in China have recently released their EV charging infrastructure deployment plans. The State Grid Corporation of China (SGCC) has proposed a series of charging station standards and it has planned to establish 1,700 EV charging stations[55] and 3 million charging posts[56] in China by 2015 (Xinhuanet, 2010). Meanwhile, the China Southern Power Grid (CSPG) released a development plan in its demonstration city (Shenzhen), including 150 charging stations and 225,000 charging posts for 2015. The city has also started charging post deployment in residential communities (5% of community[57] parking spots) and public parking lots (10% of public parking spots) (CSG, 2010). However, the current charging infrastructure development plans have been produced according to an estimate of the total volume of EVs, and little analysis has been made to compare different roles of diverse types of charging infrastructure in an EV charging network, as well as the impact of charging infrastructure distribution on the electric power grid. This study

[55] According to Charging Infrastructure Guideline from SGCC, EV charging stations refer to the stations providing fast charging services for electric vehicles. A charging station is normally designed to deploy 4 to 8 standard chargers (DC35kW – 350V/100A output/charger) or rapid chargers (DC200kW – 500V/400A output/charger).

[56] According to Charging Infrastructure Guideline from SGCC, EV charging posts provide 5kW charging output and are dispersed in residential communities and public parking areas.

[57] A community is defined as a residential development with wide ranges of dwelling numbers. The concept of community is not necessarily associated with people having common interests or sharing values, but rather by the practicalities of living in the same building or group of buildings.

therefore aims to develop a charging infrastructure assignment strategy, and uses Beijing as a case study to compare different types of charging infrastructure and predict their different impacts on the city's current power grid.

7.2 Literature Review

Energy for road transport has and still continues to be dominated by petroleum fuels. There is a rich literature research on refueling behavior and on petrol station distribution. In the United States, Kitamura and Sperling (1986) evaluated the relationship between drivers' attributes and their refueling behavior in Northern California, and found that car ownership and utilization are two key factors that are strongly related to refueling behavior. Despite the fact that there are many differences between EV charging infrastructure and petrol stations, their spatial distributions are both largely determined by local refueling/charging demands. In China, the advisory service radius for urban refueling stations is 0.9 – 1.2km (General Administration of Quality Supervision, Inspection and Quarantine, GAQSIQ and Ministry of Housing and Urban-Rural Development, MHURD, 1995). In Beijing, the current refueling station service radius ranges from 0.95km (urban districts) to 4.94km across 18 administrative districts (Beijing Municipal Amenities Committee, BJMAC, 2009).

With the development of hydrogen fuel cell vehicles in North America in the early 2000s, the need for research on appropriate assignment strategies for hydrogen refueling stations arose. For instance, Ni et al, (2005) built a hydrogen station

assignment model for the United States using population data and applied a 5km service radius to merge their estimated high demand geographical blocks. The study further evaluated the effects of various demand densities and buffer radii on the final distribution patterns. Melendez and Milbrandt (2008) introduced a distribution strategy based on the estimated spatial distribution of potential hydrogen vehicle customers. They used demographic and social economic factors, such as income and age, in the forecast process. Moreover, Kuby et al, (2009) investigated strategies for deploying an initial hydrogen refueling infrastructure in Florida under different market scales to identify appropriate refueling locations.

Although the distributions of both refueling and charging infrastructure are dependent on local demands, they have many differences in geographical deployment. For both petrol and hydrogen vehicles, refueling behaviors can only be made onsite petrol or hydrogen stations. In contrast, EVs can be charged at different electric outlets which offer a large charging flexibility. Currently, there are three promising types of EV charging infrastructure: charging posts, fast charging stations and battery swap stations (see Table 15). For EVs, providing a reliable charging service through different charging infrastructure is a key issue.

However, most present research on EV charging infrastructure concentrates on charging stations and a limited amount of previous research has focused on the different roles of charging posts and charging/battery swap stations in a charging

network. For example, Kou et al (2010) suggested an assignment method for charging stations where a potential charging demand was firstly forecasted by population and then each alternative charging station was weighed according to accessibilities, traffic flows and land costs. Finally, a cost benefit analysis was conducted to compare the profits of each alternative charging station. Similar to petrol and hydrogen stations, the study focused on the geographical siting for EV charging stations in terms of economic benefits, ignoring the charging post alternative. In the UK, the Greater London Authority (GLA, 2009) issued a London charging infrastructure development plan of 1300 charging posts[58] located at the workplace, roadsides and public car-parks by 2011. In common with Melendez and Milbrandt's methodology, the charging post assignment is based on an estimate of potential EV drivers' distribution, and demographic and social-economic data were used to forecast the demands. These analyses usually treat charging posts and fast charging stations separately with little consideration to their coordination. This study therefore investigates different charging infrastructure's unique roles, and it aims to produce and test a charging assignment methodology.

[58] Most of the charging points were being placed at the destination (workplace) and paid for by companies

Table 15 EV Charging Infrastructure

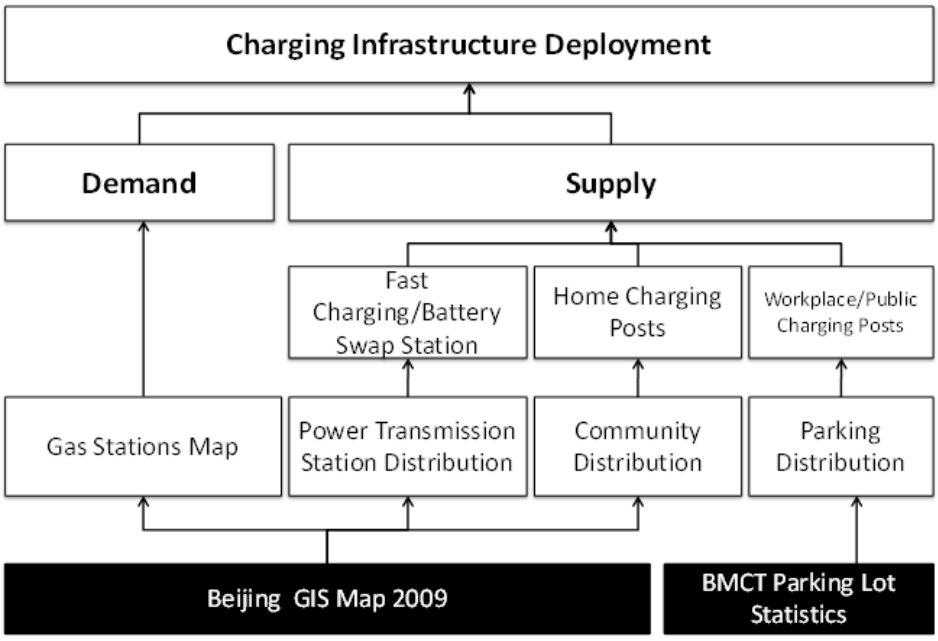
	Operating Power	Charging Duration and Time	Location	Target User	Construction Cost	Operating Cost
Charging Post	Alternating Current 5kW/post	6-10 hours; daytime and night	Parking Lots/ Communities	Private Car	20,000RMB /post	Low
Charging Station	Direct Current 200-400kW/charger (4 to 8 chargers/station)	10-30 minutes; 3-6 minutes for 80% charging daytime	Motorways/ Major Roads	Bus, Taxi and Private Car	3-5million RMB/station (land exclusive)	High
Battery Swap Station	Null	3 minutes; night	Motorways/ Communities	Bus, Taxi and Private Car	20 million RMB/station (land exclusive)	Low

Source: State Grid Corporation of China, 2010

7.3 Database Structure

As the capital city of China, Beijing is one of the six cities that have been selected to promote electric vehicles and local EV buyers are eligible for subsidies from both central and local governments (Wu, 2011). This study thus uses Beijing as the case study city to estimate the potential impact of EV charging demand.

Figure 48 Database Structure



When it comes to a geographical distribution of charging infrastructure, the regional charging demand and electric power supply/parking conditions need to be firstly identified. Figure 48 illustrates the database for the research. The variation of charging demand is measured by the distribution of petrol refueling stations. The distribution data are extracted from the BEIJING GIS Map 2009, containing a total of 1,043 petrol stations, spreading over Beijing's 18 administrative districts. With the growth of automobile market and daily driving distance, the refueling demand is expected to increase. However, according to the *2020 Beijing refueling station deployment plan* released by the municipal amenities committee (Beijing Municipal Amenities Committee, 2009), the average refueling volume of individual stations will increase, but the total number of refueling stations will be constrained to control the land use of refueling stations.

This analysis focuses on three types of charging infrastructure. They cover charging posts located at homes (home charging posts), charging posts at the workplace and public parking lots (workplace/public charging posts) and fast charging/battery swap stations. The Beijing GIS Map provides the distribution for power transmission stations, communities and public parking lots. The parking capacity data are collected from the "Transportation Administration of Beijing Municipal Commission of Transport" (BMCT, 2010) which contains the parking spaces data. There are 378,661 parking spaces across Beijing's 2,384 parking lots providing parking services for employees and the general public (see Figure 48). To avoid the deploying ratio being less than 1 post/lot, only public parking lots with more than 100 parking spaces are selected for this analysis. Thus, a total of 352,803 parking spaces in 1,841 parking lots have been chosen for the next step charging infrastructure assignment. The fast charging station locations will be selected from current refueling stations according to the estimated regional charging demand and their distances to nearest power transmission stations.

Figure 49 Distributions of Communities, Refuelling Stations, Parking Lots and Power Transmission Stations in Beijing

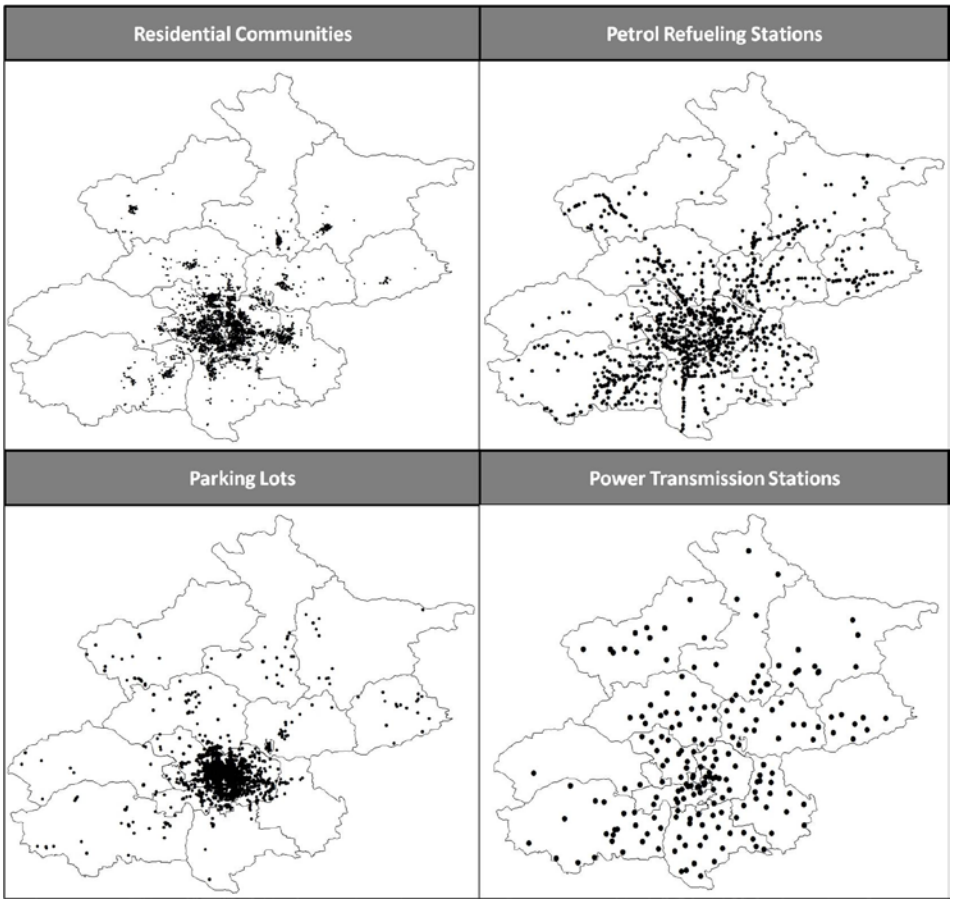


Figure 49 shows the overview distributions of petrol refueling stations, residential communities, parking lots and power transmission stations in Beijing. Obviously, the residential communities and parking lots are concentrated towards the city centre whereas the power transmission stations and petrol refueling stations are distributed in a relatively even pattern across the urban and rural areas. Among 18 administrative districts, Chaoyang district has the largest number of parking spaces (115,836), petrol stations (155) and communities (1,243) due to its large geographical area and proximity to the city centre. The "Nearest Neighbor Index[59]" for the petrol stations,

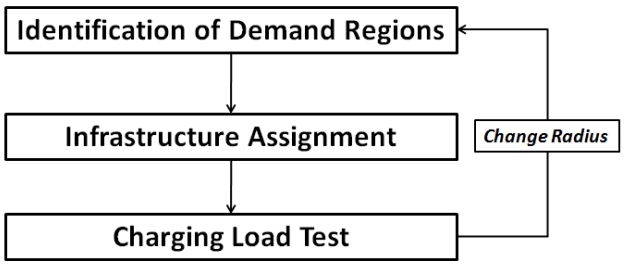
59 The nearest neighbor index is expressed as the ratio of the observed distance divided by the expected distance. The expected distance is the average distance between neighbors in a hypothetical

communities and public parking lots are 0.58 ([60]Z score: -25.80), 0.29 (Z score: -96.08) and -0.33 (Z score: -55.06) respectively, which indicates that communities have the most significant clustering pattern whilst petrol stations are relatively dispersed.

7.4 Methodology: Charging Infrastructure Assignment

In this study, the charging infrastructure assignment model is based on a loop calculation of three segments: 1. the identification of charging demand regions; 2. the charging infrastructure assignment, and; 3. the charging load test (see Figure 50). This section will describe each of them in detail.

Figure 50 Charging Infrastructure Assignment Model



7.4.1 Identification of Charging Demand Regions

Given a low market share in the early EV penetration stage and the availability of alternative charging methods at parking areas, the number of fast charging stations for EV could be less than the number of petrol stations. However, it still needs to

random distribution. If the index is less than 1, the pattern exhibits clustering; if the index is greater than 1, the trend is toward dispersion or competition.

[60] A high absolute value of Z score (>1.96) indicates a significant difference between the null hypothesis (random spatial distribution) and the test result. The null hypothesis (>95% fasle) should be rejected for community, public parking lot and petrol station distributions.

guarantee a minimum number of fast charging stations to ensure reliable and seamless charging infrastructure coverage across the whole city. In this study, the fast charging stations are designed to be deployed in some of the current petrol refueling stations, according to the estimated local charging demands and the distances to their nearest power transmission stations. Each fast charging station then defines a charging demand region. The charging infrastructure assignment in each demand region is made based on the number of local refueling stations, communities and public parking spaces in the region.

To identify the charging demand regions, the service radius of fast charging stations needs to be determined. It is obvious that while the fast charging stations' service radius is increasing (2km, 3km, 4km…, etc), the charging service duplication between neighboring fast charging stations is simultaneously increasing if every petrol station was chosen as a fast charging station. This duplication needs to be minimized by selecting some (rather than all) petrol stations in a neighboring station cluster as fast charging stations. Therefore, longer service radius will lead to fewer fast charging stations.

Figure 51 Service Coverage of a Fast Charging Station

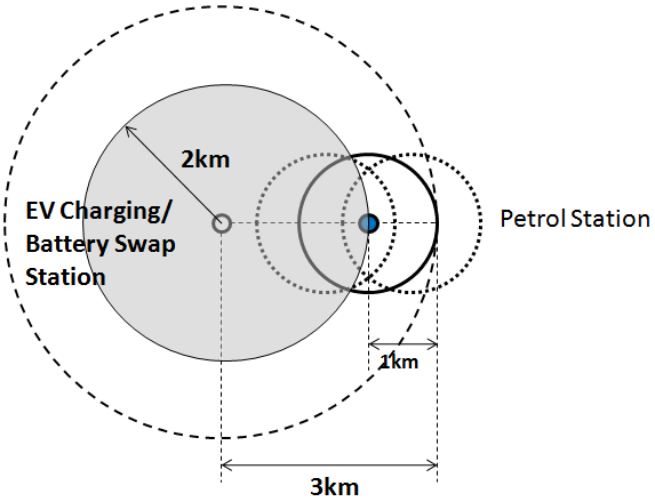


Figure 51 illustrates the case where the radius of a charging station is 3km. When a service radius of a petrol station is 1km, the service area of an EV charging station with a radius of 3km is able to fully cover the demand areas of the petrol stations which are located within 2km to the EV charging station. If a petrol station has no neighboring petrol stations in a 2km range, it will be directly assigned as an EV fast charging station, whilst those petrol stations with one or more neighboring petrol stations will be involved in the next selection step in terms of two determinants:

1. the number of neighboring petrol stations, which determines the degree of duplication, and;

2. the distance to its nearest power transmission stations, which influence the construction cost of a fast charging station and associated grid networks to transmission stations.

Hence, the fast charging station identification algorithm (see Figure 52) for petrol stations with one or more neighboring petrol stations is:

1. Buffering each petrol station with *R* km radius;

2. Calculating the number of covered petrol stations for each buffering circle;

3. Creating feature sets containing features that have an identical number of covered petrol stations;

4. Starting from the feature set with maximum covered petrol stations:

   4.1 Measuring the distances between each petrol station in the feature set to its nearest power transmission station.

   4.2 Selecting the petrol station with the shortest distance to the nearest power transmission station as a fast charging station and buffering it with *R* km radius.

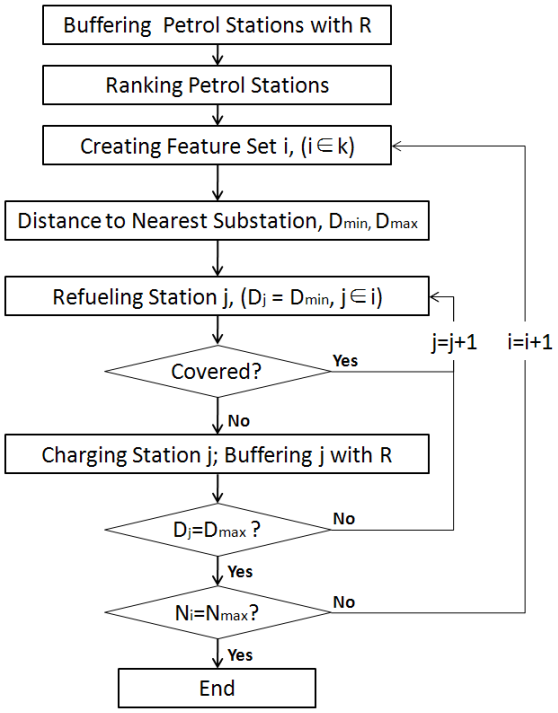
   4.3 Locating the second shortest distance from a petrol station to the nearest power transmission station: if this petrol station has not been covered by a previous buffering circle, selecting this station as an EV fast charging station and buffering it with *R* km radius; otherwise, locating the third shortest

distance between a petrol station and the nearest power transmission station.

4.4 Looping step 4.1-4.3 until all features have been iterated in the feature set.

5. Locating the feature set with second maximum number of covered petrol stations and looping step 4 until all features have been iterated.

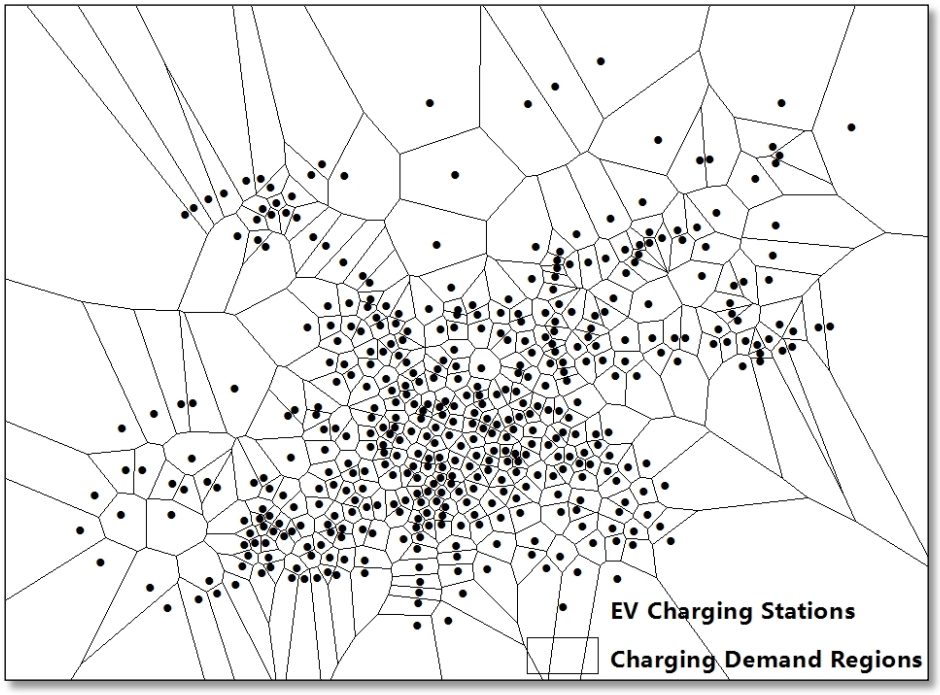
Figure 52 Identification of Demand Regions



The algorithm is processed by *ArcGIS 9.3* using Python scripts. Finally, a group of EV fast charging stations are identified and a *"Thiessen Polygon"* analysis is then taken to determine the respective charging demand regions where any location within a demand region is closer to its correspondent fast charging station than to any other fast charging station. Figure 53 shows the distribution of EV charging demand regions

and their correspondent fast charging stations.

Figure 53 EV Charging Demand Regions and Fast Charging Stations



7.4.2 Charging infrastructure assignment

Charging infrastructure assignment designates shares of charging load between fast charging/battery swap stations, home charging posts and workplace/public charging posts. For each demand region, the number of petrol stations is used to define the total charging demand in the region. Before starting the assignment in each demand region, the regional charging load shares between the three types of charging infrastructures need to be determined.

This paper predicts that the EV charging demand based on the current petrol refueling demand. The average daily petrol sale per petrol station in Beijing was 9.98 tons in

2008. As of 2011, there are 1043 petrol refueling stations in Beijing serving 4.13 million motor vehicles. According to BAIN's interviews with 40 experts (BAIN & Company, 2009), EVs are expected to take 5% to 10% of China's whole automobile market by 2020. This study assumes the number of EVs in Beijing would reach 10% of the city's vehicle stock in 2020. The Beijing Municipal Amenities Committee predicted the automobile stock will reach 5.4 million and the average daily refueling volume of petrol stations will reach 16 tons or 22,500 liters in 2020 (BJMAC, 2009b). Under the assumption of 40 liter per vehicle per refill and 10 liters per 100km (MIIT, 2011) petrol consumption, the daily number of vehicles served from a single petrol station in 2020 will be 550, with a total provision of 225,000km vehicle driving distance. According to the automobile registration statistics from the Beijing Traffic Management Bureau (BJMAC, 2009), private vehicles accounted for 79% of Beijing's entire vehicle stock in 2008. Given a significantly high increasing rate of private car ownership in Beijing (Han & Hayashi, 2008), this analysis assumes this figure will reach 90% by 2020. At present, the energy economy of typical EV models ranges from 0.10kWh/km to 0.36kWh/km (see Table 16). This study takes the value of BYD E6 (0.20kWh/km), which is serving in the taxi fleet in Shenzhen.

Table 16 Electric Vehicle Specifications

Model	Type	Manufacturer	Range	Battery	Energy Economy
Leaf	EV	NISSAN	**160km (EPA LA4 cycle)**	24 kWh, laminated Li-ion	0.15 kWh/km
E6	EV	BYD	**300km**	unknown	About 0.2kWh/km
F3DM	PHEV	BYD	**100km (EV mode)**	14.85kWh, LiFePO4	0.15 kWh/km
2008EV	EV	ZOTYE	**200km**	LiFePO4	0.12 kWh/km
i-MIEV	EV	MITSUBISHI	**160km (Japan 10-15 mode)**	16kWh, Li-ion	0.10 kWh/km
Mini E	EV	BMW	**240km (ideal); 106, 96, 104 (C/H/Com)***	35kWh, Li-ion	0.15kWh/km 0.33/0.36/0.34 (C/H/Com)
M1 – EV	EV	Chery	**160km**	60Ah, Li-ion	0.13kWh/km
BenBen Mini	EV	CHANGAN	**105km**	LiFePO4	About 0.1kWh/km

**C/H/Com: City/Highway/Combination*

Source: retrieved from car companies' websites.

Therefore, under the 10 % market share of electric vehicles, the potential charging demand for a demand region with one petrol station would be 4,050kWh providing 20,250km driving distance for EVs with 0.20kWh/km energy economy (see Equation 1). The total charging energy of each demand region can be obtained via the Equation 2.

Equation 1:

Where:

D: average charging demand at each petrol station, kWh;

P: average petrol supply at each petrol station, liter;

Fe: average petrol fuel economy of internal combustion engine vehicles, km/liter;

Em: electric vehicle market share, %;

Pm: private vehicle market share, %;

Ee: average energy economy of EVs, kWh/km.

Equation 2:

Where:

E: total charging energy demand, kWh;

Ci: the number of refueling stations in region i;

R: the total number of demand regions.

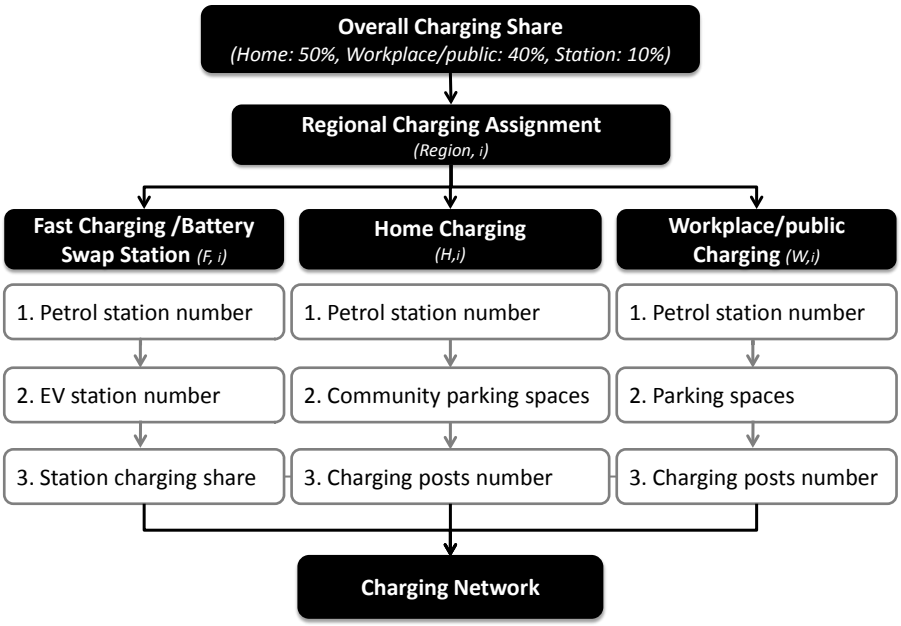
Three types of charging infrastructure have their unique advantages in a charging network. Given the high accessibility and low power output requirement (per unit of time) from the power grid, the home charging method has been widely regarded as a preferred charging mode and it is expected to take the major responsibility in a EV charging network over the longer term. Nevertheless, due to the slow charging speed,

charging posts can not entirely substitute the role of fast charging or battery swap stations. During the early stage of EV development, fast charging/battery swap stations can also largely raise the public awareness of EVs. In this study, the charging energy allocation between different charging infrastructures is based on the daily driving distance and the parking time profile in Beijing.

Long distance journeys represent a small percentage of overall travel demand in China (Deloitte, 2011), and more than 98% of drivers have an average daily car travel distance less than 160km/day. As rapid charging services are more likely to happen during long distance journeys, the charging demand at fast charging/battery swap stations is expected to take a small proportion. This study therefore allocates 90% of regional charging demand to home charging posts and workplace/public charging posts, and 10% to fast charging/battery swap stations. The charging load shares between home and workplace/public posts are determined by the average daily parking time. According to Beijing's 3rd traffic condition survey (BMCT, 2007), the average daily home parking time (10 hours overnight) is longer than the daily workplace/public parking time (8 hours in daytime). This study consequently assigns 50% of regional charging load to home charging posts and 40% to workplace/public charging posts. Figure 54 illustrates the regional charging infrastructure assignment methodology. The charging energy demands from home charging posts, workplace/public charging posts and fast charging/battery swap stations are calculated based on the regional charging demands and the number of regional petrol stations

and home/workplace parking spaces (see Figure 54).

Figure 54 Charging Energy Assignment



This assignment allocates each demand region one fast charging station. As introduced in Section 3, the number of parking spaces in each parking lot can be obtained from BMCT's data. However, for community parking lots, the ratio of parking spaces per household varies widely across thousands of residential communities in Beijing. According to the "Codes for Urban Parking Plan (Draft)", the ratio of parking spaces per household ranges from 0.2 to 0.8 for various communities with different building codes. In this paper, the ratio (0.3) of "normal residential communities" is applied (MHURD, 2009). This study refers to the suggested charging posts parameters released by State Grid (SGCC, 2010): home and workplace/public charging posts are assumed to have the same charging power output of 5kW. The number of home charging posts in each demand region is calculated according to the

residential community distribution density through Equation 3.

Equation 3:

Where

Mi: the number of home charging posts in region i;

Xi: the number of home parking spaces in region i;

X: the total number of home parking spaces;

90%: private vehicle proportion;

10%: electric vehicle proportion.

On the other hand, because both workplace and public parking spaces in Beijing are generally located in public parking lots where the charging posts can be shared by different EV drivers, the number of workplace/public charging posts of each demand region is calculated according to the regional charging load share (see Figure 54) through Equation 4.

Equation 4:

Where

E: total EV charging load, kW;

Ni: the number of workplace/public charging posts in region i;

Yij: the number of home, workplace/public parking spaces and petrol stations in region i;

Yj: total number of home, workplace/public parking spaces and petrol stations;

Wj: weights of home, workplace/public and station charging load;

P: the power output of a charging post, 5kW;

t: the average daily charging time of a charging post.

7.4.3 Charging Load Test

After the charging infrastructure assignment, the charging loads of individual charging stations need to be tested to avoid overload. Although a longer charging service radius will lead to an assignment with fewer charging stations, a longer radius assignment also results more highly-loaded charging stations that tend to cause significant disturbances to the power grid.

According to the charging standards suggested by State Grid (SGCC, 2010), the recommended rated output of an EV charger in a fast charging station is 200kW and each fast charging station is suggested to deploy 4 - 8 chargers. Therefore, when the daily operation is from 08.00 to 22.00 (14 hour) with an average of 60% charger occupation, the daily charging volume of a fast charging station should not exceed

10,080kWh (or the charging load of 1200 kW). For those high demand areas, the SGCC recommended that rapid chargers with 500kW charging output can be applied and the maximum daily charging volume of an individual fast charging station with 4 rapid chargers and 2 standard chargers is 20,160kWh (or the charging load of 2400 kWh). This paper hence sets a maximum load of 2400kW for individual charging stations and a maximum number of 10 fast charging stations that are deployed with rapid chargers to limit their negative impacts on the power grid:

1. The maximum load for individual fast charging station is less than 2400 kW;
2. The total number of fast charging stations with a daily load more than 1200 kWh is no more than 10.

The charging loads of each demand region, derived from Section 4.2, are then tested by these two conditions. If one of the conditions is unsatisfied, the infrastructure assignment model will subsequently reduce the proposed service radius of fast charging stations and the assignment process returns to Section 4.1 to formulate a new assignment. This process continues until both conditions are satisfied.

Table 17 Charging Infrastructure Assignment Result

Charging Infrastructure	Regional Load Share*	Total Load Share**	Charged Regions	Charging Post/ Station Number	Daily Charging Post/Station Load	Average Posts/Spaces Ratio	Ratio to EV
Home	50%	36%	428	496000	0.25kW	33%	1 : 1
Workplace /Public	40%	19%	289	15884	5kW	5%	1 : 31
Station	10%	45%	698	698	249kW	/	1 : 711

**Regional energy share: the charging energy allocation in individual demand regions when the demand regions have home or workplace/public charging posts.*

***Total energy share: the overall charging energy proportions among three types of infrastructure. Because some remote demand regions, which do not have home or workplace/public charging posts, only rely on fast charging/battery swap stations, the total energy share for fast charging/battery swap stations is higher than its regional energy share.*

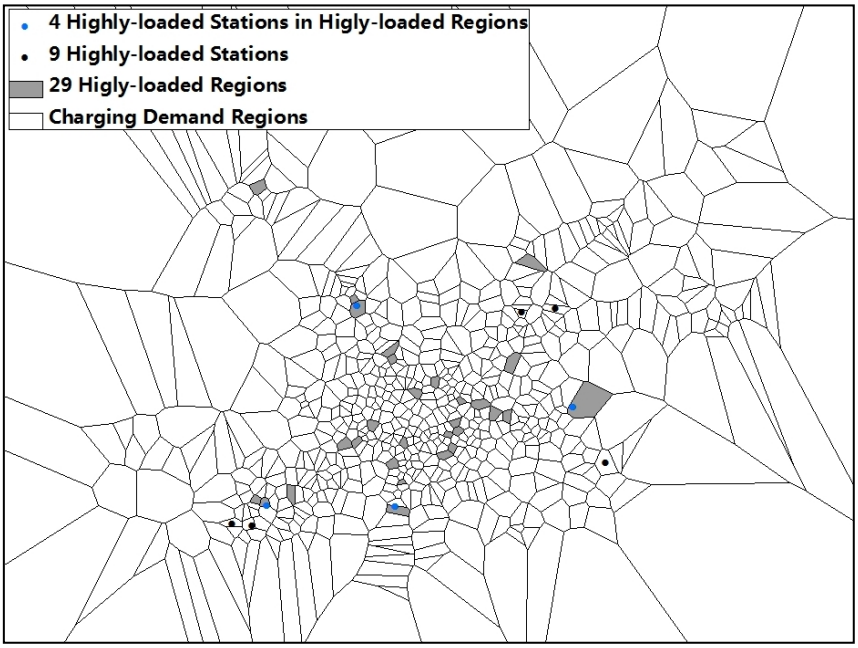
The charging infrastructure assignment result is showed in Table 17. The final service radius of a charging station is 2km which results in 698 charging demand regions. The total charging energy demand from the initial EV fleet is 4.22 million kWh/day. Compared with the average daily load of 188.96 million kWh in 2008 (SERC, 2009), the marginal demand from EVs is small (2.2%). There are 152 regions which would have workplace/public charging posts and 183 regions which would have home charging posts, while fast charging stations would be deployed in all 698 regions. The total numbers of home and workplace/public charging posts are 486,000 and 15,884, respectively. Because 221 demand regions have neither home nor workplace/public charging assignments, fast charging stations will be fully responsible for these regions' charging loads and therefore the total charging load duty for EV fast charging stations

is 45%, which is greater than 10% in the regional allocation case. The average charging post deployment ratios for home and workplace/public parking spaces are 33% and 5%, which means the current parking spaces are sufficient for deploying charging posts for the early EV charging demands. The average daily charging load of home charging posts is only 0.25kW due to their exclusive use and peoples' short daily driving distances. The charging loads of fast charging stations vary widely from 1446kW to a very low level of 3.9kW. Therefore, given the standard 1200kW charging power output, some fast charging stations need rapid chargers or battery swap infrastructure to fulfill their local charging demands. Although the charging demand would be low and daily charging time tend to be short, these fast charging stations would crucial to ensure a short charging service radius.

The regional home charging post densities range from 0 to 1568.4 posts/sq km (from 0 to 83.0 posts/sq km for workplace/public charging posts). A 5-class "*Natural Breaks*" classification is applied to exhibit the distribution patterns. It is observed that both home and workplace/public charging posts concentrate in the central area whilst the charging demand in rural areas largely relies on fast charging stations. Under this assignment, the station charging loads in those demand regions with high parking capacities are alleviated by the charging posts within the regions. In sum, only 4 of the 29 highest charging demand regions rank in the 9 regions that have highly loaded stations with daily charging loads more than 700 kW (see Figure 55). Because the spatial distribution of high charging demand region is highly correlated with the

spatial distribution of regions with high parking densities, the charging loads of EV stations in those high demand regions are effectively reduced via the load share of local charging posts. This effect is particularly significant for central areas with both the largest charging demands and parking capacities. A fast charging station with an extremely high charging load not only needs the large construction and infrastructure investment, but also generates harmonic waves deteriorating the stability and security of electric power supply. This assignment model therefore further demonstrates the charging posts' capacity in mitigating the station loads particularly in high charging demand regions (city center).

Figure 55 Highly-loaded Charging Demand Regions and Fast Charging/Battery Swap Stations



7.5 Sensitivity Analysis

The charging infrastructure assignment is influenced by a series of factors including the service radius of fast charging/battery swap stations, the regional charging load shares between different types of infrastructure and charging methods (charging/battery swap). This section analyzes the sensitivity of charging infrastructure assignment to these factors.

7.5.1 Regional Charging Energy Proportion

Shifting regional load shares between different types of charging infrastructure will produce distinct infrastructure deployment patterns causing diverse load profiles on the power grid. According to the current daily driving distance and parking time in Beijing, the baseline assignment model assumed regional charging load share was 50% (home posts) : 40% (workplace/public posts) : 10% (charging/battery swap stations) in Section 4. Given fast charging stations' large potential to promote EV's public awareness in the early stage, this section increases charging/battery swap stations' regional charging energy proportion from 10% to 40% and evaluates its influence on the assignment outcome.

Table 18 Regional Charging Proportion Sensitivity Analysis

Regional Charging Proportions	Demand Regions	Infrastructure	Load Share	Charging Post/Station Number	Average Charging Post/Station Load	Average Posts/Spaces Ratio	Ratio to EV
50%:40%:10% (H,W,S)*	689	Home	36%	496000	0.25 kW	33%	1 : 1
		Workplace /public	19%	15884	5 kW	5%	1 : 31
		Station	45%	698	196 kW	/	1 : 711
40%:20%:40% (H,W,S)		Home	24%	496000	0.17 kW	33%	1 : 1
		Workplace /public	9%	7775	5 kW	2%	1 : 64
		Station	67%	698	291 kW	/	1 : 711

**H: home charging posts;*

W: workplace/public charging posts;

S: fast charging/battery swap stations.

Table 4 compares the charging infrastructure assignment outcomes between two regional charging load assignments. It shows that with the increase of regional charging proportion for fast charging/battery swap stations, their overall charging load share correspondingly rises. In the meanwhile, both daily charging load of home charging posts and deployment density of workplace/public charging posts declined. On the other hand, the numbers of home charging posts and fast charging/battery swap stations remain at the same level. However, the increased charging load for fast charging/battery swap stations indicates the high marginal load for the current power grid requiring significant infrastructure upgrades to accommodate the charging demand from EVs.

7.5.2 Fast Charging Station Service Radius

The required number of fast charging stations is directly dependent on the charging service radius. In Section 4, a 2km service radius of a fast charging station was recommended. The 1km service radius will result an identical distribution pattern to refueling station. So this sensitivity analysis is designed to simulate two charging assignment patterns under the radii of 3km (medium scenario) and 4km (long scenario). The assignment algorithm for fast charging stations is same as the baseline case and all petrol station points are clustered with those points located within 3km radius range (and 4km for the long scenario), and the charging station selection starts from the clusters with most petrol stations. Within each cluster, the points that have a shorter distance to the power transmission stations are firstly chosen. The assignment algorithm for the regional charging load share between the three types of charging infrastructure remains consistent with the model in Section 4 (50%:40%:10%) and the assignment outcomes are listed on Table 5.

Table 19 Fast Charging Station Service Radius Sensitivity Analysis

Service Radius	Demand Regions	Infrastructure	Energy Share	Charging Post/Station Number	Daily Charging Post/Station Load	Average Posts/Spaces Ratio	Ratio to EV
Short (2km)	698	Home	36%	486000	0.25 kW	33%	1 : 1
		Workplace/public	19%	15884	5 kW	5%	1 : 31
		Station	45%	698	196 kW	/	1 : 711
Medium (3km)	440	Home	42%	486000	0.3 kW	33%	1 : 1
		Workplace/public	22%	18143	5 kW	7 %	1 : 27
		Station	36%	440	249 kW	/	1 : 1127

Long (4km)	301	Home	47%	486000	0.34 kW	33%	1 : 1
		Workplace/public	25%	19847	5 kW	10%	1 : 24
		Station	29%	301	292 kW	/	1 : 1615

According to Table 5, as the service radius of fast charging stations increases, the number of fast charging stations declines. Although the average individual station charging load (292kW) is greater in the “long scenario”, the overall energy share of station charging is smaller (29%). The home charging and workplace/public charging, in contrast, take a greater load share when the service radius increases. The reduction of the fast charging station number in the “long scenario” is achieved by both an increased number of charging posts and high charging station loads. Meanwhile, because drivers tend to rely more on charging posts in the “long scenario”, the ratio of charging posts to parking spaces in public parking lots and the daily charging load of home charging posts rises.

This sensitivity analysis demonstrates that the final charging infrastructure assignment pattern significantly differs under different service radius assumptions for fast charging stations. A longer station service radius provides fewer fast charging stations and increase charging load share for charging posts. Meanwhile, the individual charging load for fast charging station rises with the increase of service radius. The charging post deployment rate in the “long scenario” is also higher than that in the “short scenario”.

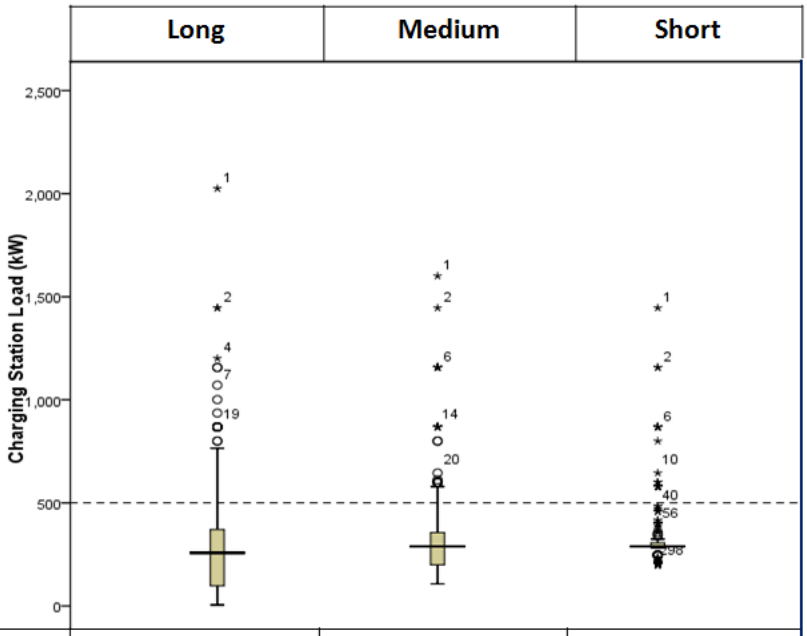
Figure 56 Charging Post Distribution in High, Medium and Low Cases



Figure 56 shows the charging post densities in long and short service radius scenarios. It can be observed that both the home chargers and workplace/public chargers densities are higher in the "short (2km) scenario" (home charger density - 47%; workplace/public charger density - 25%). This is mainly because of the larger covered area by charging stations in the "long (4km) scenario", though the charging load share

allocated to charging posts is also larger.

Figure 57 Fast Charging Station Daily Electricity Consumptions in Three Scenarios



	Long	Medium	Short
Mean	292	149	196
St. Dev	277	233	167
Energy Share	29.2%	36.4%	45.3%
High Load Stn.	66	61	45

Figure 57 compares the charging post densities and fast charging station loads for "long", "medium" and "short" service radius scenarios. It shows when the service radius declines; the variation of charging loads decreases. There are 45 fast charging stations that have a daily charging load over 400 kW in the "short scenario", as compared to 66 stations in the "long scenario". It can be seen that the peak charging loads of heavily-loaded fast charging stations can be alleviated through the short services radius assignment. The variation of charging station loads is more significant in the "long scenario" (charging load standard deviation: "long scenario": 277; "short

scenario": 167) where some fast charging stations are likely to undertake a much greater charging load than the average, which may cause negative impacts on local grids.

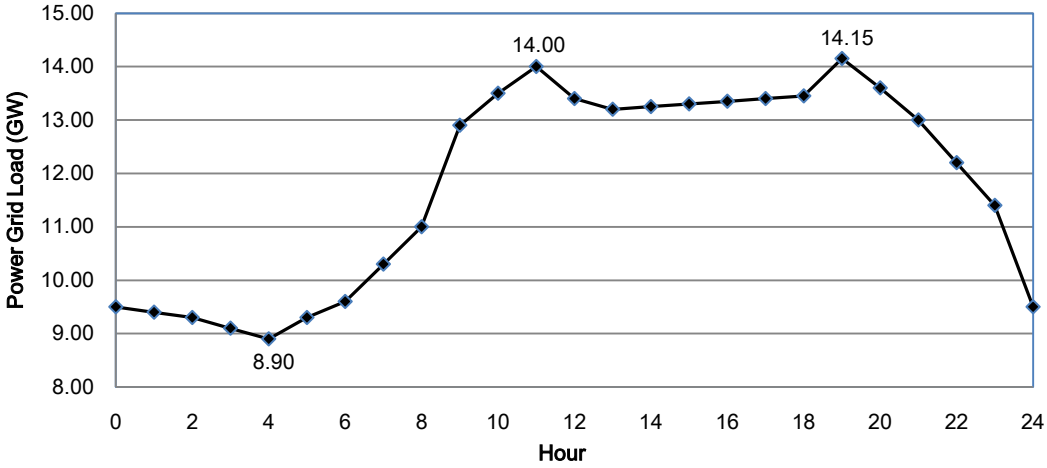
In sum, a short service radius assumption for charging/battery swap stations tends to increase overall charging load for charging/battery swap stations in a charging infrastructure network. Although the overall charging demand from EVs will probably be a major challenge for the power grid capacity in the long term, the effect of this extension is minor when the overall charging demand (2.2% of current daily consumption) is small. On the other hand, the highly loaded fast charging stations could severely undermine the stability of the whole electric power system and they have already been recognized as the major hazard in the grid network during the early deployment of fast charging stations (Gao & Zhang, 2011). Given the nature of instantaneous high power demand from fast charging stations, a short service radius reduces the number of those highly loaded outliers and helps to form a load-balanced charging network. The final assignment should be taken according to the scale of overall charging demands of the EV fleet. For a small EV market, this study recommends a 2km service radius for fast charging stations, which could have a relatively minor impact on the current power grid.

7.5.3 Charging Methods

Section 5.2 estimated the charging loads of individual fast charging/battery swap

stations under different service radius scenarios. This section will further investigate the overall charging impact of EV fleet on the daily power load profile in Beijing.

Figure 58 Summer Daily Electric Power Load in Beijing



Source: Wei et al, 2010

Figure 58 illustrates the typical Beijing's daily electricity load profile in summer season (Wei et al, 2010). It shows that the load varies significantly with time and there are two peak-time periods: 11.00 (14.00GW) when the workplace power demand reaches a high level; and 19.00 (14.15GW) when the main contribution comes from the home air condition load; whilst the daily load trough occurs at 04.00 (8.9GW).

To estimate the charging profile of EV fleet, the current daily car travel behavior in Beijing needs to be investigated. This study refers to the 3rd Beijing Integrated Transport Survey conducted by Beijing Municipal Commission of Transport (BMCT, 2007), which discovered the daily morning peak of car travel in Beijing between 07.00 and 08.00 and afternoon peak between 17.00 and 18.00. This study

consequently assumes that EV drivers will follow the current driving behavior and start their home charging from 18.00 to the next day 04.00. The daily workplace/public charging load for charging posts concentrates from 08.00 to 18.00 and the station charging load concentrates from 08.00 to 22.00. The EV charging loads from home posts, workplace/public posts and charging stations are aggregated from each demand region's load modeled in Section 4.2 and the overall daily power demand profile under the "Business As Usual" is illustrated in Figure 59.

Figure 59 The Charging as Business As Usual Scenario

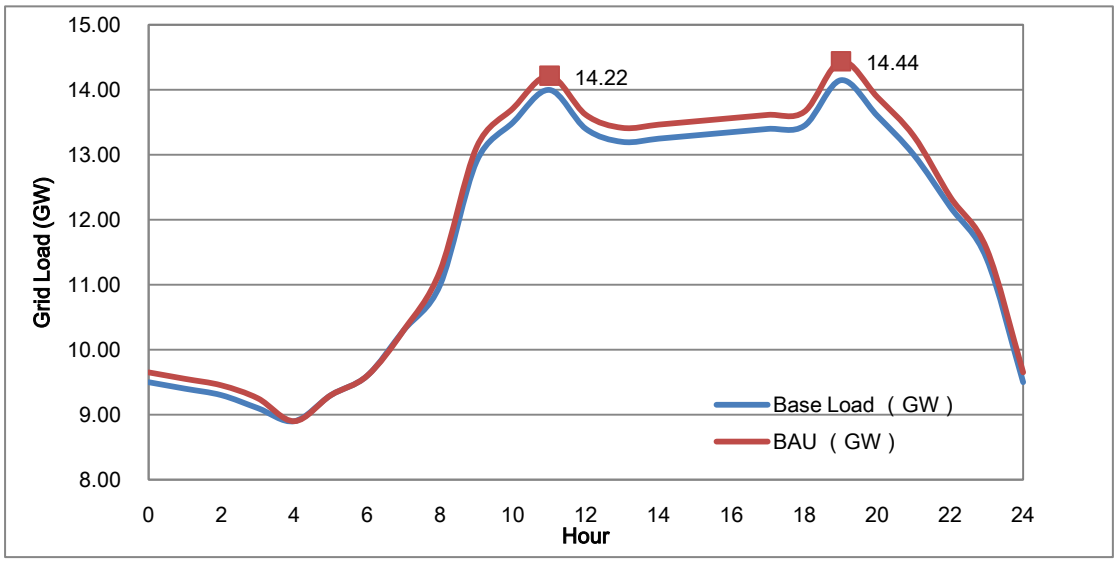


Figure 59 reveals that the overall charging energy demand (4.22GWh) from a small EV fleet only takes a small share (2.2%) of overall electricity consumption (188.96GWh). However, under the "Business As Usual" charging, the charging demand tends to happen during the original peak period, which means the power grid has to extend its capacity to accommodate the marginal demand from EVs. The peak

power demand increases from 14.15GW to 14.44GW, requiring a significant extension of electricity generation and transmission capacity of the power grid. The additional load also widens the gap between current grid's peak and off-peak load and exacerbates the grid capacity redundancy during off-peak periods. It should also be noted that the charging demand are estimated based on a small EV fleet. With the growth of EV stock, the fast increase of charging load could be a challenge for the power grid. Furthermore, local electricity infrastructure could face congestion if it is not properly extended. However, this largely relies on the spatial distribution of the EVs and the loading of the charging infrastructure.

Through charging time management techniques and price signals (Wang, et al, 2012), EV's home charging can be modified and conducted during vehicles' overnight parking period when the original power demand is low. Therefore, this research also estimates a "controlled home charging" scenario (see Figure 60) where the home charging time is virtually delayed from 18.00 - 04.00 to 22.00 - 08.00 in the next morning, while the workplace/public charging and station charging remain as the "Business As Usual" scenario.

Figure 60 The Controlled Home Charging Scenario

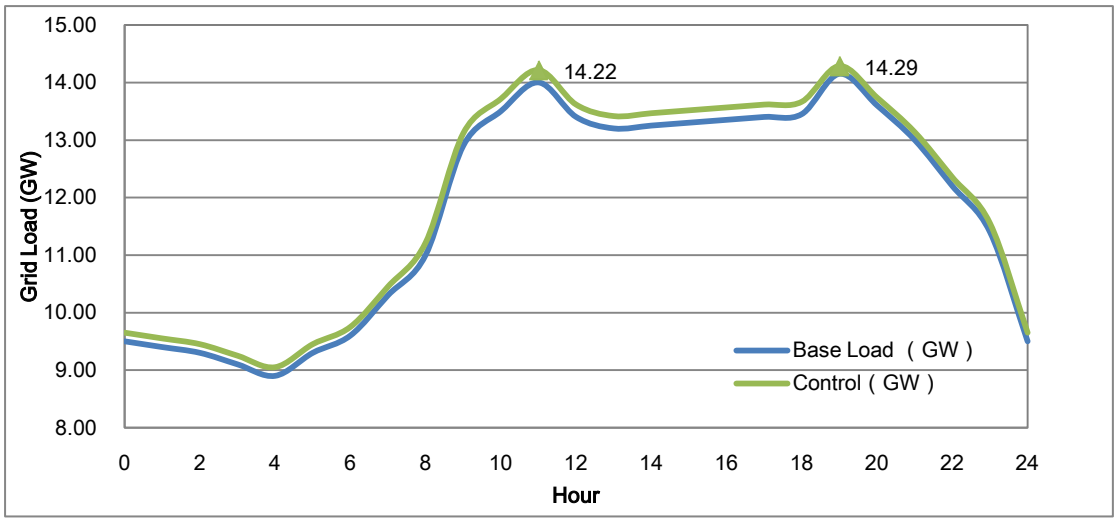
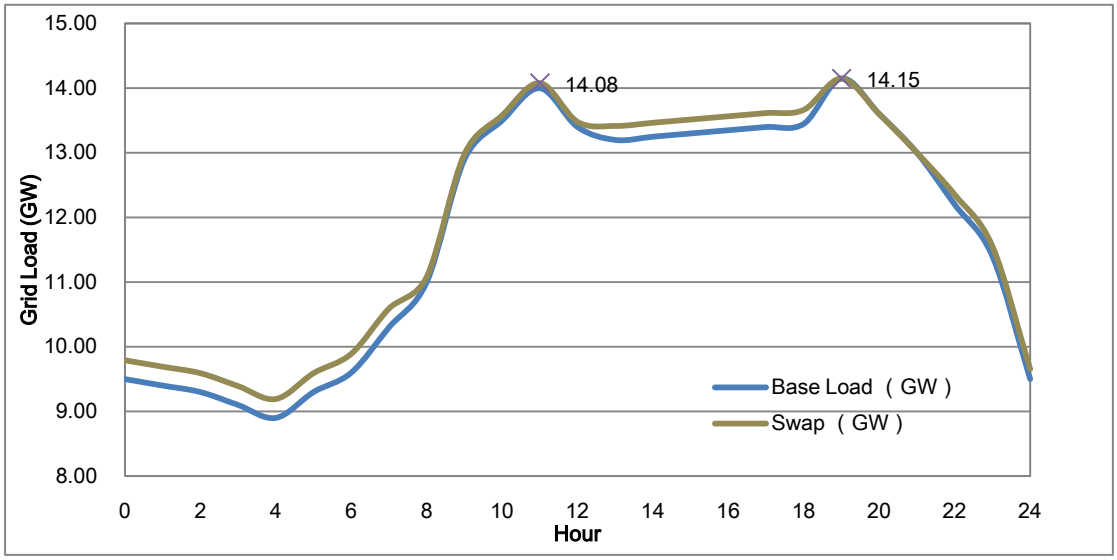


Figure 60 shows the peak demand at 19.00 has been mitigated to 14.29GW, when the majority of the marginal load comes from fast charging stations. Nevertheless, "controlled home charging" can only adjust the charging time of home charging posts, and therefore the "battery swap stations" are recommended. In addition to the ability of providing rapid charging service for customers, battery swap also offers a full charging flexibility, which means empty batteries can be charged at any time throughout a day when the load of the main grid is low. Figure 61 estimates the load profile of "battery swap" option, where the station charging demands (from 08.00 – 22.00) are re-allocated to 00.00am – 08.00 and 12.00 -18.00.

Figure 61 The Battery Swap Scenario



According to Figure 61, the new daily peak demand further declines to 14.15GW, while the morning peak demand is 14.09GW – both remain almost at the same level of the current power load. It shows that through the battery swap strategy, most of additional load demands from EVs could be accommodated by the current power grid's idle capacity during early morning and afternoon off-peak periods without significant infrastructure upgrades.

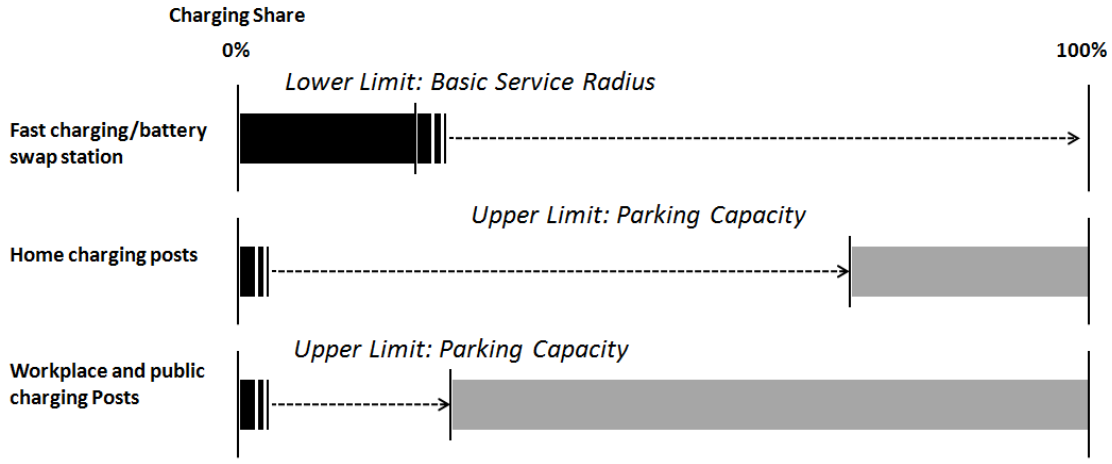
7.6 Conclusions and Discussions

This paper takes Beijing as a case study to investigate the roles of different charging infrastructure in a charging infrastructure network and to estimate different charging infrastructure assignment strategies. According to the assignment model for Beijing, a

total of 698 petrol stations are identified as deployment locations for fast charging/battery swap stations. The charging demand regions are correspondingly identified using *Thiessen Polygons*. The charging load in each demand region is estimated on the basis of the number of regional petrol refueling stations and assigned to three types of charging infrastructure, namely the fast charging/battery swap stations, home charging posts and workplace/public charging posts.

It can be seen that different types of charging infrastructure have their advantages and characteristics. To provide fast charging services, a minimum number of fast charging/battery swap stations should be guaranteed to provide a basic service radius for fast charging (Figure 62). However, fast charging/battery swap stations usually involve a large investment and should be more distributed along the highways for long-distance journeys. On the other hand, the post charging is constrained by an upper limit as a result of actual parking space and duration. With an average parking deployment rate of 0.3 spaces per household in Beijing, the current community parking spaces are unlikely to handle the entire charging demand of a developed EV market.

Figure 62 Charging Shares between Three Charging Infrastructure



In addition, due to the large load share of home charging, the fast charging/battery swap stations are likely to take a relatively smaller share of the overall charging load than that of petrol stations. These tend to yield a dispersed distribution of fast charging/battery swap stations with a long charging service radius. However, the large charging service radius could largely weaken people's confidence in the EV charging network. Therefore, the balancing of derivers' preference in short service radius and the actually low fast charging demand of fast charging stations is a core issue in establishing a charging network. As showed in Section 4.1, an assignment pattern with a short service radius leads to a great number of fast charging stations (high density) with high capital costs. Therefore, the battery swap option would be particularly beneficial due to its potential in the small scale distribution and the fast charging service.

This analysis also shows that the fast charging/battery swap stations and home charging posts, satisfying 45% and 36% of demand respectively, are expected to take the major role in an electric vehicle charging network. It also concludes that because petrol stations and parking spaces are spatially clustered together in Beijing, the deployment of home and workplace/public charging posts can effectively mitigate the fast charging station's loads, particularly for those fast charging stations with exceptionally high charging demands. In the city centre, home and workplace/public posts tend to share a substantial share of the local charging duty. In suburban areas, on the other hand, fast charging stations have a more prominent role. Moreover, the charging loads of individual fast charging stations significantly differ across the city because of different demand levels in different regions, as well as because of the load sharing by the local home and workplace/public charging infrastructure.

The sensitivity analysis found that the required number of charging stations could be reduced by extending the service radius, and thus allocating more charging loads to home and workplace/public charging posts. Due to the peak time operation of fast charging stations, a long charging service radius could reduce total charging load for fast charging stations and correspondingly narrow the daily peak and off-peak electricity demands. However, reducing the number of fast charging stations would have unbalanced charging loads and some stations would have a charging load that is much higher than the average. Under the assumption of a relatively small-scale

charging demand from a small EV fleet, this study has proposed a 2km service radius for fast charging stations to minimize the load variation among fast charging stations.

The EV charging infrastructure network has its own complexities when it is compared with petrol refueling stations distribution because of the involvement of the different charging alternatives. This study conducts an initial analysis of the charging infrastructure assignment for the early EV market in Beijing. It should be noted EV drivers are not likely to spend long time on charging EVs at fast charging stations. Therefore, rapid charging or battery swap techniques are needed. The model used in this paper also has limits. For instance, it assumed that all travel demand of EV drivers were to be met by electric vehicles. Given the parking constraints in Beijing, it found that 45% of demand would have to be met by fast charging. These results ignore self selection by which customers who are more likely to buy EVs are preferred in the model potentially changing the results. Furthermore, the value of time is ignored for this analysis and is reserved for future analyses. Future research should further estimate charging time variability of EV drivers and a quantitative cost analysis should also be taken into account for assignment optimization. In addition, the impacts of the home charging alternative on future travel and parking behavior, which would significantly influence a number of charging assignment assumptions, require further studies.

Chapter 8 Evaluation of Electric Vehicle Market Penetration in Shanghai

Jian Liu

Transport Studies Unit

School of Geography and the Environment

University of Oxford

Abstract:

This paper takes Shanghai as a case study city to estimate the city's future EV stock growth and the correspondent charging impacts on the power grid. It finds that with the estimated EV growth rates, the charging demand from EVs would not have a significant impact on the power grid in the near term. The paper compares the cost and benefit of three business operation models that aim to reduce the high upfront costs of EVs. Although the battery leasing and vehicle leasing strategies can directly decline the purchase cost of EV users, the study also shows, according to the current battery's cost and life range, substantial subsidies are vital for EV market penetration particularly in the early stages to compensate the high infrastructure (charging posts, stations and batteries) costs for charging service operators.

Key words:

Electric vehicle market penetration, Bass diffusion model, business operation models, battery leasing, electric vehicle charging infrastructure, daily charging load, charging infrastructure, battery maintenance.

8.1 Introduction

The modern global economy is largely powered by fossil energy. Oil, coal and natural gas together account for 81% of total world energy consumption of 12,267 million toe[61] in 2008 (IEA, 2010). According to current consumption rates, the proved coal, natural gas and oil reserves can only meet demand for the next 200 years, 70 years and 40 years respectively. Transport currently constitutes approximately 25% of annual global energy consumption and the road transport sector accounts for 80% of overall transport energy use (Lopez, 2006). Although in China oil at present only represents 17% of total energy consumption (more than half of which is used in the transport sector) (Yan, 2007), this share may increase, due to the fast motorization expected in the coming decades[62].

With increasing concern over oil reserves and air pollution, electric vehicles have been seen as one effective means to decarbonise the transport sector. A number of electric vehicle pilot projects have now been launched by governmental authorities and private companies. In California, Coulomb Technologies is working with the Bay Area in San Francisco to roll out charging stations, and Better Place has also announced that with the support from the U.S. Department of Transportation, they will introduce a swappable battery electric taxi program in the Bay Area. Besides, BMW has also released an EV leasing program of 450 MINI E vehicles in the Bay

[61] Toe: ton oil equivalent.

[62] In China, 66% of total energy is produced from coal, 17% from crude oil, 4% from hydro power, 2% from natural gas and 1% from nuclear power.

Area. In Japan, the Ministry of the Environment is working with Better Place to develop electric taxis in Tokyo. In London, Transport for London (TfL) has also released a charging network development plan to facilitate electric vehicle use.

In 2010, China became the world's largest new car producer and consumer. However, the average car ownership in China is only 60‰ which is significantly lower than the world average of 145‰. The large potential of car ownership growth urges the fast introduction of new energy vehicles in China's automobile market. By September 2011, 25 cities in China had been selected to introduce EV pilot programs, which aim to promote the transport electrification of public, official, municipal and postal sectors. EV charging infrastructure networks are also being largely financed by the central government and state-owned energy companies. By 2010, there were 87 charging or battery swap stations and 7031 charging posts under operation in China. In addition, SGCC (State Grid Corporation of China) plans to develop two inter-city EV charging networks in the Bohai Delta Region and the Yangzi River Delta Region by 2015 when the total number of charging/battery swap stations and charging posts will reach 2351 and 220,000. Moreover, China Southern Grid Corporation (CSGC) is currently cooperating with Better Place to provide charging infrastructure in Shenzhen – one of six cities in China with subsidies for end users.

Although EVs have been regarded as one of most promising new energy vehicles, they still face many challenges, including high battery cost and short battery range,

long-charging time and inadequate charging infrastructure. At present, a lithium-ion battery electric vehicle could cost twice as much as a counterpart internal combustion engine (ICE) vehicle, due to the high cost of the battery. For example, the price of the pure battery powered vehicle BYD e6 is RMB 256,000 (roughly 25,600 GBP), whereas the correspondent ICE version BYD F6 costs less then RMB 90,000 (roughly 9,000 GBP). Despite observed improvements in capacity, stability and safety levels of vehicle batteries in laboratories, the cost of EVs in the market perhaps will not decline to an attractive level unless an outstanding technological break-through takes place. However, it has also been discovered that the overall cost of EVs actually is not so high in terms of the whole operation life of vehicles, due to the low cost of electricity. Currently, the price of residential electricity in China is around RMB 0.5/kWh compared with about 7.5RMB/L for petrol, which means the fuel (energy) cost of an EV is only about 13%[63] of that for a comparable ICE vehicle. Therefore, innovative business operation models could play an important role to reduce the purchase cost of EVs helping EVs' penetration in the automobile market.

8.2 Literature Review and Methodology

In China, EVs and HEVs have been proposed as one of the most promising alternative fuel vehicle technologies to decarbonise the road transport sector. The central and local governments have also announced a series of development plans and targets to promote the EV growth. For example, the Ministry of Industry and Information

[63] The fuel consumption for EV and ICE vehicles are assumed to be 20kWh/100km and 10L petrol per 100km, respectively.

Technology (MIIT) has planned to develop a market of 5 million EVs by 2020 accounting for 2% of the national vehicle fleet. The scale of the EV fleet will not only determine the energy consumption and carbon emissions savings from EVs, but it will also directly affect the charging demand from the power grid. The EV stock growth pattern will also determine the required amount of charging infrastructure. According to the latest Energy Efficient and New Energy Vehicle Development Master Plan for 2012 to 2020, the annual EVs and PHEVs production will reach 5 million. This paper, therefore, aims to forecast the EVs' market penetration in a bottom-up perspective based on the observed historical ICE automobile growth in China. The forecast takes Shanghai as the case study city and applies the Bass diffusion model to estimate the EV market penetration from 2010 to 2050. The forecast outcome may differ from the government's targets, but it may reflect the actual EVs' future growth in the market. Moreover, the analysis is able to offer a picture of market penetration profile rather than a point estimate on a specific year. A daily charging profile is also modelled based on the EV stock forecast and the estimated daily parking probability profile.

A range of previous analyses have shown that in spite of the current high upfront cost of EVs, the relatively low electricity cost compared with petroleum fuels could enable EV users to reimburse their initial purchase cost during the vehicle operation stage. However, under current battery prices, the payback period would be significantly longer than consumers' typical acceptable level. In the United Kingdom for example, consumers would apply a very high discount rate (60%), which indicates that they are

looking to an 18-month payback period for fuel costs (King Review, 2008). In order to cut the high purchase cost, some innovative business operating models have been recommended, such as battery leasing and vehicle leasing schemes, where an operator provides the batteries and vehicles at the beginning, and instead of purchasing the expensive batteries and vehicles, EV users pay a contract fee to the operator who will be responsible for business operation, and battery and infrastructure maintenance. This paper hence estimates the potential of new business operating models in Shanghai. The cost forecasts for battery leasing and vehicle leasing scenarios are made in contrast to the business as usual (BAU) scenario, where the consumer purchases batteries and vehicles as current ICE vehicle users do. Furthermore, this study calculates the revenue profile of the operator under the battery leasing scenario.

Shanghai is one of the six Chinese cities that have introduced alternative fuel vehicle purchase subsidies in the private vehicle market. Data such as vehicle stock and daily driving profile are also readily available. Shanghai is also a major metropolitan city which has geographical, economic and political features. EV research for Shanghai could provide a comparison to the case in Beijing, which is investigated n Chapter 7.

The EV stock in Shanghai is simulated by the Bass diffusion model. The Bass diffusion model can be used to estimate the vehicle stock growth in China. The Bass diffusion model was developed by Frank Bass in 1969 to describe the market penetration process of new products (Bass, 1969). The model has successfully

predicted the market penetration of various products such as colour TVs, air conditioners and CD players, and has now been widely applied in market and management science. The Bass diffusion model can be summarised as:

Formula 11:

Where:

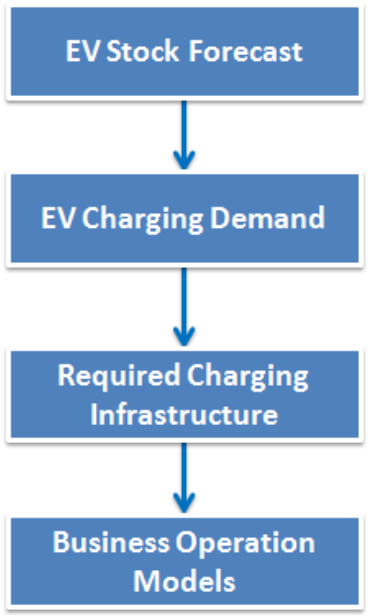
f(t): the rate of change of new EV buyers;

p: the coefficient of innovation;

q: the coefficient of imitation.

To estimate the EV charging impacts on the power grid, we first need to model the charging behaviour of EVs. This study uses the daily traffic volume profile in Shanghai to forecast the daily charging probability distribution in the city. The modelled charging volume is overlaid on the power grid's base load to reveal the charging impact. Finally, three business operation models are compared in the case study city via a break-even analysis. The payback periods for both EV users and the charging service operator are simulated. The battery and charging infrastructure cost data are retrieved from the China National Off-shore Oil Company (CNOOC). Figure 63 presents the structure of the paper.

Figure 63 Paper Structure



8.3 Electric Vehicle Stock Modelling

This research uses the vehicle stock and daily driving distance to forecast the total charging energy demand from the EV fleet in Shanghai. From 2001 to 2009, the vehicle stock[64] in Shanghai increased from 550,100 to 1,473,000 with an annual growth rate of 10.35% (Shanghai Statistics Yearbook, 2010). However, vehicle ownership in Shanghai is only 77‰. The high growth rate is likely to remain in the future.

China's private car ownership remained at a minimal level before entering the World Trade Organization (WTO) in 2001. The civilian vehicle stock was 6.25 million for

[64] The vehicle stock statistics here only refers to passenger and freight automobiles. Motor cycles and tractors are not included.

the whole country and 0.49 million in Shanghai in 2000 (NBS, 2000). After 2001, China's vehicle stock increased at a remarkably high rate, mainly due to the growth of the private car market. In 2010, the national civilian vehicle stock reached 46 million and 1.7 million in Shanghai. The annual civilian vehicle stock growth rate in Shanghai (10.35%) is much lower than the national average (16%).

In 2009, the State Council released the "Automobile Industry Regulation and Recovery Plan" that aims to form an annual 500,000 new energy vehicle[65] production capacity with the aim of reaching a share of 5% of total passenger vehicle sales in 2011. The Ministry of Science and Technology also issued the "Twelfth Five-Year Plan for Electric Vehicles" in 2010. It estimated that China's EV stock will reach 1 million in 2015 and the cost of power battery will be reduced by 50% as compared with the cost in 2010. In addition, the Ministry of Industry and Information Technology released the "Fuel Efficient and New Energy Vehicle Industry Plan – Drafting Version" in 2010, which estimated the accumulated sales for new energy vehicle will reach 5 million, or about 2% of the total vehicle stock, in 2020. In addition, some cities have also announced their local target for electric vehicle development. For example, Beijing aims to have a market of 30,000 EVs with correspondent charging infrastructure by 2012 (Beijing Municipal Government, 2011). In Shenzhen, the new energy vehicle stock is estimated to reach 24,000 in 2012 and 443,000 by 2020, which will account for 20% of Shenzhen's total vehicle stock

[65] The "new energy vehicle" in this plan refers to battery electric vehicles, plug-in electric vehicles and hybrid electric vehicles.

(Shenzhen Utility, 2010). Shanghai is one of the six subsidized cities to promote private EV market and the ownership growth rate is expected to accelerate accordingly. This paper simulates the EV stock growth at a higher rate than the national average, assuming it will reach 4% of the city's total vehicle stock in 2020.

The Bass diffusion model simulates the new product adoption process as an interaction between current users (innovators) and potential users (imitators). In this study, "p" captures the fraction of consumers who will make the EV purchase decision independently of other consumers and whose travel demand (relatively short range and operation cost sensitive) tends to be better satisfied by EVs. The empirical evidence of adoption patterns range from 0.01 and 0.03. "q" captures the fraction of consumers whose EV purchase decision is highly dependent on others, and the historical values for imitation coefficient are between 0.3 and 0.7. This study fits the Shanghai previous years vehicle stock increasing rate (from 2000 to 2010) to formulate the Bass curve for Shanghai's total vehicle stock growth (see the red line in Figure 64) via the SPSS (statistical package for the social science) non-linear regression (NLR) model. The coefficients of innovation and imitation are found at 0.01 and 0.05. For the EV stock growth, this study remains the imitation coefficient (0.05) for the baseline scenario – same to the ICE vehicle stock growth profile from 2000 to 2010.

The black curve in Figure 64 depicts the total vehicle stock profile between 2000 and

2100, while the red curve represents the estimated EV stock profile. By subtracting the EV stock from total vehicle stock, the blue curve then shows the ICE vehicle stock profile. According to this forecast, the EV stock would reach 0.13 million in 2020 accounting for 4% of the total vehicle stock. In 2050, the EV stock would be 1.18 million - about 15% of the total vehicle stock. The ICE vehicle stock would peak at 6.82 million in 2057. Then the ICE vehicle stock would decline and be overtaken by the EV fleet in 2086, when the total vehicle stock would reach 9.7 million.

In the baseline scenario, the growth rate for EVs is assumed to be the same as growth rate for the total vehicle stock from 2000 to 2010. However, if there were an improved efficiency in information communications in the next few decades, the EV market adoption could be higher. Therefore, this study sets a “high EV growth scenario”, where the imitation coefficient is set at 0.08 instead of 0.05. The dotted red curve in Figure 64 shows the EV stock growth based on a high imitation rate. In this scenario, the EV stock would reach 0.16 million in 2020 and exceed the ICE vehicle stock in 2061, 25 years earlier than in the baseline scenario. Under the high imitation rate, the EV stock would reach nearly 9.5 million accounting for 97% of the total vehicle stock in 2100 (see Table 18).

Figure 64 Electric, ICE and Total Vehicle Stock Profiles

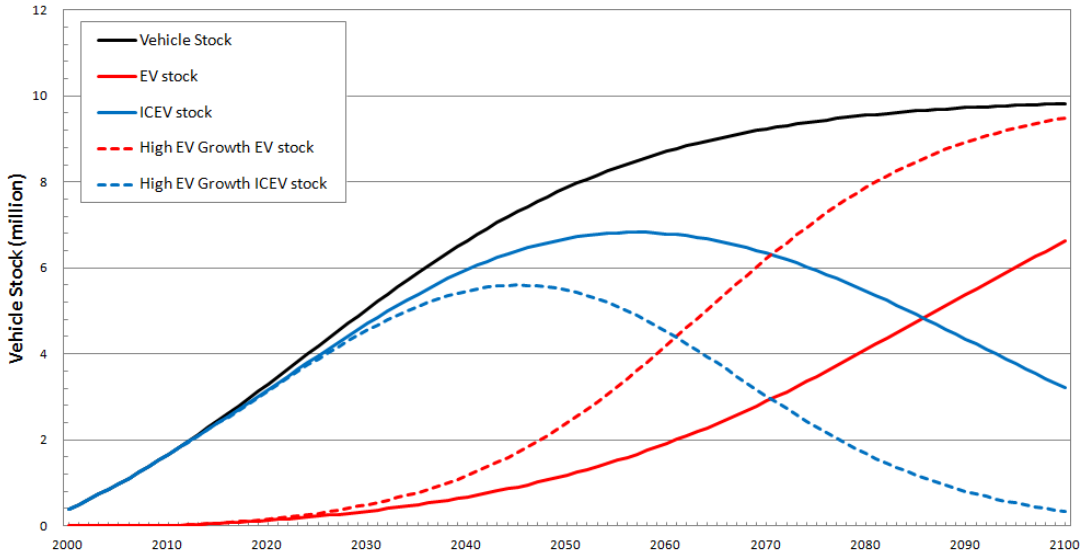


Table 20 Electric Vehicle, ICE Vehicle and Total Vehicle Stocks and EV Overtake Year

				Vehicle Stocks (million)				
				2010	2020	2050	2100	Overtake Year
Baseline	EV	p=0.001	q=0.05	0.00	0.13	1.18	6.62	2086
	ICEV			1.67	3.17	6.69	3.21	
	Total	p=0.01	q=0.05	1.67	3.30	7.87	9.83	
High Imitation	EV	p=0.001	q=0.08	0.00	0.16	2.39	9.49	2061
	ICEV			1.67	3.14	5.48	0.34	
	Total	p=0.01	q=0.05	1.67	3.30	7.87	9.83	

Total vehicle stock p and q are derived from the 2000 to 2010 vehicle stock statistics. Both p and q are also calibrated by the estimated 2020 EV stock where EVs account

for 4% of the total vehicle stock. From Table 18, it can be seen that for both “baseline” and “high imitation” scenarios, the innovation coefficient q is very low. It could be largely attributed to the local vehicle control policies which have resulted in a significant lower vehicle ownership increasing profile than that in other Chinese cities.

EV ownership in the long term highly depends on the assumed innovation and imitation coefficients. When the imitation rate shifts from 0.05 to 0.08, the EV stock rises from 1.18 million to 2.39 million by 2050 and from 6.62 million to 9.49 million by 2100. The total EV fleet tends to grow at a low rate under both scenarios. Applying both imitation coefficients, the EV stock would be less than 200,000 by 2020. A small number of EV vehicles means the potential revenue from EV operation is inadequate and financial subsidies are essential for stimulating the EV market in the early stages.

In addition to the vehicle stock statistics, the driving profile that indicates the daily driving distance in the city is also needed to forecast the charging energy demand of EVs. There have been a number of reports that surveyed average daily driving distance in China. According to the results of an online survey conducted by Deloitte, the average driving distance in Chinese cities is about 54km/day (Deloitte, 2010). Ernst & Young also conducted a survey and found that Chinese drivers’ average daily driving distance is 46km/day (Ernst & Young, 2010). In 2005, the Beijing Municipal Commission of Transport (BJMCT) conducted the third integrated transport survey

for the city which shows the average daily driving distance in Beijing is 44km/day (BJMCT, 2007). In the integrated transport survey for Shanghai undertaken by the municipal government in 2009, the average daily driving distance is 39km/day (Shanghai Municipal Government, 2011). Although there could be measurement error, it is reasonable to assume that the daily driving distance in Shanghai is lower than that in Beijing and the country's average level. In this study we assume that drivers' daily driving distance in Shanghai in 2020 will remain at the same current level.

This research uses the BYD e6 as the model vehicle to evaluate the charging energy demand. BYD e6 is a pure-electric-powered car manufactured by BYD Auto in China. It is labelled with 300km one-charge-range[66] and 21.5kWh/100km energy consumption (Electric Vehicle News, 2010) (see Table 19).

Table 21 BYD e6 Specifications

Items	e6
One-Charge Range (km)[67]	300
Battery Capacity (kWh)	64.5
Energy Consumption (kWh/100km)	21.5
Motor Power (kW)	75
Maximum Speed (km/h)	140

[66] This is according to the specifications of BYD e6 taxis that are in operation in Shenzhen (Green Car Congress, 2010).

[67] Under a favorable driving condition.

Charging Time (min)[68]	40 to 1200
Curb Weight (kg)	2360
Price (RMB)[69]	256,000

Source: BYD Auto, 2011

The average daily charging energy demand in 2020 is 4,193,120 kWh (see Equation 8).

Equation 8: –

Where

E: daily charging energy demand (kWh);

D: average daily driving distance (km);

N: number of electric vehicles;

C: energy consumption (kWh/100km);

μ: charging efficiency (%).

8.4 Charging Demand Modelling

This study uses the daily traffic profile (traffic volume through a day) to model the EV charging load on the power grid. According to Shanghai daily traffic volume

[68] Depending on charging infrastructure types.

[69] Excluding subsidies.

statistics (Shanghai Municipal Government, 2011), traffic is distributed as follows throughout the day:

the morning and afternoon traffic peaks happen during:

05:00 to 07:00: shoulder peak

07:00 to 09:00: morning peak

09:00 to 17:00: inter-peak

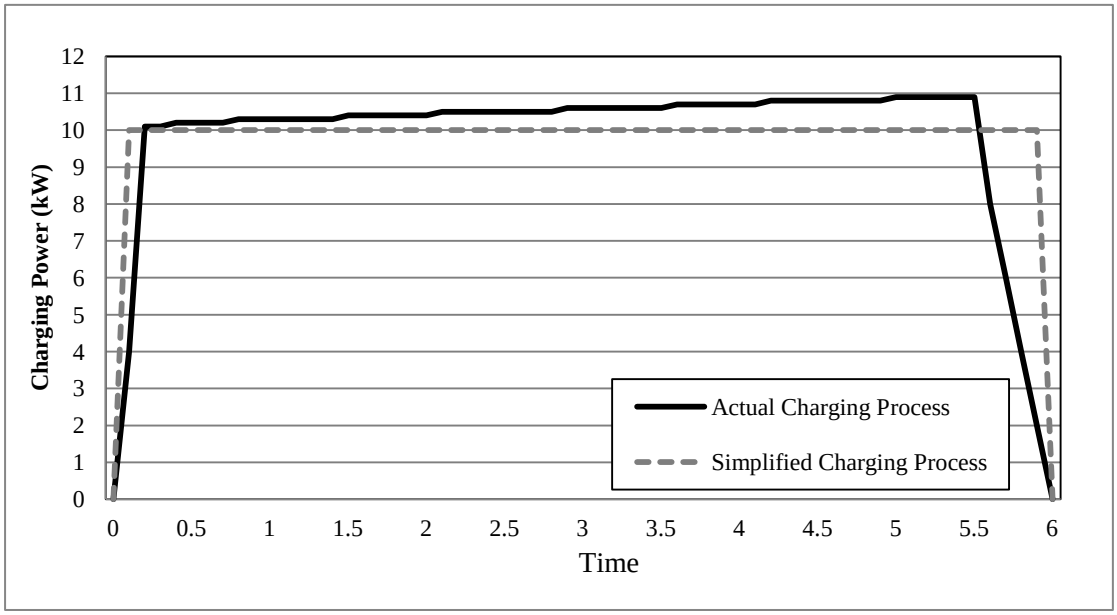
17:00 to 19:00: evening peak

19:00 to 00:00: shoulder peak

00:00 to 05:00: off peak

During the charging process, the charging power actually changes due to battery terminal voltage (see the solid line in Figure 65). However, given that the charging power variation is small during low-speed charging, this paper applies the BYD C10 DC charger for charging modelling and simplifies the charging profile as the dotted line over the six- hour charging process.

Figure 65 Simplified BYD e6 C10 DC100 (6 hours) Charging Process



Source: Tian, et al, 2010

Therefore, the charging power profile performs a uniform distribution through a charging process. The charging power every hour throughout a day is calculated by Equation 9.

Equation 9 ———

Where:

P_i: charging power demand at hour i (kW), i=0, 1, 2…23;

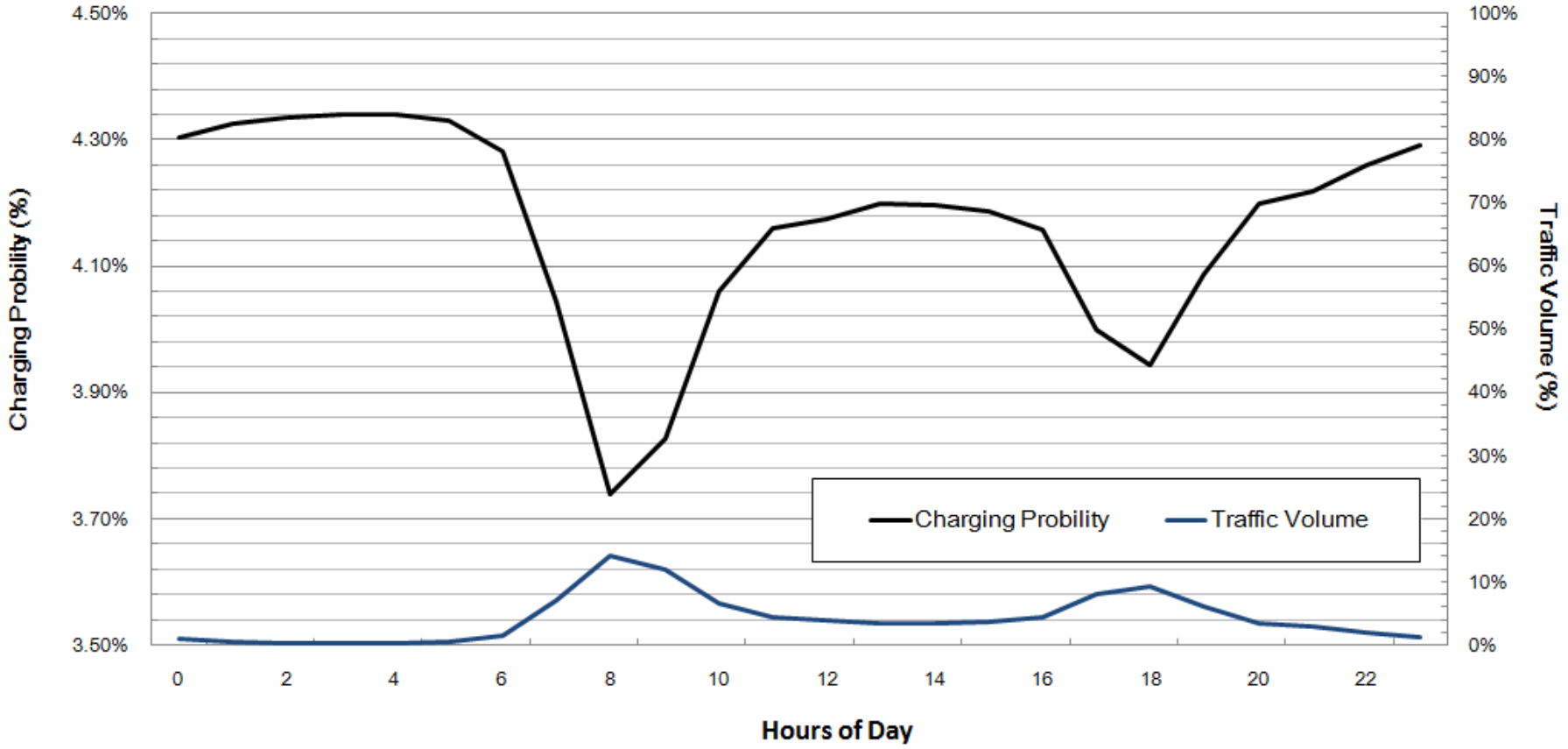
T_i: the ratio of travel volume at hour i in the whole day;

E: daily charging energy demand (kWh).

Figure 66 exhibits two opposite curves: charging probability and traffic volume profiles over a day. When the travel volume reaches morning and afternoon peaks, the charging power demand touches the daily troughs. The daily traffic volume peaks at

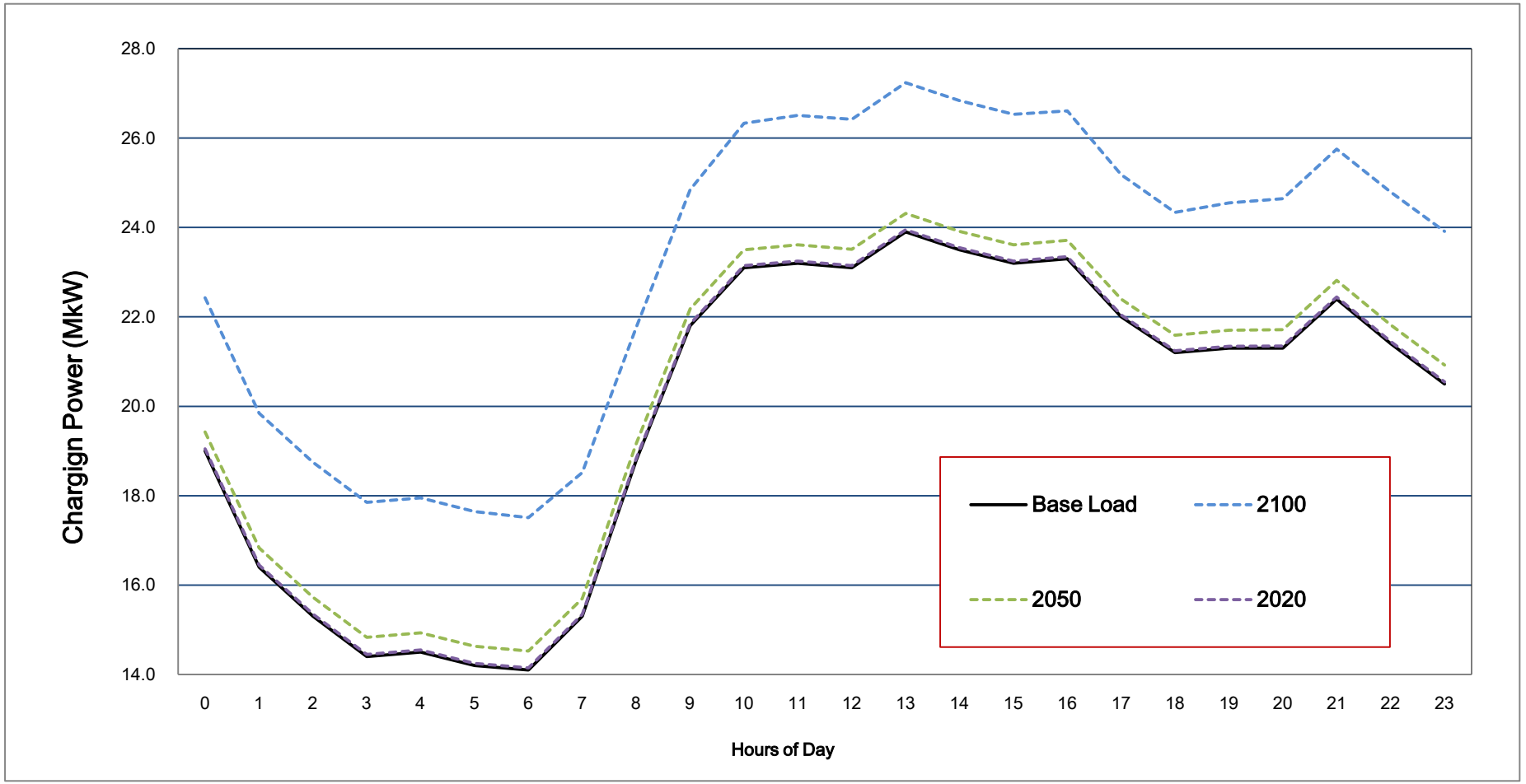
08:00 and 18:00 during morning and evening peaks. The daily charging power ranges from a minimum of 143,903 kW (18:00) to a maximum of 158,341 kW (03:00). The daily charging peak starts at 22:00 and lasts seven hours Until 05:00 the next morning).

Figure 66 Shanghai Daily Traffic Volumes and Estimated Charging Profiles



By integrating the estimated charging profiles and the current power load on the grid, we can evaluate the EV charging impacts. Figure 67 shows the power grid load profiles before and after the plug-in of the EV fleet. Three dotted curves present the power grid load profiles in 2020, 2050 and 2100. Figure 67 shows that in 2020, although the marginal charging demand from EVs increases the load of the power grid throughout the day, the marginal energy demand from EVs is relatively small compared with the base load. Because the base load peak time is at 13:00 when the marginal charging load is during the afternoon inter-peak period, the effects of additional charging demand on the power grid is at a limited level. The base load peaks at 23.90 GW at 13:00. The marginal charging demand at this time is 0.18 kWh, which only accounts for 0.75% of the base load. The largest charging demand occurs in the early morning when the base load is significantly lower than the daily average level, which helps the current grid accommodate the charging demand from the EV fleet. However, in the long term, particularly for the scenario in 2100, with the growth of total EV stock, the charging demand would become significantly high which would require effective charging time management and charging infrastructure upgrade.

Figure 67 Daily Power Grid Loads Before and After Plug-in EVs



8.5 Charging Infrastructure

In contrast to ICE vehicles, EVs are powered by electricity that is stored in an on-board power battery. The battery could be charged via various charging types of infrastructure including fast charging stations, roadside/parking area charging posts or home chargers. In the United States, the EV charging infrastructure is generally classified into three charging levels[70] representing different output powers and charging speeds (Morrow et al, 2008), where Level 1 (1.44 kW power output) and Level 2 (3.3 kW power output) chargers are placed in private garages and public car parks; Level 3 (60 kW to 150 kW power output) chargers are located in charging stations providing fast charging service.

In the "Electric Vehicle Charging Infrastructure Standard Design" issued by China Electric Power Research Institute (CEPRI), charging infrastructure is categorized to alternating current (AC) charging posts and charging stations (CEPRI, 2010). A charging post has a standard charging power output of 5 kW and is designed to be located in residential communities[71] and public car parks for slow charging. The charging stations are equipped with 4 to 10 AC or DC (direct current) chargers with the charging powers ranging from 5 kW to 200 kW. In addition to EV chargers, a charging station also needs a power distribution system to connect to the main power

[70] The three charging levels (level 1, 2 and 3) are defined by Electric Power Research Institute and codified in the National Electric Code.

[71] Residential communities in China refer to the dwelling units, typically managed by a common property companies.

grid. Moreover, Active Power Filters and Reactive Power Compensators are also required for medium and large charging stations to alleviate the harmonic waves' influence on the power grid.

In addition to charging posts and charging stations, depleted batteries could also be switched with fully charged ones at battery swap stations. In this case, the whole "recharging process" takes minutes and the empty batteries can be charged any time through the grid's off-peak period. In Israel, Japan and Demark, Better Place has introduced its battery swap stations with USD 500,000 each. The entire swap process only takes one minute (Squatriglia, 2009). In China, the CEPRI has also released its battery swap station plans which are mainly designed to serve electric buses and taxis. A battery swap pilot program operated in Beijing for electric buses during the 2008 Olympic Game and the battery swap process took about 3 minutes. It has now become a regular service for the Beijing NO.81 and NO.84 electric bus fleets (Caijing, 2011). The cost of a fast charging station or swap station depends on its service capacity. In Beijing, the charging/swap stations are divided into four classes. The power storage capacity ranges from 1,700 kWh to 6,800 kWh serving 100 to 500 electric cars per day (Beijing Evening News, 2010). According to estimates by Accenture, the capital cost of a typical swap station is similar to that of a fast charging station: around about RMB 5,000,000, excluding land costs (Accenture, 2011). China National Off-shore Oil Corporation (CNOOC), on the other hand, estimates the cost at RMB 3,000,000 per swap station (Xie, 2011). This study assumes the lower level of RMB 3,000,000

for both fast charging and battery swap stations.

There are a number of estimates of the cost of EV batteries. In “The Twelfth Five Year Plan for Electric Vehicles” released by Chinese Ministry of Science and Technology, the EV battery cost is expected to be around RMB 1.5 per Wh in 2010, roughly equivalent to RMB 90,000 for a battery with 60 kWh capacity (MOT, 2010). The report by Accenture suggests an average cost of EV power batteries of about RMB 70,000 for 2010 (Accenture, 2010). With regards to the cost of charging posts, the estimate ranges from RMB 20,000 (CEPRI) to RMB 30,000 (Lu et al, 2010). This paper adopts the lower levels for EV batteries (RMB 20,000 each) and charging posts (RMB 30,000 each).

The scale of charging infrastructure depends on the size of the EV fleet. The shares of the different types of infrastructure are determined by the proposed charging strategy. Although there are a number of strategies for EV infrastructure, as suggested by different government departments and local authorities in China (see Table 1), the infrastructure usually consists of charging posts, charging stations and battery swap stations. It should be noted that when the deployment of battery swap stations increases, the charging infrastructure (charging posts and charging stations) tends to decline.

Both charging stations and battery swap stations are public infrastructure that requires

fast service particularly for long distance travel. In order to compare the cost implications of different charging infrastructure, two separate charging infrastructure deployment strategies are suggested in this study: Strategy 1 - Charging posts and fast charging stations; Strategy 2 - Charging posts and battery swap stations.

In each strategy, the infrastructure deployment is calculated under the high and low EV stock growth profiles, which means the numbers of fast charging stations and battery swap stations are determined by the number of proposed charging posts. Because charging posts would provide the majority of charging supply and long-distance travel is expected to take a minor amount of overall travel demand, charging posts would account for 87% in strategy 1's infrastructure cost in 2050 (see Figure 68. Due to the high capacity of battery swap stations, strategy 2 could require fewer battery swap stations and fast charging stations than the fast charging stations in strategy 1. However, in addition to battery swap stations and fast charging stations, the battery swap option also needs extra batteries in storage. Through the introduction of advanced supply chain management, this analysis estimates that swap stations would need to prepare 20% of circulating batteries in storage. Because the life cycle of EV batteries is 5 years, in addition to purchasing batteries for new EV drivers every year, the battery swap operators will also need to renew their batteries purchased in previous years, which leads to a high proportion of battery cost in the entire charging infrastructure cost.

Figure 68 Estimated Charging Infrastructure Cost in 2050

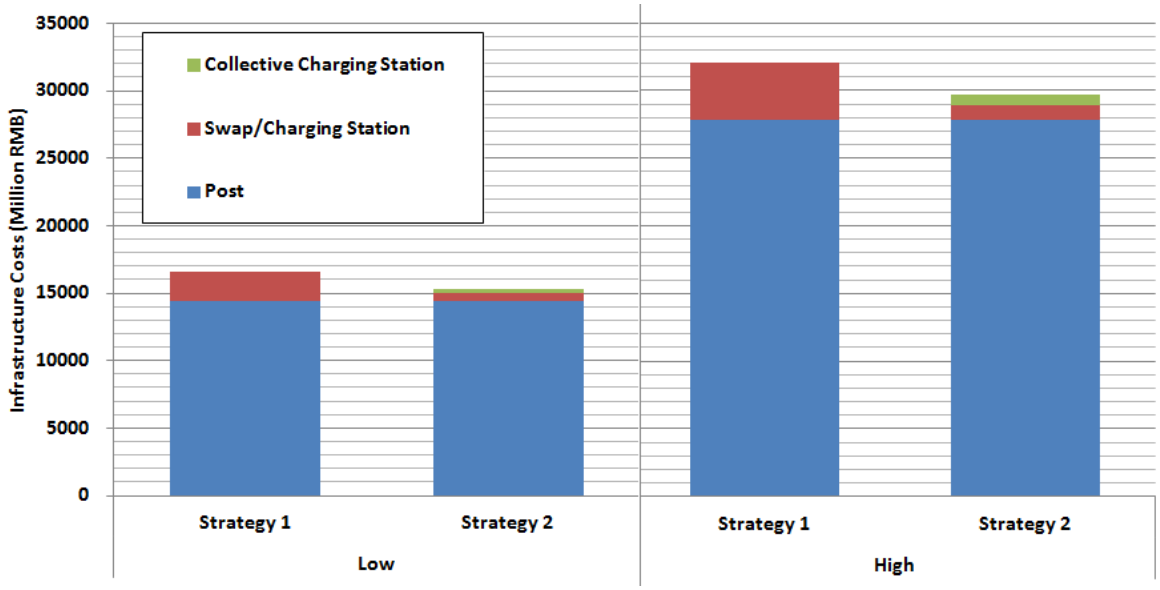


Figure 68 illustrates the charging infrastructure costs of two strategies under the low and high EV growth scenarios. In strategy 1, the infrastructure consists of charging posts and fast charging stations, while the infrastructure in strategy 2 consists of three components: charging posts, swap stations and fast charging stations. It shows that under both high and low EV growth rates, charging posts constitute the majority of charging infrastructure costs (87% and 95% in strategy 1 and 2, respectively). Due to the faster charging process, strategy 2 needs a fewer number of battery swap stations than that in the strategy 1 (charging stations), leading to a lower total cost. In contrast to the low EV growth scenario, the high EV growth rate clearly raises the infrastructure cost. However, Figure 68 only compares the estimated charging infrastructure costs, excluding any battery investment. In reality, the introduction of battery swap stations would be accompanied with battery leasing options, where the

charging service operator would undertake the high investment cost on batteries. The total infrastructure cost in this case could be substantially higher and largely influence the operator's payback period. This influence is simulated and discussed in the following section.

8.6 Business Operation Models

Both the vehicle purchase price and the fuel price determine a customer's purchase decision. Due to the high cost of the batteries, the price of EVs is still significantly higher than that of standard ICE vehicles. As shown in Table 19, BYD e6 is now priced at RMB 256,000, or almost 3 times more expensive than its counterpart ICE model – BYD F6. However, the operation costs of an EV could be significantly lower than those of an ICE vehicle. Based on the energy economy of BYD e6 (21.5kWh/100km) and the current electricity rate in Shanghai (RMB 0.617/kWh), the energy cost of BYD e6 is RMB 0.13/km. In contrast, the fuel consumption of BYD F6 is 8.3L/100km, leading to a fuel cost of RMB 0.66/km. Therefore, it has long been suggested that the high purchase cost of EVs could be compensated during the course of vehicle operation.

Nevertheless, a number of previous break-even analyses have showed that the marginal purchase cost of EVs is difficult to be paid back within a (preferred) short period. For instance, the premium of BYD e6 (pure EV) to BYD F6 (counterpart ICE

vehicle) is RMB 146,000, which means under the current fuel and electricity price, the payback distance could be more than 270,000 kilometres. For a normal driver with an annual driving distance of 20,000 km, the payback period would be longer than 10 years, which inevitably reduces EVs' market acceptance.

In a battery leasing scheme, a customer purchases an EV without the battery and then enters into a contract with a charging service operator, who would provide batteries and charging service (including electricity and charging infrastructure) for the customer. Instead of buying an expensive battery initially, the customer would pay a service fee to the operator during the course of the vehicle use. In this case, the customer can purchase an EV with a low initial cost (excluding the battery cost) while the operator is also able to generate profit through operating the charging service business. This scheme also facilitates the battery management and benefits the recycling market for the used batteries. Furthermore, a centralized management of batteries would make it possible to minimize the peak time charging, and thus mitigate the charging load burden on the power grid.

Currently, the battery leasing scheme has been applied by Better Place Ltd, who further developed the business model as a mileage-based contract, where customers enter into contracts to purchase driving distance for their EVs (similar to a mobile telephone contract). The initial premium cost of an EV is expected to be subsidized by the monthly revenue based on provided charging service by the operator.

In addition to battery leasing, a customer may also choose a vehicle leasing scheme where the customer can obtain an EV for free and the operator's revenue is based on a monthly fee, which will be higher than the fee he would receive from leasing batteries only. In a vehicle leasing scheme, the operator needs to bear the vast initial cost to purchase both vehicles and batteries for consumers, though it would charge a high monthly rate and could achieve a greater profit in the long term.

Table 22 EV Purchase Costs and Monthly Rates

	Purchase Cost (RMB)	**Monthly Rate (RMB)**
Scenario - BAU	136,000 (after subsidy)	0
Scenario - Battery Leasing	46,000 (after subsidy)	3000
Scenario - Vehicle Leasing	0	4900
Electricity rate: RMB 0.617[72]		
Energy efficiency: 21.5kWh/100km[73]		
Annual driving distance: 14,235km		
Used battery price: 50% of purchase		
Discount rate: 8%		
Battery life: 5 years		
Maintenance cost: annual 5% of capital		

Sources: CNOOC and BYD

Table 22 summarizes the assumptions for cost estimates. Cost profiles under both

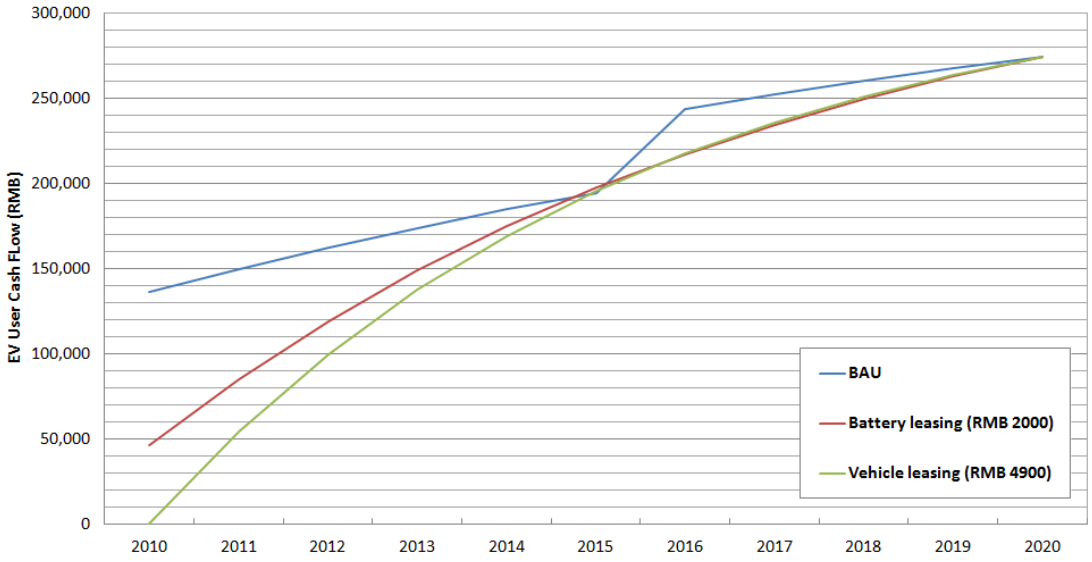
[72] Source: "Shanghai Electricity Fee Adjustment Notification", 2008

[73] Source: "Shanghai's Fourth Integrated Survey for Transport", 2009

business operation models are estimated and compared with the BAU profile presented in Figure 69. The purchase cost under the battery leasing scenario is RMB 46,000; while in the vehicle leasing scenario, EV users have no initial cost for the vehicle or the battery. Given vehicle depreciation during vehicle use, the monthly fee for vehicle leasing scenario would decrease over time and this study assumes the monthly fee in a year will be 90% of that in the previous year. It is also assumed that a battery's operating life is 5 years. After that initial 5-year period the battery enters the used (second-hand) battery market at 80% of its purchase price. Therefore, in the BAU scenario (consumers purchase EVs including batteries), the EV user would sell the used battery and purchase a new battery in 2016, while in the battery leasing and vehicle leasing scenarios, the operator would replace the battery with a new one every five years and the replaced batteries are expected to flow into the used battery market.

Figure 69 presents EV users' cost profiles under three business operation models. It can be seen that the customer is offered an initial purchase cost reduction via an increased operating cost in the following years. For both alternative business models (battery leasing and vehicle leasing), the operator needs to charge a high contract fee (RMB 2000 per month for battery leasing and RMB 4900 for vehicle leasing) to reimburse the initial battery (or the whole vehicle in vehicle leasing scenario) investment.

Figure 69 Cost Profiles of EV Users



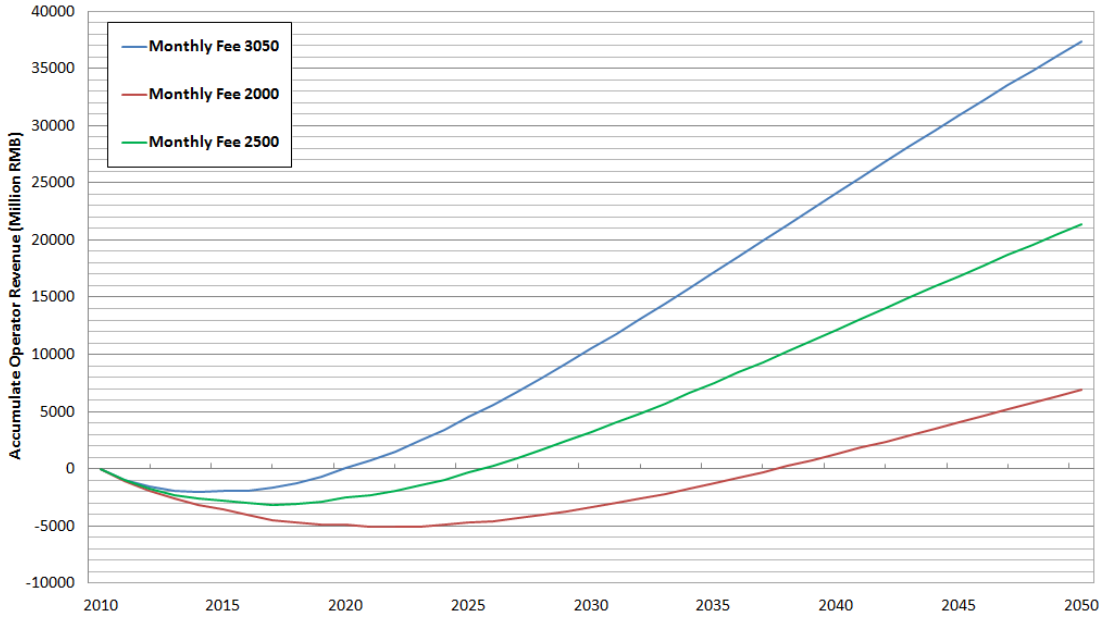
With regard to the service operator, in addition to the battery, he would also provide charging infrastructure, electric energy and the charging service. The operator would also be responsible for replacing used batteries as well as maintaining batteries, charging and battery swap infrastructure. Figure 70 simulates revenue profiles of operators in the battery leasing scenario.

The revenue of operators depends on a series of factors, including the number of EV customers in contract, annual driving distance, the scale of charging infrastructure and battery prices. The customer number and scale of charging infrastructure are modelled according to the estimated EV stock growth projections discussed in Section 3. With technological progress, the costs of charging infrastructure (charging posts, stations and swap stations) are assumed to decrease 2% per annum and the energy efficiency of EVs is assumed to improve 1% per annum. With different scales of charging

infrastructure, the maintenance cost for the operator would vary and the annual maintenance cost in this study is assumed at 5% of the capital cost for both charging infrastructure and batteries. This section then compares operators' revenue profiles under the battery swap scenario and it assumes the operator would provide and maintain the batteries for EV drivers. They would also be responsible for charging infrastructure construction and maintenance. Therefore, from the year 2016, the operator would renew used batteries for previous year customers, as well as purchase new batteries for the new customers every year.

The charging infrastructure growth is estimated on the basis of two growth rates. The blue line in Figure 70 shows the cost profile of battery leasing operators under the monthly leasing rate of RMB 2000. The electricity price is expected to remain at the current levels in Shanghai. The cost profiles are calculated in 2010 prices. The discount rate is assumed to be 8% per annum.

Figure 70 Cost Profiles of Battery Leasing Operators



Assumptions:

Maintenance cost: 5% of capital cost

Battery life: 5 years

Used battery price: 50% of its purchase price

Vehicle energy efficiency improvement: 1% per year

Discount rate: 8% per annum

Due to the expected long-term cost reduction of batteries and charging infrastructure, the battery leasing operators could undertake a relatively longer payback period than consumers do. Although operators need to make the initial investment for the infrastructure and purchase the new batteries for incremental EV users every year, their annual revenue would reimburse the cost when the EV stock grows and exceeds a certain threshold. From Figure 70 it can be seen that RMB 2000 per month contract (the green curve) would lead to a payback period of 28 years for charging operators. However, such a long payback period could largely impede the operator's

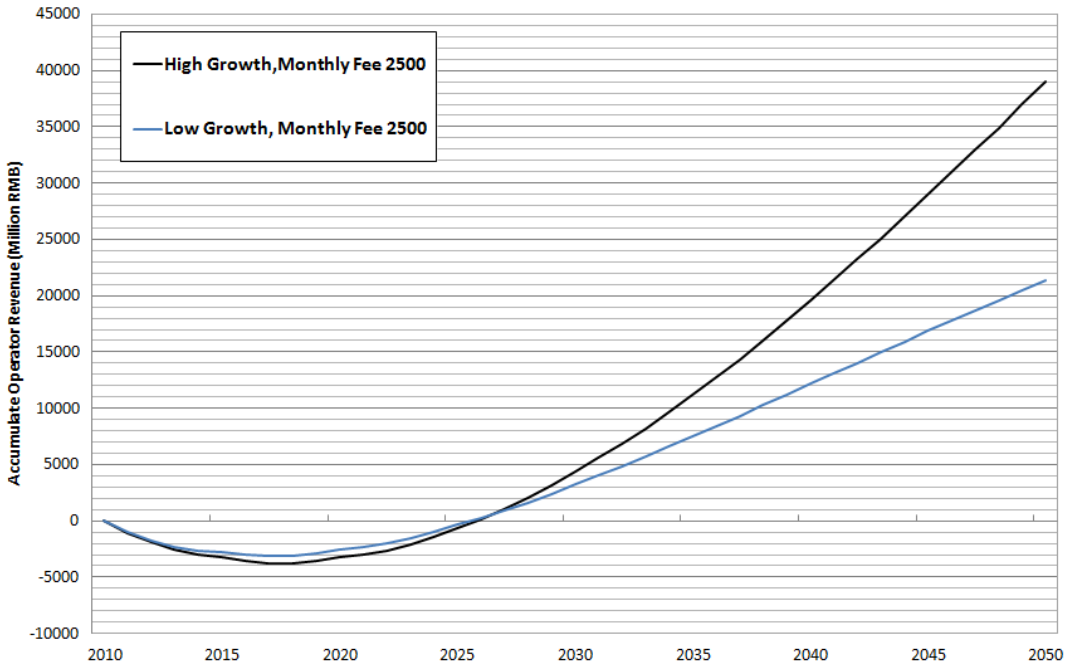
participation. In order to cut down the long payback period, this study tests an increased monthly fee of RMB 2500 per month and RMB 3050 per month (the red and blue curves showed in Figure 70). The increase of monthly fee directly reduces the payback to 16 years (under the monthly rate of RMB 2500) and 11 years (under the monthly rate of RMB 2000). It can also be seen that in all three scenarios, the operator would face a deficit in early years and the amount of the deficit could be large if the monthly rate were low.

In addition to different monthly fees, this analysis also compares the operator's revenue profiles between the low and high EV growth scenarios. In the case of low EV growth rate, the battery and charging infrastructure cost would also increase at a relatively low rate. With the increasing number of EV customers in the market, the revenue would grow and gradually compensate the annual costs. The annual revenue would then rise at an accelerated rate and finally achieve an overall cost-benefit in the long term.

Figure 71 presents operators' cost profiles under high and low EV growth scenarios. It shows the high EV stock growth would not significantly change the payback period. On the other hand, with a higher investment at an early stage, the operator's revenue in the high EV growth scenario could rise significantly faster than that in the low EV growth scenario. This is because under the high EV growth rate, the total number of customers would increase faster and reach the critical break-even point sooner. When

the total EV stock reaches a threshold level where the increase of new EV users slows down, the annual revenue of operators is expected to be high in the high EV growth scenario.

Figure 71 Cost Profiles of Operators under High and Low EV Growth Scenarios



From the break-even analysis above we can conclude that the battery leasing strategy needs a high monthly fee to customers to shorten the payback period within an acceptable range for the operator. However, even though in the long payback scenario (28 years), the monthly cost (RMB 2000) would still be higher than the acceptable level. By comparing the cost profile curves, it can be seen that the payback period is highly sensitive to the monthly leasing rates. The payback time under the monthly leasing rate of RMB 2500 is 2026 in the low EV stock growth scenario, 5 years later than in the scenario with a RMB 3,050 monthly rate. The figure also shows that there

is no significant payback period difference between the high and low EV stock growth scenarios, although the high growth rate would generate significantly higher revenues at a later stage in the market penetration process. This is mainly because: 1, high EV growth indicates operators' high annual revenue from EV users, but; 2, high EV growth would also mean the operation costs for battery supply, infrastructure deployment and maintenance. So in overall, the payback period is not significantly changed.

In conclusion, although the battery leasing scheme offers an attractive option for consumers, the high battery price and maintenance cost, particularly during the early stage of market penetration, is a challenge for the operator. Therefore, the government support (such as subsidies or tax credits for battery purchase and infrastructure construction) in the early market diffusion stage is crucial for this business model. When the market is fully developed and the EV stock exceeds a critical quantity, the charging operator could independently maintain the battery leasing business without subsidies.

8.7 Conclusions

This paper firstly uses statistics of Shanghai's recent vehicle growth to forecast the future EV stock growth in low and high increasing scenarios. Due to the expected automobile control policy and the fast development of public transport infrastructure

in the city, the increase of the EV stock in Shanghai are expected to follow the historical ICE vehicles growth pattern and remain at a relatively low rate. In both high and low EV growth scenarios, the EV vehicle stock would overtake that of ICE vehicles after 2050.

The vehicle stock increase (according to the vehicle stock increasing profile from 2001-2009 in Shanghai) and vehicle population control policies in the city (including vehicle plate number auction and large public transport infrastructure investment) in this chapter refer to the facts in the city of Shanghai. As many large Chinese cities (such as Beijing and Guangzhou) face similar situation in Shanghai, some research conclusions could be related to those cities. However those characteristics in each city should be fully considered when an EV market growth is estimated for the city, such as the impacts of the plate number lottery and the odd-even number restriction in Beijing.

The study then refers to the daily traffic volume statistics to predict the daily parking and charging probability profile in Shanghai. Combined with the current daily power grid load, section 4 estimates the potential impacts of EV charging loads on the power grid. It shows that the charging load highly relates to the predicted EV stocks. The daily low power charging peaks are likely to occur in the early morning and afternoon when the base utility loads are relatively low. The modelling result indicates that the marginal charging demand in the short term (2020) would be relatively insignificant,

whereas the capacity of the power grid needs to be extended to cope with the extra charging demand in the long term. The EV charging demand in 2050 and 2100 would take 2.07% and 16.68% of the current base load.

With the EV stock estimates, the required charging infrastructure is also calculated based on two charging infrastructure combinations: the combination of charging posts and fast charging stations and the combination of charging posts and battery swap stations. It is found that the infrastructure cost for both combinations are very similar. However, given the required batteries, the total infrastructure cost of battery swap scenario would be much higher for the operator, though the upfront cost for customers would significantly decline. Furthermore, the separation of batteries and EVs and the standardized battery swap mechanism are the prerequisites of the battery leasing option.

Section 6 models the cost profiles for EV users under three business operation models and the operator's revenue profile under the battery leasing scenario. It concludes that although the battery leasing and vehicle leasing strategy would directly reduce the purchase cost of EVs, without charging a high monthly fee the payback period could be extremely long. Although the battery operator is perhaps able to accommodate a relatively long payback period due to the high revenue in the end, the reduced contract fee would still be higher than the level typically accepted by the market. The battery leasing strategy could exploit the potential of low electricity cost during the

vehicle operation stage and promote consumers' purchase preference. Nevertheless, the current high battery and infrastructure cost would probably remain as a remarkable challenge for the charging service operator particularly in the near term. Therefore, those innovative business operation models would still need substantial political and financial support in the early stage of EV penetration.

Chapter 9 Conclusions

9.1 Conclusions

For some time electric vehicles have been recommended as one of the most promising alternative fuel vehicles technologies that could reduce China's energy reliance on imported oil in the near term, and the country's carbon emissions in the long run. However, the development of electric vehicles is still facing a number of obstacles. This thesis covered a number of barriers for electric vehicle development and concentrated on four key aspects that have not been fully investigated or are still controversial in China. These include the lifecycle energy consumption and carbon emissions of electric cars based on the China's energy mix; the expected electric car driving profile (including daily driving distance and driving time) and its impact on the energy use and carbon emissions; the deployment strategies of charging infrastructure for the early electric car market based on the people's driving behaviour and power grid capacity, and; the business operation models that could reduce the purchase cost of electric cars and accelerate their market diffusion in the early stage.

To estimate the AFVs' lifecycle energy use and emissions, Chapter 5 and 6 have applied the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model to estimate the lifecycle energy consumption and carbon emissions of a variety of low carbon vehicle technologies, according to the energy mix in the United States and China. A break-even analysis was conducted for the year of 2020 taking into the consideration of private and external costs using the concept of social cost of carbon. The estimates of energy consumption and greenhouse gas emissions of plug-in hybrid electric vehicles have taken account of the observed driving profile in China. It is found that fuel cell vehicles with gaseous hydrogen produce the least lifecycle CO_2 emission throughout the whole well to wheel process. Due to the zero pump to wheel and high well to pump carbon emissions, it showed EVs are the second low carbon emission option, and followed by fuel cell vehicles running on gaseous hydrogen. Compared with petrol and diesel, biomass-based fuels can effectively substitute the petroleum fuel consumption, even though they have few advantages in CO_2 reductions during fuel production in refineries and fuel combustion in vehicle engines. However, the carbon absorption during biomass growing significantly reduces lifecycle emissions of biomass-based fuels. Due to the high fuel economy, carbon emissions from hybrid electric vehicles are significantly lower than those from petrol/diesel powered internal combustion engine vehicles. It was also found that the fuel cycle carbon emissions represent the largest portion (over 95%) of lifecycle carbon emissions for all vehicle/fuel systems.

With regard to the market acceptance, the break-even analysis has showed that flexible fuel vehicles with E85 (blend of 85% ethanol and 15% petrol in volume) and spark ignition direct injection engine vehicles with E90 have a large potential to competing with new generations of alternative vehicle/fuel systems in the United States' market in 2020, due to their relatively low social (external) costs. Under the policy package comprising of vehicle purchase and fuel tax credits, the payback periods of these two options could be highly attractive for consumers. In spite of yielding the lowest CO_2 emissions, fuel cell vehicles with hydrogen have an extremely long payback period compared with petrol-powered ICE vehicles, and this may require an extremely high level of tax credit for their market survival. Although the payback distances of alternative fuel vehicles are typically longer than those of conventional ICE vehicles, economic incentives can be introduced to promote the acceptance of alternative fuel vehicles. It is up to the government to decide how committed it is to lowering CO_2 emissions and to implementing a package to change consumers' preferences and behaviour, such as private sector vehicle purchase subsidies and tax credits.

The lifecycle assessments have showed automotive energy consumption and carbon emissions always concentrate on the fuel combustion stage. For petrol, diesel, natural gas, liquid petrol gas and bio-fuel vehicles, their fuel combustion happens in the downstream vehicle operation stage. Their energy use and carbon emissions, therefore, are dependent on the fuel combustion efficiency of ICEs. For electrics and fuel cell

vehicles that use electricity and hydrogen, the fuel combustion (producing electricity and hydrogen) happens in the upstream stage, thus the energy use and carbon emissions are mainly dependent on the combustion efficiency of power plants. The current energy conversion efficiency of ICEs ranges from 20% to 30%, which is lower than the average level of power plants. For coal plants, the average combustion efficiency of standard boilers is approximately 33% and could be increased to 50% with integrated gasification combined cycle technologies. For natural gas plants, the combustion efficiency of standard boiler is about 35% and could reach 60% with natural gas combined cycle technologies. On the other hand, the energy conversion efficiency of EV motors can reach 90%, which is higher than the upstream fuel production (processing and refinery) efficiency of petroleum fuels ranging from 80% to 85%. Given the increasing deployment of carbon capture and storage in future power plants, EVs are expected to have a larger potential in energy use and carbon emissions savings than what can be achieved by ICE vehicles.

Although it has been acknowledged that EVs can offer substantial carbon saving and air quality benefits during the vehicle operation stage, their overall environmental performance is also dependent on the upstream process of electricity generation and transmission. Given the high carbon intensity electricity generated from China's thermal plants, the actual carbon emissions saving from EVs need further analysis.

Rather than include a variety of alternative fuel options, this research concentrated on

the lifecycle assessment for plug-in hybrid electric vehicles in China in Chapter 6, given their advantage in integrating both electric and ICE operating modes, with a particular focus on the implication of peoples' driving profile in China. It demonstrated that PHEVs could be a promising AFV transmission option according to the current driving behaviour in Chinese cities. However, the current electricity mix in China, where coal takes the majority of total feedstock use, would indicate the current WTP carbon emissions of electricity generation is likely to be high in China. To mitigate the upstream carbon emissions, a number of clean coal combustion technologies (for example, Integrate Gasification Combined Cycle and Carbon Capture and Storage pilot projects have been introduced by the State Grid Corporation of China. Through these technological improvements, considerable reductions in carbon emissions during the WTP stage of electricity generation could be achieved in China over the next decade. Similar to hybrid electric vehicles in the United States, hybrid electric vehicles could achieve a remarkable carbon reduction thanks to the high fuel efficiency of vehicles during the pump to wheel stage. However, hybrid electric vehicles still wholly rely on petroleum fuels and it means their long-term carbon emissions saving would be limited. For fuel cell vehicles, because the production, compression, liquefaction and transport for hydrogen involve significant energy use and emissions plus the high cost of fuel cell technology, they are not expected to penetrate the Chinese market in the near term.

The thesis also revealed that due to the observed low levels of daily driving distances

in China, the all-electric mode of plug-in hybrid electric vehicles is expected to be able to substitute for most of current vehicle distances driven. The expected link between economic and travel demand growth means that the high utility factor of PHEVs is expected to decrease with the increasing daily travel in the next decade China. Nevertheless, the reduction in energy consumption and greenhouse gas emissions of plug-in hybrid electric vehicles can still be substantial, provided the all-electric range of plug-in hybrid electric vehicles can be increased via the improvement of the battery capacity.

Comparing the research findings from Chapters 5 and 6, it shows that according to current electricity generation mixes, electric vehicles would generate more lifecycle carbon emissions in China where coal generates 80% of the country's electricity (State Electricity Regulatory Commission, 2009) than in the United States where natural gas provides 40% feedstock in power plants (IEA, 2009). Due to the high carbon intensity of the power plants and the power grids in China, electric vehicles would cause greater lifecycle greenhouse gas emissions in China than those in the United States. In the United States, both natural gas and crude oil take a greater proportion in the power grid's feedstock sources than coal do, and this generates significantly less combustion stage greenhouse gas emissions than coal. On the other hand, the vast amount of coal resource in China provides large energy feedstock stock for electric vehicles, and the development of electric vehicles could largely mitigate the country's petroleum fuel consumption and its reliance on imported oil. China has

relatively small natural gas reserves, which indicates that the dedicated natural gas vehicles and flexible fuel vehicles running natural gas would only substitute for a very small proportion in the total vehicle fleet. With regard to biomass-based fuels, the conventional biomass-based fuels that are produced from starch (mainly from food plants) would not be a significant carbon reduction option due to the excessive use of fertilizers and pesticides. Because hybrid electric vehicle and plug-in hybrid electric vehicle technologies can be applied to almost all vehicle-fuel combinations, the government should still make a consistent effort to support these R&D activities. With new natural gas import contracts to Russia (Higashi, 2009) and mid-Asian counties (China Stakes, 2008), as well as the growing LNG imports from Australia and Indonesia (Priestley, 2010), natural gas is expected to play an increasingly important role in China's electricity generation, which could alleviate EVs' environmental impacts.

Although the renewable energy industry is developing rapidly in China, electricity generated from renewable sources will continue to account for a relatively small proportion in the overall energy supply in the short and medium term China, where most electricity will continue to be generated from natural gas and coal. Chapter 6 also shows that the daily driving distance in China is significantly shorter than that in the United States. The low daily driving distance along with the daily battery charging (which could also apply to the United States) would lower the battery capacity requirement for EV batteries and hence would facilitate market penetration of EVs. It

should also be noted that the energy use and carbon emissions profiles of electric vehicles in both countries will be jointly determined by the energy mix of power plants, the development of power transmission infrastructure and people's driving behaviour.

Although the electricity transmission network has already been established, electric vehicles still need a widespread charging infrastructure, which currently is still rare and this is currently regarded as a considerable barrier for electric vehicle market acceptance. As the accessibility of the charging infrastructure determines the people's charging behaviour, and this is directly linked to the electric vehicles' impacts on the power grid, a charging infrastructure study is needed to discover the optimum infrastructure deployment strategy based on the current driving and parking behaviour in China. Chapter 7 takes Beijing as a case study city to explore roles of different charging infrastructure in an electric vehicle charging system and to compare the charging infrastructure assignment strategies. The study has recommended that battery swap stations and home charging posts could jointly take the major role in an EV charging system. It has also found that the deployment of home and workplace/public charging posts can effectively mitigate the charging load of fast charging stations. In the city centre, home and workplace/public posts have tended to share a substantial proportion of the local charging load. In suburban areas, fast charging stations would have a prominent role to service long distance trips. Moreover, the charging loads among individual fast charging stations would be

significantly different, given the estimated high geographical deviation of charging energy demand, as well as the uneven distribution of home and workplace/public charging infrastructure. The research has estimated the required number of charging stations and demonstrated that this number could be reduced by allocating more charging loads to home and workplace/public charging posts. Due to the peak time operation feature of charging stations, a long charging service radius (so that covers more home and workplace/public charging posts) could reduce charging load for fast charging stations and correspondingly narrow the gap between the daily peak and off-peak electricity demands. However, the reduction of fast charging stations would magnify the charging load unbalance between stations and some stations would have a charging load much higher than the average.

The study also found that different types of charging infrastructure have their distinct advantages and characteristics, and that they should play different roles in a charging infrastructure system. To provide fast charging services, a minimum number of fast charging/battery swap stations should be guaranteed to ensure a basic service radius for fast charging accessibility. However, fast charging/battery swap stations usually involve a large investment and should be concentrated along highways serving long-distance journeys. The simultaneous operation of a large number of fast charging stations could also cause a large charging load on the main power grid. On the other hand, the home post charging is constrained by an upper limit as a result of parking space shortages. With the low parking space deployment rate in Chinese cities, the

current community (home) parking spaces are unlikely to be able to handle the entire charging demand from a developed electric vehicle market. Finally, due to the significant share of home charging and post charging, the fast charging/battery swap stations are likely to take a relatively smaller share of the overall charging energy than that of petrol stations. These factors tend to yield a more dispersed distribution of fast charging/battery swap stations, with a longer charging service radius than that of refuelling stations. However, the long charging service radius could substantially weaken people's confidence in the electric vehicle charging service. The contradictions between the low fast charging demand (due to expected high home charging share) and derivers' preferences for the short service radius of fast charging stations (requiring more fast charging stations) has emerged as the core issue in electric vehicle charging infrastructure deployment. An assignment pattern with an acceptable (short) service radius would lead to a great number of fast charging stations (high density) with high capital costs, whereas the long service radius would reduce the charging frequency. By avoiding the wide distribution of charging and grid infrastructure, the battery swap option could be an ideal solution to lower the high capital cost of electric vehicle charging infrastructure. Through charging infrastructure potential investigation in the case study city, the battery swap strategy has been suggested as the best means to reduce the high deployment cost of charging infrastructure. Although battery swap solutions are able to provide fast charging service with fewer impacts on power grid, there are also some clear concerns on battery swap infrastructure, such as the difficulty of standard establishment for

vehicles, batteries and chargers. The coordination of home/fast chargers and battery swap strategies could be complicated task for cities with different driving behaviour, urban layout and parking facility provisions.

Even though the cost of charging infrastructure could be reduced through the design of infrastructure deployment and the battery swap strategy, the high purchase price of electric cars still significantly hinders their adoption. Chapter 8 therefore discussed three business operation models that could help reduce the high upfront cost of batteries. The study took a case study of Shanghai, which is one of six pilot cities that have introduced electric car purchase subsidies for private automobile market. It predicted Shanghai's electric vehicle stock growth to 2100 in high and low increasing scenarios using the Bass diffusion model. The analysis showed in both scenarios, the break-even points, where the EV stock will catch up with the ICE stock, would happen after 2050 (2061 in high increasing scenario; 2086 in low increasing scenario). The study simulated the daily electric vehicle charging loads according to current daily driving profile and the predicted electric vehicle fleets in 2020, 2050 and 2100. It found that differing to the case in Beijing, the potential peak of electric vehicle charging load in Shanghai could occur during the city's afternoon peak demand, which would require a significant improvement of current power supply capacity. According to the estimated EV stock in 2050, it predicted the correspondent scale of charging infrastructure and the cost. The cost share between fast charging stations and charging posts are dependent on the number of proposed fast charging stations and

charging posts. When the ratio of electric vehicles to charging posts is 1:1, the charging posts would account for the majority of infrastructure cost. For the charging scenario with the battery swap option, the batteries stored in the swap stations would take a significant share of the total infrastructure cost. The study discovered that although the battery swap option could provide a faster charging service for electric vehicle drivers, it would require a significantly higher capital investment than that for fast charging stations. In addition, the battery swap operation would need a unified standard for batteries, vehicles and chargers, and this in turn would require significant regulation from both political and industrial sectors.

The cost-benefit analysis was conducted for both electric vehicle drivers and charging service operators from 2010 to 2050. The three business operation models were simulated to estimate electric vehicle drivers' cost profiles. It found that both the battery leasing and the vehicle leasing models could effectively reduce the consumers' purchase cost. However, the evaluation for battery leasing model demonstrated that without a high charging (pricing) rate, the payback period would be long, and this is likely to affect the whole electric vehicle market penetration period. The large investment costs incurred in the purchase of new batteries for the incremental electric vehicle users would lead to substantial annual deficits for operators. A net annual profit would only be achievable when the electric vehicle market is large and become stable. According to the current battery cost and petroleum fuel prices, the market acceptance of electric vehicles is still low. The innovative business operating models

might be able to reduce the high upfront purchase cost for electric vehicle users, but it would still present a significant profit challenge for the service operator. Therefore, the correct economic and political incentives are vital, particularly for the early stage development. Moreover, a well-established used battery market would be essential for a battery leasing operation system.

Both Chapter 7 and 8 investigated the deployment of electric vehicle charging infrastructure and they took two case study cities to estimate the required scale of charging infrastructure. Chapter 7 used the distribution of current petrol refuelling stations to predict the charging demand in Beijing, while Chapter 8 used the daily driving data to forecast the city's total charging demand in Shanghai. Serving a same number of electric vehicles, these two methods resulted in similar estimates for the required scale of charging infrastructure in both Cities. However, the different driving time profiles and base load profiles in the two case study cities indicated that the electric vehicle charging could have distinctive load impacts on the power grid. Although Chapter 7 concentrated on the geographical distribution of charging infrastructure and Chapter 8 concentrated on the cost evaluation, both chapters covered a variety of different charging infrastructures including the battery swap option.

From the discussion of Chapter 5 to 7, it can be concluded that there are currently still some near term barriers that need to be overcome for electric vehicle's development.

The current automobile market has been dominated by ICE vehicles, and therefore, electric vehicles have to, at the minimum level, provide an equivalent performance and convenience to ICE vehicles with an acceptable cost and to further improve their environmental benefits. This must involve further progress in battery technologies, renewable sources adoption in power plants, the power grid capacity and the charging infrastructure provision (battery swap equipment in particular).

Energy (in terms of reducing petroleum fuel use) and environmental benefits (in terms of vehicle emissions reduction) have provided the basic rationale for introducing electric vehicles and both are highly dependent on the upstream electricity generation. However, the low carbon renewable feedstock only takes a small share in China's electricity mix. For power plants, more renewable feedstock (hydro, wind and solar) should be adopted to provide low carbon electricity. The current power grids that are designed and built for fossil fuels also need to be upgraded to accommodate a larger share of the intermittent electricity generated from renewable sources. The power grid also needs to improve its storage and management capacity to coordinate the power supply and electric vehicles' charging demand. This could be achieved by the improved electricity storage in the main grid and the introduction of smart grid technologies, such as smart meters with Information and Communication Technologies (ICTs) applications. Moreover, the development of electric vehicles could also facilitate the deployment of electricity distributed generation, which allows the power generation from many smaller more local sources, and this could further cut

environmental impacts of electricity generation from large power plants. Furthermore, the future power grid should integrate predictions for both renewable power generation (through weather forecasts) and charging demand (through driving profile estimates) to maximize the use of the electricity powered by renewable sources. EV charging will cause load pressure particularly when the vehicle stock is large. To better address the EV charging pressure, some techniques such as charging time management and battery swap could be applied. But the capacity of power grid still needs to upgrade to cope with the EV charging demand in the long term.

Apart from the energy industry sector, the low battery capacity (short range in particular) is the main concern for most consumers, and it is regarded as being the electric vehicles' most obvious disadvantage as compared with ICE vehicles. Although the current advanced electric vehicles can offer a competitive driving power and torque as compared to ICE vehicles, their all-electric driving range is still low. The range-anxiety largely weakens the consumers' confidence in electric vehicles and it also causes additional challenges in establishing the charging infrastructure.

Currently, there are still some disputes on the selection of different types of charging infrastructure structure, and some Chinese cities have distinctive strategies for charging infrastructure deployment. According to the comparison between various charging infrastructure deploying configurations in Chapter 7, this research recommended that a charging infrastructure network should combine charging posts

and battery swap stations. The off-peak charging of charging posts has a relatively small impact on the power grid compared with fast charging stations, and electric vehicle batteries can be charged during the grid's off-peak load period through battery swap stations. In addition, the implementation of the battery swap strategy usually involves the selection of proper business operation models that could potentially promote electric vehicles' acceptance in the early stage of their market penetration (See Figure 72)

Figure 72 Key Recommendations for EV Development in China

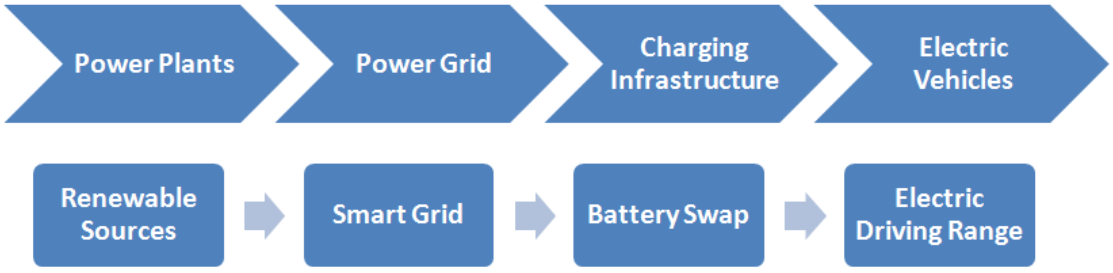


Figure 72 shows a series of key breakthroughs needed for the electric vehicle development. Because the performance of current electric vehicles is still significantly worse than that of ICE vehicles, it is recommended that the near-term financial and political support should be concentrated on R&D projects. The government needs to confirm the AFV development pathway and encourage cooperation among car makers, battery manufacturers and research institutes to achieve the critical electric vehicle technological breakthroughs. In particular, technological improvements are urgently

needed to enhance the renewable energy power generation (such as improving the capacity of photovoltaic cells and concentrated solar plants as well as reducing their costs), in operationalising the smart grid (such as introducing supply and demand forecast/management to mitigate negative impacts of the use of intermittent energy sources), and in investing in the batteries and the swap infrastructure (reducing their capital costs). Progress in these three sectors would improve the competitiveness of EVs to ICE vehicles, and they would form the foundation for introducing the next step policies. The demonstration programs, which are usually operated in niche sectors (such as public transport, postal delivery and sanitary service vehicles) with a relatively small implementation scale, can help manufacturers to discover the market requirements and adjust vehicle models for mass production. Demonstration programs can also help the utility companies and charging service providers to accumulate the operation experience and to formulate the charging infrastructure deployment strategies. The private market tax credits and subsidies should be launched to further eliminate the cost difference between EVs and ICE vehicles when the performance of electric vehicles is comparable to that of ICE vehicles. These credits and subsidies could also facilitate the R&D activities necessary to further improve electric vehicle capacities and reduce their production costs. Although diverse political measures are needed during different stages of electric vehicle development, the policy makers may also need to choose some measures to formulate policy packages for their practical implementation, and to involve the government, research institutes and car companies to achieve the technological breakthroughs. The demonstration and pilot programs

need to be encouraged by local governments and authorities. The private sector electric vehicle purchase subsidies and tax credits for end users could be introduced to accelerate the electrification of vehicle fleet. Turning to the electric vehicle promotion policies conducted in China, a similar policy implementation track can be identified. However, although some cities have introduced large scale subsidies and tax credits for consumers, the current battery as well as the upstream power generation – transmission technologies are still immature and require substantial R&D efforts.

As the development of electric vehicles is dependent on a series of factors involved in different aspects, this thesis has made use of a variety of research methods.

Due to the complicated inter-connections between many fuel (electricity) production pathways in the energy industry, the lifecycle assessment has been seen as an ideal approach to undertake the energy consumption and greenhouse gas emissions analysis for electric vehicles. The GREET model has been well-developed by the US Department of Energy to produce a comprehensive lifecycle assessment that covers both fuel and vehicle cycle impacts. The model requires a substantial amount of data input, and this has caused a particular challenge for the research in China. Currently, the public and published energy industry data in China are far less comprehensive than those in the United States. Moreover, the GREET model was introduced by the DOE and designed for the United States data format. Therefore, substantial efforts are needed for data collection and conversion to a GREET acceptable data format. Some

Chinese universities have also developed their alternative fuel vehicle lifecycle models with a Chinese background (such as the Tsinghua-CA3EM [74]). However these models are not publicly available and currently only focus on the fuel cycle impacts.

So far, few research methods have been specifically developed for charging infrastructure deployment analysis. This thesis introduced a charging infrastructure distribution model based on a GIS package provided by ESRI. The model included three types of charging infrastructure and it distributed them with the principle to minimizing the negative impacts of charging loads on the power grid. The model used the current distributions of gas refuelling stations, home and workplaces and public parking areas to estimate the distribution of potential charging demand. The study also forecasted the charging load patterns under different charging infrastructure deployment scenarios. However, the infrastructure deployment and the grid impact assessment are still two separated parts in the current model. Future studies should attempt to integrate them within a united model to facilitate the infrastructure planning.

The thesis adopted the Bass diffusion model to simulate the electric vehicle market penetration. The Bass diffusion model has been widely applied in economic and marketing research and provides an effective means to estimate the electric vehicle

[74] Tsinghua-CA3EM (China Automotive Energy, Emission and Economy Model) is a well-to-wheel lifecycle assessment model developed by the Tsinghua University.

growth in China. On the other hand, rather than being developed a purely new market, the development of electric vehicles in China is in an established automobile market with competition from ICE vehicles. In addition, the introduction of electric vehicles in current Chinese cities usually involves political and financial incentives that could lead to a significantly different diffusion pattern to a product in a full competitive market. Therefore, it is important to explore the proper parameters of Bass model that could properly reflect the ICE vehicles and the political interventions that might influence the electric vehicle market diffusion in China.

Both break-even analysis and net present value methods have long been applied in cost-benefit appraisal. As high purchase cost and low operation cost is a common characteristic of various alternative fuel vehicles, the net present value method could be used to provide a full-scale cost estimate. In a real market, however, consumers would place a high value on the purchase cost, and the pay-back period would be an essential factor for the alternative fuel vehicles' market success. In this case, the break-even analysis provided an effective way to improve the market acceptance prediction. It should be noted that for both the break-even analysis and the net present value method, the calculation results largely depend on the cost forecast and assumed discount rate. Although there have been several cost forecasts serving data input for net present value and break-even analysis, they usually integrate policy interventions (subsides and taxes), so the elimination of these political effects was a challenging task. Moreover, the social cost of carbon is a crucial parameter in measuring

environmental benefits of alternative fuel vehicles. However, this study found that the current social cost of carbon would be too low to produce a significant environmental value for alternative fuel vehicles (including electric vehicles).

9.2 Policy Implementation Schedule

From the discussion in previous chapters, we can see that the introduction of electric cars could effectively reduce the energy consumption and carbon emissions for China's transport sector particularly if the upstream low carbon electricity generation and the high efficient power transmission system can be developed.

However, key technology bottlenecks are currently still confining the development of electric cars. In order to promote the development, central government, local authorities, automobile companies, battery suppliers, infrastructure constructors and service providers should cooperate to explore developing strategies for China's EV industry. This section makes some recommendations for political, academic and industrial sectors with their implementation schedule.

Initially, the central government should propose a long-term electric car development plan that needs to identify the key EV modes (HEV, PHEV or pure EV) for different development stages. HEVs offer a significantly higher fuel economy than ICE vehicles, and the technology has been well-developed by many large car

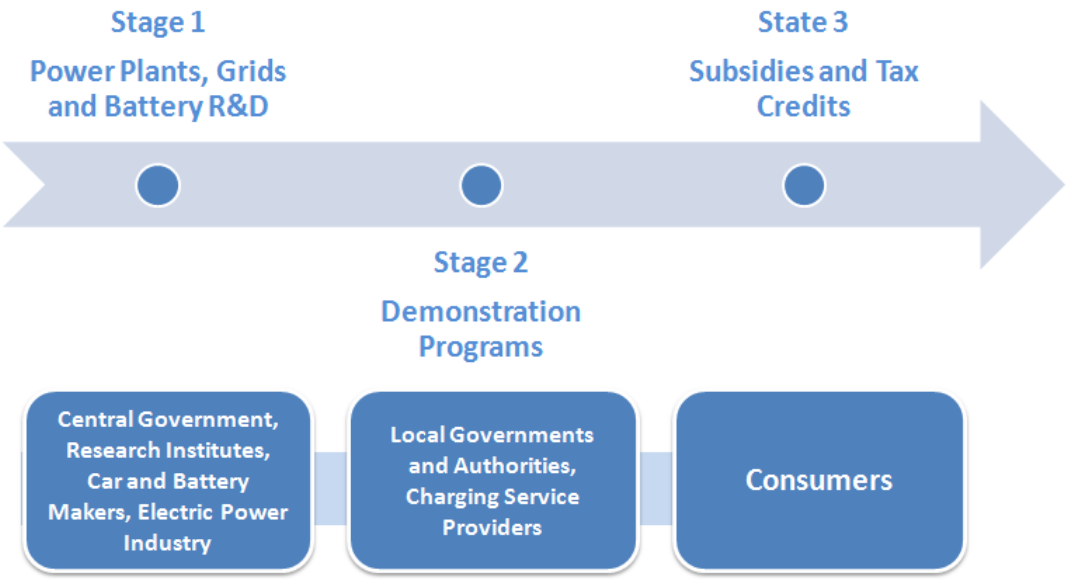
manufacturers. The configuration of both ICE and electric power-train enables conventional vehicle companies to remain, and promote their advantages in ICE design and production, which involves less system transition costs. The conventional vehicle companies, such as Toyota and General Motors, have been developing their HEV technologies over a long period, and they have accumulated substantial experience. In contrast, Chinese car makers have already fallen behind in the global HEV technological R&D development. There are still remarkable performance/cost gaps between current China-made HEVs and the world's leading HEVs. Nevertheless, PHEVs and BEVs are relatively new technologies for both Chinese and world's leading car manufacturers. Given the larger potential in oil/emission savings and grid benefits, PHEVs and BEVs could provide more promising AFV options than HEVs. It is expected that the technological advances will be at the core advantage in future EV competition. Therefore, the central government should focus on the battery R&D projects to improve the performance (including range, power and speed) of EVs. The central government should also encourage the cooperation between related research institutes, universities and car manufacturers. In particular, industrial alliances or joint ventures should be formulated along the whole EV supply chain to break key technological bottlenecks, including the low battery capacity, expensive solar and wind power plants and the smart power grid. It is suggested that PHEV or EV could be developed and deployed first for buses and public official vehicles to demonstrate their utility and refine the business operation models.

In the medium term, the government should promote the deployment of EV charging infrastructure via regional demonstration and pilot programs. As there are diverse types of charging infrastructure which could lead to various charging scenarios, pilot programs should make a comparison between them in terms of their costs, user acceptance and power grid impacts. The charging infrastructure interface and battery swap procedure should also be standardized at this stage. The demonstration projects should integrate charging service operators and test different business operation models. The government perhaps needs to help the operators establish the links to upstream electricity providers, battery manufacturers and end users. The pilot EV programs should utilize the electricity from renewable sources if applicable to experiment with the feasibility of low carbon electricity generation and EV charging integration. Financial incentives and industrial regulations (such as low carbon vehicle/AFV credits and fuel economy regulations) would also be an effective measure to stimulate the whole EV supply chain production capacity. In China, state-owned corporations take the charge of the power grid operation and infrastructure construction, which could help the formation of national EV charging standards and facilitate the development of charging infrastructure. From the demonstration programs, EV and battery manufacturers could accumulate operating data which could be used to further improve the design of electric cars.

When the demonstration programs can justify the potential of electric cars, the large-scale financial incentives (for example, vehicle purchase subsidies) for private

customers should be implemented to encourage electric car market penetration in the early stage. The private sector electric car purchase subsidies have already been implemented in six Chinese cities. Although a large investment is perhaps able to raise the current market acceptance, it will also be a great fiscal burden for the government. Although some new business operation models have been recommended to reduce the high capital cost, their effectiveness still needs further investigation. Some valuable experiences can be derived from the mobile phone market, where the concept of fixed term contract between the telecommunication operator and consumers that has been well-accepted and it could offer implications for the EV market. In summary, the sustainable growth of electric car purchase still fundamentally relies on the maturity of battery technology, the vehicle performance and the deployment of the charging infrastructure. It further proves the importance of the early stage R&D and demonstration efforts that should minimize disadvantage of electric cars, and provide favourable circumstances for the introduction of private sector subsidies (See Figure 73).

Figure 73 Policy Implementation Schedule and Stakeholders in Each State



9.3 Future Development

From this research, it can be concluded that the development of electric cars is actually associated with many factors in diverse fields, such as technological advances, public concerns over environmental issues, political will and economic solutions. As one of many new technologies which tend to fundamentally change people's way of working and living, the large potential of electric cars would only be seen when the synchronized development can be made in associated fields, such as power generation, the power transmission and storage system. For instance, when electric cars can run on low-carbon electricity and be intelligently charged, there will be substantial savings in transport petroleum use without causing significant increases in carbon emissions. In the meantime, the introduction of electric cars could improve the operation efficiency of power grid system by balancing the load turbulence, while

reducing the infrastructure investment and avoiding power supply failure. The link between electric cars and the electric power grid could further facilitate the power generation from intermittent renewable energy (such as solar and wind). With the progress of smart grid technology, charging activities can be carried out more strategically when demand is low, making the use of low-cost generation and extra system capacity, or when renewable electricity is high. In the long term, smart grid technologies could further enable electric cars to feed electricity back into the power supply system.

In addition to the positive environmental effects, the development of electric cars would also be driven by their benefits to the economy. The reliance on imported oil makes China' economy vulnerable to foreign oil supply interruptions. The oil imports can cause oil-induced price inflation and high foreign investment to secure overseas oil supplies. It has also been revealed that the financial turbulences associated with petrol dollars have become a primary contributor to global economic imbalances (Jackson, 2009). As an emerging industry in China, electric cars could also become a new driver for economic growth. China is now facing a critical moment for the electric car development. Technological progress (across battery, vehicle, power plants and the power grid), public awareness and behaviour and the political support are all essential factors to form an electric car development ecosystem.

Although financial and economic measures could accelerate the market acceptance,

electric cars are not likely to directly replace petrol and diesel vehicles in the near future. The economic historians (Arthur, 2009) have found that it usually takes a long period for a new technology to have a massive impact on productivity and people's life. For example, James Hargreaves invented Spinning Jenny in 1764, and this is regarded as one of the most profound technological breakthroughs in the industrial revolution. However, the large scale industrialization in Britain began from the 1810s, and the significant increase of working class salaries came in the 1840s. Similarly, despite being firstly used in the 1880s, electricity had few effects on productivity improvement until the 1920s. These examples indicate that a specific technology cannot fully exert all its potential benefits when it has only been introduced in an isolated/niche market. The benefits can only be observed when it is extensively implemented. For instance, when automobiles were firstly invented, they are just luxuries for the wealthy. With the wide spread of highway infrastructure and refuelling stations, automobiles have then become common commodities in modern society. It shows a clear interaction between a new technology and its peripheral environment: the infrastructure is able to facilitate the growth of the technology, while the development of the technology would in turn stimulate the establishment of the infrastructure. Though it may take decades for a new technology to win the entire society's acceptance, the virtuous cycle between the technology and its peripheral environment would ensure a long-term development. It also demonstrates the path dependence and the difficulty of new technologies to replace old well established ones.

In fact, this process has been observed repeatedly in the last century. Computers have been widely used in commercial sector as early as the 1960s. Personal computers, in particular, have become a standard facility in most offices in the United States before 1990. However, apart from the limited application in editing and printing works, computers had only a small effect on improving working efficiency. This is because the conventional office configuration could not fully exploit all the functionality of computers. The real strength of computers became observed when the intranet and internet were introduced in offices. When every computer in the office is inter-connected and further connected to the external suppliers and clients' computers, their large capacity of communications and teleworking can be exploited. People can communicate and cooperate via online electronic spreadsheets instead of papers or taking part in face-to-face meetings. Just as electricity cannot be effectively used in factories designed for steam engines, computers can hardly perform in conventional offices designed for papers.

In transport sector, the road transport system now is designed and established for ICE vehicles. Although an EV could be more energy efficient with fewer emissions than an ICE vehicle, it requires upstream upgrades in energy production and transmission industries, as well as downstream reforms in the refuelling (recharging) infrastructure. With a less-developed energy industry and infrastructure network, the early stage growth of EVs, when ICE vehicles still take main stream in road transport, could be

very slow. Nevertheless, with the fast development of ICT and the smart grid technologies, which largely promote the establishment of low carbon electricity generation and charging network, EVs would play an increasingly important role in the transport industry. Via the bi-directional information and electricity transmission between EVs and the power grid, EVs eventually could even offer more convenience and economic benefits for users than ICE vehicles can.

Compared with other countries, China has the technological, cost, resource and market advantages for the electric car development. China has become one of leading countries in battery technology research and is the world's largest EV battery provider. Some companies, including BYD (based in Shenzhen) and Lishen (based in Tianjin), have accumulated long term R&D experiences in battery design and manufacture. In addition, the battery manufacture industry is labour intensive and China currently holds a clear advantage in cost control for battery mass production. Taking the BYD F3DM as an example, it can be seen that the retail price of the PHEV model was only about half of that of Toyota HEV - Prius (HEV) in the Chinese market. Furthermore, China also processes a vast reserve of lithium (world's 3rd largest reserve) and rare earth (50% of world's reserve), which provide the critical materials for manufacturing lithium batteries and electric motors. What is more important is that China has the fastest growing vehicle market in the world. The annual vehicle production has reached 14 million in 2009 and the average increase of 10% has been maintained over the recent past. The large potential of the vehicle market provides an outstanding

environment for the development of the EV industry.

9.4 Research Limitations

Some of the research limitations have been presented in topic chapters from Chapter 5 to Chapter 8. This section aims to provide a thorough discussion of the main limitations in the thesis.

Firstly, this research predicts the low operation costs of alternative fuel vehicles could compensate the high initial cost of vehicle purchase costs. This prediction is based on the assumption that the current high fuel tax and relative low electricity tax will remain. However, with the development of new energy vehicle industry, the government could face a loss in petrol and diesel duty revenues and could hence introduce an electricity tax/duty to compensate the loss. The direct result is the payback period for EVs will be longer due to the increased operation cost. This could apply for both EV customers and charging service operators. The influence resulted from the introduction of electricity tax/duty could be relatively small in China as fuel tax revenue takes a minor share of current governmental financial revenue than that does in European countries. However, more in-depth studies are needed to fully evaluate the potential influence on the EV market under this scenario.

Although this thesis focuses on the financial cost factor in the market potential

analysis for the EV development in China, some other non-price factors are also important factors in mass market EV uptake in the context of China. Safety, vehicle market availability by market segments, performance, comfort and brand loyalty have been shown to be important factors affecting technology choice. For instance, some recent battery ignition and explosion caused by traffic accidents in China have significantly raised the public concern of EVs and correspondently lowered the market acceptance. Therefore it is recommended that the future studies need to include these as utilities in choice modelling, such as the field of discrete choice modelling to forecast the EV market growth.

In Chapter 7, the EV charging infrastructure deployment and the grid impact assessment are two separated parts in the current model. In order to better estimate the impacts of various charging deployment strategies on the power grid, these two segments should be integrated by future studies. In addition, the grid impact assessment in this chapter only considers a typical single working day scenario, due to the limitation of data. A comprehensive study also needs to assess the weekly and seasonal scenarios.

Furthermore, in Chapter 8, the Bass model is applied to predict the future EV growth in Shanghai. The selection of Bass model is because EV diffusion highly relies on the interaction between users and potential users. The interaction is not only through communication and media pathways, but also through infrastructure deployment. The

development of infrastructure for previous users could also increase the number of potential users. However, the complexity of car market in Shanghai should also be noted. The growth of car stock in city is highly influenced by the government's vehicle population control policies (such as the plate number auction). In addition, the development of EVs will not grow in a single market and will face the competition of petrol cars which have already dominated the automobile market. It indicates the difficulties in selecting and calibrating the 'p' and 'q' which directly determines the model output.

Apart from the limitations outlined above, there are also a number of limitations spread over this research, such as the selection of discount rates. The details are also introduced throughout the discussion in correspondent chapters.

9.5 Recommendations for Future Research

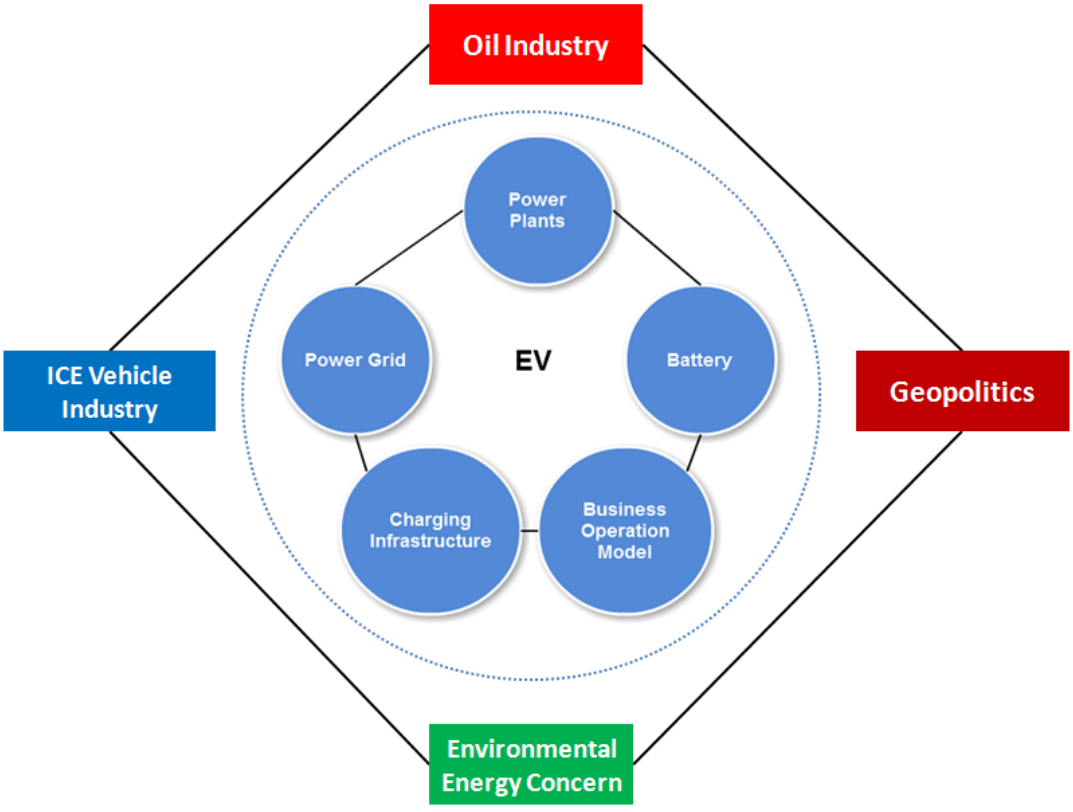
EV research in the short and medium term will continue to concentrate on the improvement of capacity and safety of EV batteries. The last decade has seen a successful commercialization of small and medium lithium-ion batteries, but the cell operation consistency in battery modules for EVs needs further R&D work. The battery packages in EVs still require further tests. The current batteries' range, life and charging speed are also significantly lower than the levels required for EVs to penetrate the market. In addition, a well-established battery recycle market is essential

for battery life cycle emissions control and cost reduction. With regard to the energy consumption and emissions assessment, future research should extend the lifecycle analysis boundary and include a thorough review of energy use and the emissions profile across the total vehicle cycle (production, recycle and disposal). For the cost benefit analysis of AFVs, the external cost of other emissions, including CO, NO_2, SO_x, PM10 and PM2.5, could also be integrated within the evaluation. It is expected that the EV stock growth will have a tipping point and after that point, growth will accelerate. Therefore, further research needs to accurately identify this critical point, so that better prediction and deployment can ensure the required charging infrastructure in place. For the charging infrastructure deployment, this thesis has proposed an EV charging infrastructure configuration that contains three types of charging outlets based on the current driving and parking behaviour in China. In order to better estimate the charging impacts on the power grid, the charging activity profile needs an improved model which should reflect the weekly and seasonal variations of charging frequency.

From the study of the EV development in China, it can be seen that the development of EVs depend on many inter-connected factors. Although this thesis has discussed four different aspects within the EV field, there are actually inseparable internal relationships between these aspects. Some have been traditionally regarded within the EV research field, such as battery technology, while others have recently begun to receive more academic attentions, including renewable energy power plants, smart

power grids and charging infrastructure. This thesis focused on these core aspects and it made estimates of the future EV development accordingly. It should also be noted that the development of EV will also be influenced by some other issues which were not considered as typical topics in EV research, such as the future progress of the ICE vehicle and oil industries, geopolitics and the global climate change. These external issues will also determine the success of EVs. Future research should further investigate those "external" issues and their impacts on EVs (see Figure 74).

Figure 74 Core and External Issues within EV Studies



Although the development of EVs will bring substantial benefits, there would also be some negative effects. One significant concern is the impact on the oil industry. The

oil industry covers oil recovery, refining and sales, and it currently constitutes a major part of the energy industry in many countries, and it provides large employment opportunities around the world. It is also closely linked with a wide range of manufacturing and processing industries in the supply chain that are the pillar industries for many countries' economies. Similar implications can also be applied to the car manufacturing industry. Declining oil demand would reshape the current oil and car industries and the whole associated supply chain, and consequently, it would have a profound impact on the global economy. Furthermore, petrol and diesel taxes are an important tax source for governments in all countries. The current high cost of fuel products (particularly in Europe and Japan) is partly attributed to the high tax rates imposed on them. The shift to electrified transportation would cause a great uncertainty over the future fuel tax policy configuration and the government revenue. Researchers, therefore, should fully consider these potential negative effects of EV development and offer measures to minimize the impact with an acceptable economic and political cost.

Academic research will accompany the whole process of EV development in China, and this would cover the various fields and topics serving different stages of the development. Past research has focused on the improvement of the vehicle itself and this has been achieved through conducting many energy consumption and emissions analyses for EVs. At present, more efforts are being made in the associated sectors of the supply chain, including the power grid and the charging infrastructure. These

studies will help the industry identify the market demand and produce the required battery/vehicle models, while policy makers can also compare various promotion measures and choose proper policies (packages) via the research findings. This thesis has made a summary of previous studies within the EV field and it has introduced the current EV progress in China. Several crucial and urgent issues have formed the focus of this research so that specific recommendations can be made. Some conclusions from this research differed to the current mainstream views in academia, including the implementation timing of policies and charging infrastructure deployment strategies, and these findings could offer enlightenment for future studies.

Appendices

Appendix 1 GREET Life Cycle Assessment Tables
Vehicle Technologies, Passenger Cars: Well to Pump Energy Consumptions and Emissions

(Btu or grams per mmBtu of fuel available at fuel station pumps)

Year: 2020	Baseline CG and RFG	Grid-Connected SI PHEV: Gasoline and Electricity	Electricity (transportation)
Total Energy	445,358	1,028,783	1,870,314
WTP Efficiency	69.2%	49.3%	34.8%
Fossil Fuels	434,597	914,432	1,606,544
Coal	79,901	588,701	1,322,591
Natural Gas	206,153	198,540	187,558
Petroleum	148,543	127,192	96,395
CO2 (w/ C in V	30,813	120,029	248,713
CH4	148.108	201.661	278.905
N2O	0.550	2.074	4.272
GHGs	34,679	125,688	256,959
VOC: Total	28.443	24.743	19.406
CO: Total	29.004	45.186	68.527
NOx: Total	85.819	153.675	251.552
PM10: Total	18.317	159.347	362.767
PM2.5: Total	6.891	43.438	96.153
SOx: Total	32.964	215.521	478.841
VOC: Urban	14.519	8.968	0.963
CO: Urban	5.225	6.749	8.947
NOx: Urban	12.795	22.177	35.709
PM10: Urban	2.116	2.364	2.722
PM2.5: Urban	1.266	1.346	1.461
SOx: Urban	7.760	37.507	80.415

Vehicle Technologies, Passenger Cars: Well to Wheel Energy Emission Changes (%, relative to petrol vehicles)

Year: 2020	Grid-Connected SI PHEV: CG and RFG	Electric Vehicle
Total Energy	-38.7%	-39.7%
Fossil Fuels	-43.5%	-47.8%
Coal	380.2%	671.3%
Natural Gas	-57.5%	-71.6%
Petroleum	-71.7%	-95.7%
CO2 (w/ C in V	-32.8%	-29.7%
CH4	-40.7%	-43.7%
N2O	11.0%	-60.0%
GHGs	-32.7%	-30.5%
VOC: Total	-43.9%	-90.5%
CO: Total	-1.1%	-97.4%
NOx: Total	-20.9%	-24.6%
PM10: Total	224.5%	363.9%
PM2.5: Total	133.1%	201.9%
SOx: Total	176.0%	324.7%
VOC: Urban	-46.7%	-99.2%
CO: Urban	-0.5%	-99.4%
NOx: Urban	-20.7%	-51.6%
PM10: Urban	25.3%	-39.6%
PM2.5: Urban	7.7%	-56.1%
SOx: Urban	94.1%	185.6%

Vehicle Technologies, Passenger Cars, Well to Wheel Energy Consumptions and Emissions (per Mile)

Petrol Vehicle

Item	Btu/mile or grams/mile		
	Feedstock	Fuel	Vehicle Operation
Total Energy	574	1,412	4,458
Fossil Fuels	547	1,391	4,458
Coal	138	219	0
Natural Gas	286	633	455
Petroleum	123	540	4,003
CO2 (w/ C in V	46	91	342
CH4	0.405	0.255	0.010
N2O	0.001	0.002	0.012
GHGs	56	98	346
VOC: Total	0.023	0.104	0.151
CO: Total	0.069	0.060	3.482
NOx: Total	0.223	0.160	0.069
PM10: Total	0.030	0.052	0.029
PM2.5: Total	0.011	0.020	0.015
SOx: Total	0.069	0.078	0.006
VOC: Urban	0.003	0.062	0.094
CO: Urban	0.003	0.021	2.166
NOx: Urban	0.009	0.048	0.043
PM10: Urban	0.000	0.009	0.018
PM2.5: Urban	0.000	0.005	0.009
SOx: Urban	0.007	0.027	0.004

Grid-Connected Hybrid Electric Vehicle

Item	Btu/mile or grams/mile		
	Feedstock	Fuel	Vehicle Operation
Total Energy	364	1,640	1,948
Fossil Fuels	346	1,435	1,835
Coal	98	1,048	564
Natural Gas	127	260	197
Petroleum	121	127	1,074
CO2 (w/ C in V	28	205	88
CH4	0.324	0.069	0.005
N2O	0.001	0.003	0.012
GHGs	37	208	92
VOC: Total	0.019	0.029	0.108
CO: Total	0.032	0.056	3.482
NOx: Total	0.103	0.197	0.058
PM10: Total	0.284	0.026	0.047
PM2.5: Total	0.073	0.012	0.021
SOx: Total	0.033	0.387	0.001
VOC: Urban	0.001	0.016	0.067
CO: Urban	0.001	0.012	2.166
NOx: Urban	0.005	0.038	0.036
PM10: Urban	0.000	0.004	0.029
PM2.5: Urban	0.000	0.002	0.013
SOx: Urban	0.005	0.068	0.001

Electric Vehicle

Item	Btu/mile or grams/mile		
	Feedstock	Fuel	Vehicle Operation
Total Energy	366	2,165	1,353
Fossil Fuels	348	1,826	1,163

Coal	107	1,683	957
Natural Gas	90	164	136
Petroleum	151	-21	70
CO2 (w/ C in V	28	308	0
CH4	0.373	0.005	0.000
N2O	0.001	0.005	0.000
GHGs	38	310	0
VOC: Total	0.023	0.004	0.000
CO: Total	0.024	0.069	0.000
NOx: Total	0.077	0.264	0.000
PM10: Total	0.469	0.022	0.021
PM2.5: Total	0.119	0.011	0.007
SOx: Total	0.026	0.622	0.000
VOC: Urban	0.001	0.001	0.000
CO: Urban	0.001	0.011	0.000
NOx: Urban	0.004	0.044	0.000
PM10: Urban	0.000	0.003	0.013
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CO: Urban	0.001	0.011	0.000
NOx: Urban	0.004	0.044	0.000
PM10: Urban	0.000	0.003	0.013
PM2.5: Urban	0.000	0.002	0.005
SOx: Urban	0.004	0.104	0.000

Appendix 3 Charging Impacts on the Power Grid in Beijing

Hour	Base Load (MkW)	BAU (MkW)	Control (MkW)	Swap (MkW)
0	9.50	9.50	9.80	9.91
1	9.40	9.40	9.70	9.81
2	9.30	9.30	9.60	9.71
3	9.10	9.10	9.40	9.51
4	8.90	8.90	8.90	9.01
5	9.30	9.30	9.30	9.41
6	9.60	9.60	9.60	9.71
7	10.30	10.30	10.30	10.41
8	11.00	11.20	11.20	11.09
9	12.90	13.10	13.10	12.99
10	13.50	13.70	13.70	13.59
11	14.00	14.20	14.20	14.09
12	13.40	13.60	13.60	13.60
13	13.20	13.40	13.40	13.40
14	13.25	13.45	13.45	13.45
15	13.30	13.50	13.50	13.50
16	13.35	13.55	13.55	13.55
17	13.40	13.60	13.51	13.40
18	13.45	13.86	13.56	13.45
19	14.15	14.56	14.26	14.15
20	13.60	14.01	13.71	13.60
21	13.00	13.41	13.11	13.00
22	12.20	12.50	12.50	12.50
23	11.40	11.70	11.70	11.70
24	9.50	9.80	9.80	9.80

Appendix 4 - Charging Infrastructure Deployment using Python Script

1. calculate 'station number' and 'belong to'

```
import arcgisscripting
gp=arcgisscripting.create()
gp.OverwriteOutput=1

gp.Workspace=r"J:\Thrid Year\work 1\Scenario_3km.gdb"

#gp.Addfield("gas_refuelling_stations","gas_stations","SHORT")
#gp.Addfield("gas_refuelling_statinos","belong_to","TEXT")

demand="gas_refuelling_stations"

gp.Buffer_analysis(demand,"buffer","3000 Meters")

gp.Intersect_analysis(demand+";"+"buffer","Intersect")

cur1=gp.UpdateCursor(demand)
```

```
row1=cur1.Next()

while row1:

    cur2=gp.SearchCursor("Intersect")
    row2=cur2.Next()

    while row2:
        if row1.order_==row2.Order1:
            row1.gas_stations=row1.gas_stations+1
            row1.belong_to=row1.belong_to+","+str(row2.Order_)
            cur1.UpdateRow(row1)

        row2=cur2.Next()
    row1=cur1.Next()

#gp.Delete_Management("Intersect")
#gp.Delete_Management("Buffer")
```

2. points reduction

```
import arcgisscripting
```

```
gp=arcgisscripting.create()
gp.Workspace=r"J:\Thrid Year\work 1\Scenario_3km.gdb"

gp.OverwriteOutput=1

#gp.Addfield_Management("gas_refuelling_stations","in_","SHORT")
#gp.CalculateField_Management("gas_refuelling_stations","in_","0")

#gp.Near_Analysis("gas_refuelling_stations","transformer_substations")

#gp.Buffer_Analysis("gas_refuelling_stations","buffer","3000 Meters")

cur1=gp.UpdateCursor("gas_refuelling_stations","gas_stations=1")
row1=cur1.Next()

while row1:
        row1.in_=1
        cur1.UpdateRow(row1)
        row1=cur1.Next()

cur2=gp.SearchCursor("gas_refuelling_stations","gas_stations>1        and
in_=0","","","gas_stations D")
```

```
row2=cur2.Next()

while row2:
	Max=row2.GetValue("gas_stations")
	print "OBJECTID=",row2.OBJECTID
	print "Max=",Max


gp.MakeFeatureLayer("gas_refuelling_stations","layer0","gas_stations"+
"="+str(Max))
	count=gp.GetCount("layer0")
	print "count layer 0 all=",count

	cur3=gp.UpdateCursor("layer0","in_=0","","","NEAR_DIST A")
	row3=cur3.Next()

	while row3:

		print
"section:",row3.OBJECTID,"has",row3.gas_stations,"stations"
		ID=row3.GetValue("Order_")
```

```
cur=gp.UpdateCursor("gas_refuelling_stations","Order_"+"="+str(ID))
        row=cur.Next()

        if row.in_==0:
            row.in_=1
            cur.UpdateRow(row)
            print "row.in_=",row.in_


gp.MakeFeatureLayer("buffer","buffer1","Order_"+"="+str(ID))


gp.MakeFeatureLayer("gas_refuelling_stations","layer","in_=0")

gp.SelectLayerByLocation("layer","WITHIN","buffer1","","NEW_SELE
CTION")
            count2=gp.GetCount("layer")
            print "layer points=",count2

            cur4=gp.UpdateCursor("layer","in_=0")
            row4=cur4.Next()
```

```
            while row4:
                row4.in_=-1
                cur4.UpdateRow(row4)
                print "row4.OBJECTID=",row4.OBJECTID
                print "row4_in=",row4.in_
                row4=cur4.Next()

        row3=cur3.Next()

    row2=cur2.Next()
```

3. add gas com park

```
import arcgisscripting
gp=arcgisscripting.create()

gp.Workspace=r"J:\Thrid Year\work 1\Scenario_3km.gdb"

gp.OverwriteOutput=1

demand="demand_regions_301"
```

```
points1="gas_refuelling_stations"

points2="public_parking_1841"

points3="community_4936"


gp.AddField_Management(demand,"gas_stations","SHORT")

gp.AddField_Management(demand,"parking_lots","SHORT")

gp.Addfield_Management(demand,"communities","SHORT")

gp.Addfield_Management(demand,"seats","LONG")


gp.CalculateField_Management(demand,"gas_stations", "0")

gp.CalculateField_Management(demand,"parking_lots", "0")

gp.CalculateField_Management(demand,"communities", "0")

gp.CalculateField_Management(demand,"seats", "0")



#count gas stations:


gp.Intersect_analysis(demand+";"+points1,"Intersect")


cur1=gp.UpdateCursor(demand)

row1=cur1.Next()
```

```
while row1:

    cur2=gp.SearchCursor("Intersect")
    row2=cur2.Next()

    while row2:
        if row1.ObjectID==row2.FID_demand_regions_301:
            row1.gas_stations=row1.gas_stations+1
            cur1.UpdateRow(row1)

        row2=cur2.Next()
    row1=cur1.Next()



#count parks

gp.Intersect_analysis(demand+";"+points2,"Intersect")

cur1=gp.UpdateCursor(demand)
row1=cur1.Next()

while row1:
```

```
    cur2=gp.SearchCursor("Intersect")
    row2=cur2.Next()

    while row2:
        if row1.ObjectID==row2.FID_demand_regions_301:
            row1.parking_lots=row1.parking_lots+1
            row1.seats=row1.seats+row2.seats_1
            cur1.UpdateRow(row1)

        row2=cur2.Next()
    row1=cur1.Next()



#count communities:

gp.Intersect_analysis(demand+";"+points3,"Intersect")

cur1=gp.UpdateCursor(demand)
row1=cur1.Next()

while row1:
```

```
    cur2=gp.SearchCursor("Intersect")
    row2=cur2.Next()

    while row2:
        if row1.ObjectID==row2.FID_demand_regions_301:
            row1.communities=row1.communities+1
            cur1.UpdateRow(row1)

        row2=cur2.Next()
    row1=cur1.Next()

gp.Delete_Management("Intersect")
```

Appendix 5 Bass Diffusion Model

EV Stock Growth with Baseline Scenario

Appendix Bass Diffusion Model - EV stock growth
Baseline Scenario

	Total			EV			ICEV stock
Year	rate	acc.rate	acc.stock (million)	rate	acc.rate	acc.stock (million)	(million)
1999	0.01	0.01	0.28	0.00	0.00	0.00	0.28
2000	0.01	0.02	0.39	0.00	0.00	0.00	0.39
2001	0.01	0.03	0.50	0.00	0.00	0.00	0.50
2002	0.01	0.04	0.61	0.00	0.00	0.00	0.61
2003	0.01	0.06	0.73	0.00	0.00	0.00	0.73
2004	0.01	0.07	0.85	0.00	0.00	0.00	0.85
2005	0.01	0.08	0.98	0.00	0.00	0.00	0.98
2006	0.01	0.09	1.11	0.00	0.00	0.00	1.11
2007	0.01	0.11	1.25	0.00	0.00	0.00	1.25
2008	0.01	0.12	1.38	0.00	0.00	0.00	1.38
2009	0.01	0.14	1.53	0.00	0.00	0.00	1.53
2010	0.01	0.15	1.67	0.00	0.00	0.00	1.67
2011	0.02	0.17	1.82	0.00	0.00	0.01	1.81
2012	0.02	0.18	1.97	0.00	0.00	0.02	1.95
2013	0.02	0.20	2.13	0.00	0.00	0.03	2.10
2014	0.02	0.21	2.29	0.00	0.00	0.05	2.24
2015	0.02	0.23	2.45	0.00	0.01	0.06	2.39
2016	0.02	0.25	2.62	0.00	0.01	0.07	2.55
2017	0.02	0.27	2.78	0.00	0.01	0.09	2.70
2018	0.02	0.28	2.95	0.00	0.01	0.10	2.85
2019	0.02	0.30	3.13	0.00	0.01	0.12	3.01
2020	0.02	0.32	3.30	0.00	0.01	0.13	3.17
2021	0.02	0.34	3.47	0.00	0.01	0.15	3.32
2022	0.02	0.35	3.65	0.00	0.02	0.17	3.48
2023	0.02	0.37	3.82	0.00	0.02	0.19	3.64
2024	0.02	0.39	4.00	0.00	0.02	0.21	3.80
2025	0.02	0.41	4.18	0.00	0.02	0.23	3.95
2026	0.02	0.43	4.35	0.00	0.02	0.25	4.11
2027	0.02	0.44	4.53	0.00	0.03	0.27	4.26
2028	0.02	0.46	4.71	0.00	0.03	0.29	4.41
2029	0.02	0.48	4.88	0.00	0.03	0.32	4.56
2030	0.02	0.50	5.05	0.00	0.03	0.34	4.71
2031	0.02	0.51	5.22	0.00	0.04	0.37	4.85
2032	0.02	0.53	5.39	0.00	0.04	0.40	4.99
2033	0.02	0.55	5.56	0.00	0.04	0.43	5.13
2034	0.02	0.56	5.72	0.00	0.05	0.46	5.26
2035	0.02	0.58	5.88	0.00	0.05	0.49	5.39
2036	0.02	0.60	6.04	0.00	0.05	0.53	5.52
2037	0.02	0.61	6.20	0.00	0.06	0.56	5.64
2038	0.02	0.63	6.35	0.00	0.06	0.60	5.75
2039	0.02	0.64	6.50	0.00	0.06	0.64	5.86
2040	0.01	0.66	6.64	0.00	0.07	0.68	5.96
2041	0.01	0.67	6.78	0.00	0.07	0.72	6.06
2042	0.01	0.69	6.92	0.00	0.08	0.76	6.16
2043	0.01	0.70	7.05	0.00	0.08	0.81	6.24

2044	0.01	0.71	7.18	0.00	0.09	0.86	6.33
2045	0.01	0.73	7.31	0.00	0.09	0.91	6.40
2046	0.01	0.74	7.43	0.01	0.10	0.96	6.47
2047	0.01	0.75	7.55	0.01	0.10	1.01	6.53
2048	0.01	0.76	7.66	0.01	0.11	1.07	6.59
2049	0.01	0.77	7.77	0.01	0.11	1.12	6.64
2050	0.01	0.78	7.87	0.01	0.12	1.18	6.69
2051	0.01	0.79	7.97	0.01	0.12	1.25	6.73
2052	0.01	0.80	8.07	0.01	0.13	1.31	6.76
2053	0.01	0.81	8.16	0.01	0.14	1.38	6.78
2054	0.01	0.82	8.25	0.01	0.14	1.45	6.80
2055	0.01	0.83	8.34	0.01	0.15	1.52	6.82
2056	0.01	0.84	8.42	0.01	0.16	1.59	6.82
2057	0.01	0.85	8.50	0.01	0.17	1.67	6.83
2058	0.01	0.85	8.57	0.01	0.18	1.75	6.82
2059	0.01	0.86	8.64	0.01	0.18	1.83	6.81
2060	0.01	0.87	8.71	0.01	0.19	1.92	6.79
2061	0.01	0.88	8.78	0.01	0.20	2.00	6.77
2062	0.01	0.88	8.84	0.01	0.21	2.09	6.74
2063	0.01	0.89	8.90	0.01	0.22	2.19	6.71
2064	0.01	0.89	8.95	0.01	0.23	2.28	6.67
2065	0.01	0.90	9.01	0.01	0.24	2.38	6.63
2066	0.01	0.90	9.06	0.01	0.25	2.48	6.58
2067	0.00	0.91	9.11	0.01	0.26	2.58	6.53
2068	0.00	0.91	9.15	0.01	0.27	2.68	6.47
2069	0.00	0.92	9.20	0.01	0.28	2.79	6.41
2070	0.00	0.92	9.24	0.01	0.29	2.90	6.34
2071	0.00	0.93	9.28	0.01	0.30	3.01	6.27
2072	0.00	0.93	9.31	0.01	0.31	3.12	6.19
2073	0.00	0.93	9.35	0.01	0.32	3.24	6.11
2074	0.00	0.94	9.38	0.01	0.34	3.36	6.03
2075	0.00	0.94	9.41	0.01	0.35	3.48	5.94
2076	0.00	0.94	9.44	0.01	0.36	3.60	5.85
2077	0.00	0.95	9.47	0.01	0.37	3.72	5.75
2078	0.00	0.95	9.50	0.01	0.38	3.84	5.66
2079	0.00	0.95	9.52	0.01	0.40	3.97	5.56
2080	0.00	0.95	9.55	0.01	0.41	4.09	5.45
2081	0.00	0.96	9.57	0.01	0.42	4.22	5.35
2082	0.00	0.96	9.59	0.01	0.43	4.35	5.24
2083	0.00	0.96	9.61	0.01	0.45	4.48	5.13
2084	0.00	0.96	9.63	0.01	0.46	4.61	5.02
2085	0.00	0.96	9.65	0.01	0.47	4.74	4.91
2086	0.00	0.97	9.67	0.01	0.49	4.87	4.80
2087	0.00	0.97	9.68	0.01	0.50	5.00	4.69
2088	0.00	0.97	9.70	0.01	0.51	5.13	4.57
2089	0.00	0.97	9.71	0.01	0.53	5.26	4.46
2090	0.00	0.97	9.73	0.01	0.54	5.39	4.34
2091	0.00	0.97	9.74	0.01	0.55	5.51	4.22
2092	0.00	0.97	9.75	0.01	0.56	5.64	4.11
2093	0.00	0.98	9.76	0.01	0.58	5.77	3.99
2094	0.00	0.98	9.77	0.01	0.59	5.89	3.88
2095	0.00	0.98	9.78	0.01	0.60	6.02	3.76
2096	0.00	0.98	9.79	0.01	0.61	6.14	3.65
2097	0.00	0.98	9.80	0.01	0.63	6.26	3.54
2098	0.00	0.98	9.81	0.01	0.64	6.38	3.43
2099	0.00	0.98	9.82	0.01	0.65	6.50	3.32
2100	0.00	0.98	9.83	0.01	0.66	6.62	3.21

High Increasing Scenario

High Increasing Rate Scenario

	Total			EV			ICEV stock
	rate	acc.rate	acc.stock (million)	rate	acc.rate	acc.stock (million)	(million)
1999	0.01	0.01	0.28	0.00	0.00	0.00	0.28
2000	0.01	0.02	0.39	0.00	0.00	0.00	0.39
2001	0.01	0.03	0.50	0.00	0.00	0.00	0.50
2002	0.01	0.04	0.61	0.00	0.00	0.00	0.61
2003	0.01	0.06	0.73	0.00	0.00	0.00	0.73
2004	0.01	0.07	0.85	0.00	0.00	0.00	0.85
2005	0.01	0.08	0.98	0.00	0.00	0.00	0.98
2006	0.01	0.09	1.11	0.00	0.00	0.00	1.11
2007	0.01	0.11	1.25	0.00	0.00	0.00	1.25
2008	0.01	0.12	1.38	0.00	0.00	0.00	1.38
2009	0.01	0.14	1.53	0.00	0.00	0.00	1.53
2010	0.01	0.15	1.67	0.00	0.00	0.00	1.67
2011	0.02	0.17	1.82	0.00	0.00	0.01	1.81
2012	0.02	0.18	1.97	0.00	0.00	0.02	1.95
2013	0.02	0.20	2.13	0.00	0.00	0.04	2.10
2014	0.02	0.21	2.29	0.00	0.00	0.05	2.24
2015	0.02	0.23	2.45	0.00	0.01	0.06	2.39
2016	0.02	0.25	2.62	0.00	0.01	0.08	2.54
2017	0.02	0.27	2.78	0.00	0.01	0.10	2.69
2018	0.02	0.28	2.95	0.00	0.01	0.12	2.84
2019	0.02	0.30	3.13	0.00	0.01	0.14	2.99
2020	0.02	0.32	3.30	0.00	0.02	0.16	3.14
2021	0.02	0.34	3.47	0.00	0.02	0.18	3.29
2022	0.02	0.35	3.65	0.00	0.02	0.21	3.44
2023	0.02	0.37	3.82	0.00	0.02	0.23	3.59
2024	0.02	0.39	4.00	0.00	0.03	0.26	3.74
2025	0.02	0.41	4.18	0.00	0.03	0.30	3.88
2026	0.02	0.43	4.35	0.00	0.03	0.33	4.02
2027	0.02	0.44	4.53	0.00	0.04	0.37	4.16
2028	0.02	0.46	4.71	0.00	0.04	0.41	4.30
2029	0.02	0.48	4.88	0.00	0.04	0.45	4.43
2030	0.02	0.50	5.05	0.00	0.05	0.49	4.56
2031	0.02	0.51	5.22	0.00	0.05	0.54	4.68
2032	0.02	0.53	5.39	0.01	0.06	0.60	4.80
2033	0.02	0.55	5.56	0.01	0.07	0.65	4.91

2034	0.02	0.56	5.72	0.01	0.07	0.71	5.01
2035	0.02	0.58	5.88	0.01	0.08	0.78	5.11
2036	0.02	0.60	6.04	0.01	0.08	0.85	5.19
2037	0.02	0.61	6.20	0.01	0.09	0.92	5.28
2038	0.02	0.63	6.35	0.01	0.10	1.00	5.35
2039	0.02	0.64	6.50	0.01	0.11	1.08	5.41
2040	0.01	0.66	6.64	0.01	0.12	1.17	5.47
2041	0.01	0.67	6.78	0.01	0.13	1.27	5.51
2042	0.01	0.69	6.92	0.01	0.14	1.37	5.55
2043	0.01	0.70	7.05	0.01	0.15	1.48	5.58
2044	0.01	0.71	7.18	0.01	0.16	1.59	5.59
2045	0.01	0.73	7.31	0.01	0.17	1.71	5.60
2046	0.01	0.74	7.43	0.01	0.18	1.83	5.60
2047	0.01	0.75	7.55	0.01	0.20	1.96	5.58
2048	0.01	0.76	7.66	0.01	0.21	2.10	5.56
2049	0.01	0.77	7.77	0.01	0.22	2.24	5.52
2050	0.01	0.78	7.87	0.02	0.24	2.39	5.48
2051	0.01	0.79	7.97	0.02	0.26	2.55	5.42
2052	0.01	0.80	8.07	0.02	0.27	2.71	5.35
2053	0.01	0.81	8.16	0.02	0.29	2.88	5.28
2054	0.01	0.82	8.25	0.02	0.31	3.06	5.19
2055	0.01	0.83	8.34	0.02	0.32	3.24	5.10
2056	0.01	0.84	8.42	0.02	0.34	3.42	5.00
2057	0.01	0.85	8.50	0.02	0.36	3.61	4.89
2058	0.01	0.85	8.57	0.02	0.38	3.80	4.77
2059	0.01	0.86	8.64	0.02	0.40	4.00	4.64
2060	0.01	0.87	8.71	0.02	0.42	4.20	4.51
2061	0.01	0.88	8.78	0.02	0.44	4.40	4.38
2062	0.01	0.88	8.84	0.02	0.46	4.60	4.23
2063	0.01	0.89	8.90	0.02	0.48	4.81	4.09
2064	0.01	0.89	8.95	0.02	0.50	5.01	3.94
2065	0.01	0.90	9.01	0.02	0.52	5.22	3.79
2066	0.01	0.90	9.06	0.02	0.54	5.42	3.64
2067	0.00	0.91	9.11	0.02	0.56	5.62	3.48
2068	0.00	0.91	9.15	0.02	0.58	5.82	3.33
2069	0.00	0.92	9.20	0.02	0.60	6.02	3.17
2070	0.00	0.92	9.24	0.02	0.62	6.22	3.02
2071	0.00	0.93	9.28	0.02	0.64	6.41	2.87
2072	0.00	0.93	9.31	0.02	0.66	6.59	2.72
2073	0.00	0.93	9.35	0.02	0.68	6.77	2.58
2074	0.00	0.94	9.38	0.02	0.69	6.95	2.44
2075	0.00	0.94	9.41	0.02	0.71	7.12	2.30
2076	0.00	0.94	9.44	0.02	0.73	7.28	2.16
2077	0.00	0.95	9.47	0.02	0.74	7.44	2.03
2078	0.00	0.95	9.50	0.02	0.76	7.59	1.91
2079	0.00	0.95	9.52	0.01	0.77	7.74	1.79
2080	0.00	0.95	9.55	0.01	0.79	7.87	1.67
2081	0.00	0.96	9.57	0.01	0.80	8.01	1.56

2082	0.00	0.96	9.59	0.01	0.81	8.13	1.46
2083	0.00	0.96	9.61	0.01	0.83	8.25	1.36
2084	0.00	0.96	9.63	0.01	0.84	8.37	1.26
2085	0.00	0.96	9.65	0.01	0.85	8.48	1.18
2086	0.00	0.97	9.67	0.01	0.86	8.58	1.09
2087	0.00	0.97	9.68	0.01	0.87	8.67	1.01
2088	0.00	0.97	9.70	0.01	0.88	8.76	0.94
2089	0.00	0.97	9.71	0.01	0.88	8.85	0.86
2090	0.00	0.97	9.73	0.01	0.89	8.93	0.80
2091	0.00	0.97	9.74	0.01	0.90	9.00	0.74
2092	0.00	0.97	9.75	0.01	0.91	9.07	0.68
2093	0.00	0.98	9.76	0.01	0.91	9.14	0.62
2094	0.00	0.98	9.77	0.01	0.92	9.20	0.57
2095	0.00	0.98	9.78	0.01	0.93	9.26	0.53
2096	0.00	0.98	9.79	0.01	0.93	9.31	0.48
2097	0.00	0.98	9.80	0.00	0.94	9.36	0.44
2098	0.00	0.98	9.81	0.00	0.94	9.41	0.40
2099	0.00	0.98	9.82	0.00	0.95	9.45	0.37
2100	0.00	0.98	9.83	0.00	0.95	9.49	0.34

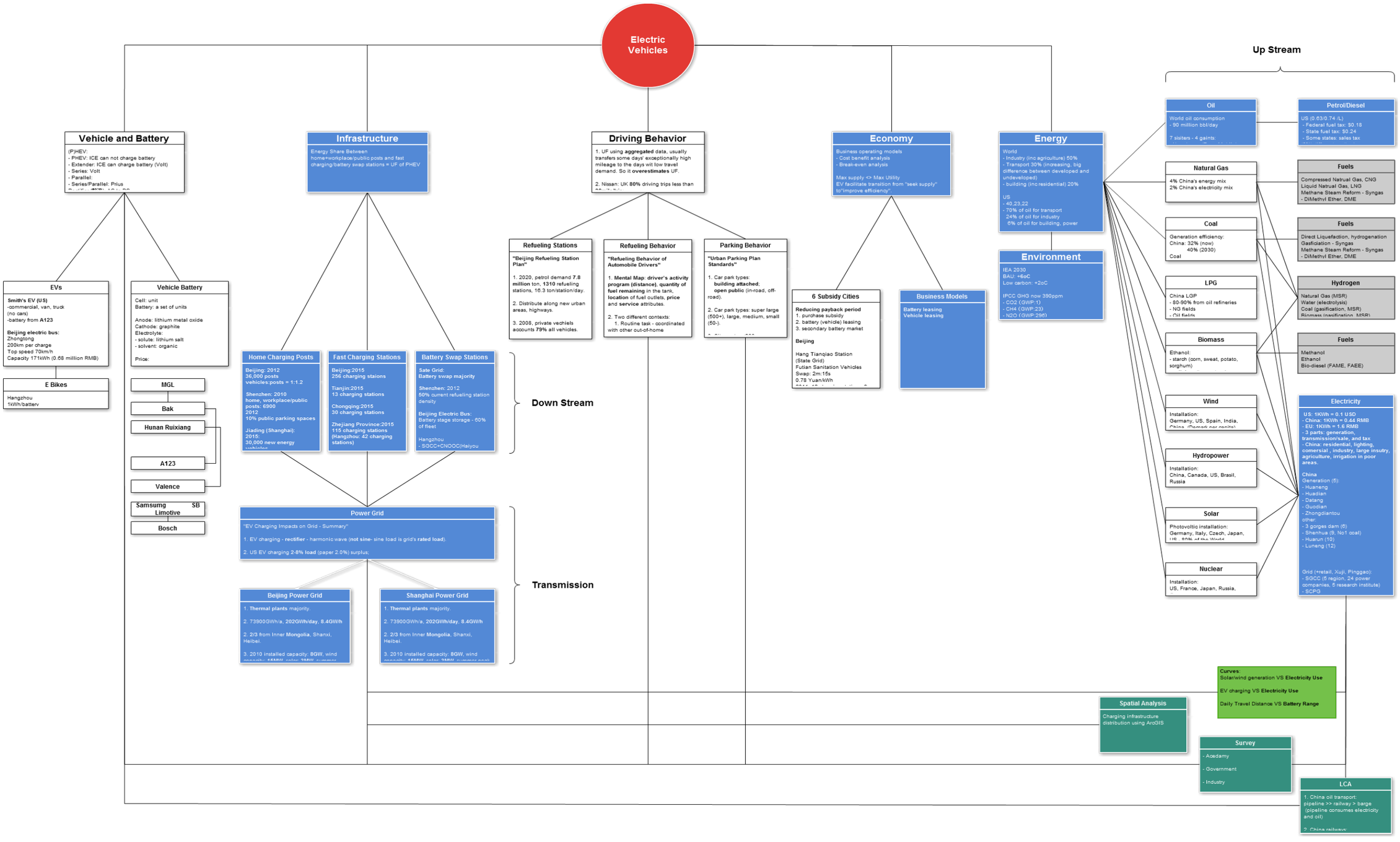
Appendix 6 Business Operation Models

Private Cost (RMB)			
Year	BAU	Battery leasing	Vehicle leasing (RMB 4900)
2010	136000	46000	0
2011	149600	85064	54444
2012	162177	119082	99815
2013	173808	148735	137623
2014	184563	174609	169131
2015	194510	197211	195387
2016	243667	216976	217267
2017	252174	234280	235500
2018	260041	249447	250694
2019	267316	262758	263356
2020	274045	274455	273908

Operator Cost (Million RMB)

Year		Low Growth			High Growth	
	Monthly Fee RMB 3050	Monthly Fee RMB 2000	Monthly Fee RMB 1770	Low Growth, Monthly Fee RMB 2500	High Growth,Monthly Fee RMB 2500	
2011	-952	-1074	-1101	-1016	-1084	
2012	-1593	-1948	-2026	-1779	-1933	
2013	-1951	-2637	-2787	-2310	-2560	
2014	-2052	-3158	-3400	-2631	-2978	
2015	-1922	-3525	-3876	-2761	-3199	
2016	-1898	-4068	-4543	-3035	-3559	
2017	-1670	-4468	-5081	-3136	-3737	
2018	-1258	-4738	-5501	-3081	-3742	
2019	-679	-4889	-5811	-2884	-3583	
2020	48	-4931	-6022	-2560	-3270	
2021	714	-5070	-6337	-2316	-3011	
2022	1508	-5110	-6560	-1959	-2609	
2023	2417	-5061	-6699	-1500	-2071	
2024	3428	-4930	-6760	-950	-1405	
2025	4529	-4725	-6752	-318	-617	
2026	5590	-4573	-6800	266	162	
2027	6725	-4356	-6784	920	1054	
2028	7926	-4080	-6710	1637	2051	
2029	9185	-3750	-6584	2409	3150	
2030	10493	-3372	-6409	3230	4345	
2031	11768	-3026	-6266	4019	5553	
2032	13082	-2637	-6081	4848	6848	
2033	14429	-2212	-5857	5712	8226	
2034	15802	-1753	-5599	6606	9681	
2035	17196	-1265	-5309	7526	11209	
2036	18561	-797	-5038	8421	12759	
2037	19939	-305	-4739	9335	14373	
2038	21328	209	-4417	10266	16049	
2039	22723	742	-4073	11209	17781	
2040	24120	1291	-3710	12162	19565	
2041	25488	1825	-3359	13093	21368	
2042	26854	2372	-2991	14030	23215	
2043	28216	2929	-2610	14970	25102	
2044	29570	3495	-2217	15912	27025	
2045	30915	4068	-1813	16852	28979	
2046	32231	4628	-1418	17772	30942	
2047	33535	5193	-1015	18689	32929	
2048	34825	5761	-605	19601	34933	
2049	36100	6332	-189	20507	36952	
2050	37357	6902	231	21405	38981	

Appendix 7 EV Factors Network



Appendix 8 Sohu Online Survey Questionnaire

1. Would you consider Hybrid Electric Vehicles (HEVs) or Electric Vehicles (EVs) when choosing a car to buy?

A. Yes

B. No

C. Not sure

2. Compared with conventional gasoline vehicles, what do you think is the biggest strength of HEVs and EVs?

A. Lower operation costs

B. Environmentally friendly

C. Other (please specify)

3. What are your concerns about HEVs and EVs? (You may tick more than one choice)

A. Expensive

B. Lower performance, quality or reliability when compared to standard gasoline cars

C. Repair and after-sales services insufficient

D. Limited models for selection

E. Other (Please specify)

4. How much more would you be prepared to pay for a HEV or EV when compared to an ICE vehicle?

A. Nothing

B. Less than 10%

C. Less than 20%

D. Less than 30%

E. More than 30%

5. Under what payback period would you be prepared to buy a HEV or EV?

A. Less than 6 months

B. 6 months to 1 year

C. 1 to 1.5 years

D. 1.5 to 2 years

E. 2 to 3 years

F. 3 to 5 years

G. More than 5 years.

6. If you had a plug-in HEV or an EV, what is the maximum amount of charging time you would find acceptable if charging took place in your 'community'?

A. Less than 3 hours

B. Less than 6 hours

C. Less than 9 hours

D. More than 9 hours

7. If you had a plug-in HEV or an EV, what is the maximum amount of charging time you would find acceptable if charging took place at 'charging stations'?

A. Less than 5 mins

B. Less than 10 mins

C. Less than 15 mins

D. Less than 20 mins

E. Less than half an hour

F. More than half an hour

8. What would be your minimum acceptable distance per charge is?

A. 100 km

B. 150 km

C. 200 km

D. More than 200 km

9. Your acceptable lowest vehicle maximum speed is

A. 100 km/h

B. 150 km/h

C. 200 km/h

D. More than 200 km/h

10. What is the purpose of your most common trips?

A. Commuting

B. Shopping

C. Social (visiting friends and family, etc)

D. Travel on holiday/Sightseeing

E. Other (Please specify)

11. Please specify your average travel distance per day in km.

12. Your common trips' origin and destination can be described as

Origin:

City ( )

Road/Street ( )

Community ( )

Closest public transport station ( )

Destination:

City ( )

Road/Street ( )

Community ( )

Closest public transport station ( )

13. Your gender ( )

14. Your age ( )

15. Your home city ( ) District/county ( )

16. Your occupation ( )

17. Your average monthly income ( )

If your are an automobile driver, please continue to questions 18 – 28; otherwise, please go to question 28:

18. Please specify your vehicle model (for example, Toyota-Camery-2.0L). If you have more than one vehicle please provide the model most often used one.

19. In general, your average driving speed is ( ) km/hr.

20. In general, you drive for ( ) minutes every day.

21. According to your experience, during each driving trip

21.1 The time the vehicle stops due to traffic jams, traffic signals, etc. is …% of the overall driving time

21.2 The time the vehicle travels at than 15 km/h is …% of the overall driving time

21.3 The time the vehicle travels at normal speed (between 15 an 40 km/h) is …% of the overall driving time

21.4 The time the vehicle travels fast (between 40 and 80 km/h) is …% of the overall driving time

21.5 The tine the vehicle travels at speeds higher than 80 km/h is …% of the overall driving time

22. You usually travel ( ) times per day (one-way to work counts as one)

23. Please indicate the time at which you usually travel every day

AM:

5-6 ( ) 6-7 ( ) 7-8 ( ) 8-9 ( ) 9-10 ( ) 10-11 ( ) 11-12 ( ) 12-13 ( )

PM:

13-14 ( ) 14-15 ( ) 15-16 ( ) 16-17 ( ) 17-18 ( ) 18-19 ( ) 19-20 ( )

20-21 ( ) 21-22 ( )

Other:

22 to 5 ( )

24. Please indicate your ideal speed assuming free-flow conditions

25. Do you usually overtake other cars?

A. No

B. It depends

C. Yes, if conditions allow

26. Your car typically consumes …. litres of petrol per month.

27. You normally park your vehicle in

When going home

Community-administered parking areas ( )

Roadside parking around my community ( )

Administered parking near my community ( )

Parking lots near public transport interchanges ( )

My own garage ( )

Other ( )

When going out

Parking areas provided by work place, school, shopping areas, etc ( )

Parking areas near the work place, school, shopping areas, etc ( )

Roadside parking around work place, school, shopping areas, etc ( )

28. Please feel free to express any opinion, ideas or suggestions regarding the development of electric vehicles in China. These may relate to the production, purchase or usage, or to potential government supporting policies.

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Collaboration Work in the Thesis

The Chapter 5 and Chapter 6 of this thesis are co-authored by Jian Liu and Dr Georgina Santos.

In Chapter 5 - Decarbonising the Road Transport Sector: Breakeven Point and Consequent Potential Consumers' Behaviour for the US case, I conducted the GREET model analysis, cost calculation for alternative fuel vehicles and chapter writing. Dr Georgina Santos contributed in data collection, scenario comparisons and policy recommendations (Section 5.6 and 5.7) and conducted chapter review.

In Chapter 6 - The PHEV Potential for Urban Transport in China: the problem of energy sources and charging behaviour, I conducted the GREET modelling for China, utility factor analysis and chapter writing. Dr Georgina Santos contributed in methodology, conclusions making (Section 6.2 and 6.6) and conducted the chapter review.

I am the first author of both papers. The majority of both papers represents the work of mine.

Chapter 5 and 6 have been sent to the International Journal of Sustainable Transport.
Chapter 7 has been sent to the Transport Research, Part C: Emerging Technologies.
Chapter 8 has been sent to the Journal of Transport Policy.

Jian Liu

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