Modelling the Prospects and Impacts of Methanol Use in Transportation in China at Computable General Equilibrium

by

Mahsa Nami
B.A.Sc. in Chemical Engineering
University of Toronto, 2015

Submitted to the MIT Institute for Data, Systems, and Society and Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of Master of Science in Technology and Policy and Master of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2017

Author . . . .
MIT Institute for Data, Systems, and Society
and Department of Mechanical Engineering
May 12, 2017

Certified by . . . .
William H. Green
Hoyt C. Hottel Professor of Chemical Engineering
Thesis Supervisor

Certified by . . . .
Wai K. Cheng
Professor of Mechanical Engineering
Thesis Reader

Accepted by . . . .
Munther Dahleh
Director, Institute for Data, Systems, and Society

Accepted by . . . .
Rohan Abeyaratne
Chairman, Committee on Graduate Students

Modelling the Prospects and Impacts of Methanol Use in Transportation in China at Computable General Equilibrium

by

Mahsa Nami

Submitted to the MIT Institute for Data, Systems, and Society and Department of Mechanical Engineering
on May 12, 2017, in Partial Fulfillment of the
Requirements for the Degrees of
Master of Science in Technology and Policy and
Master of Science in Mechanical Engineering

Abstract

The use of methanol as a transportation fuel is not a new phenomenon. However, factors such as price fluctuations, resistance to widespread introduction by special interest groups, and governmental policies have stood in the way of the widespread use of methanol in covering transportation demand. In this thesis, a computable general equilibrium energy-economy model of the world, the Economic Projection and Policy Analysis (EPPA) model, is used to evaluate the potential for methanol vehicle penetration in the private passenger vehicle market in China depending on the cost competitiveness of the technology combination compared to electric and conventional vehicles, the relative prices of methanol and gasoline, and the application of various policies. The use of methanol in light duty passenger vehicles has risen heavily in China due to the abundance of coal in the country and the ability to use it as the feedstock for methanol production in China, thereby reducing China's reliance on foreign oil imports. Additionally, the lower price of methanol fuel compared to gasoline has led it to be an attractive fuel choice from the customer perspective due its favorable economics, with a growing number of individuals converting their conventional vehicles to be able to run on methanol.

Since China is not a country abundant with natural gas, the two leading options for obtaining methanol are obtaining it through the use of coal as the feedstock locally or importing it from other countries which are producing methanol using natural gas. Methanol fuel production pathways and the vehicle technology are introduced in EPPA as a substitute for conventional Internal Combustion Engine (ICE) vehicles. Engineering cost estimates as well as existing transportation expenditure trends in China are used for obtaining the input shares and elasticities of substitution as inputs to the model. Simulations are then run until 2050 to understand the rate at which the methanol vehicle technology penetrates the market when competing with electric vehicles and conventional vehicles in the base case scenario. Accordingly, changes in greenhouse gas emissions and particulate emissions are calculated. On the policy side, various sets of policies are tested: instituting a gasoline tax, banning methanol imports for use in passenger private vehicles, applying various combinations of vehicle subsidies for methanol and electric vehicles, and instituting a carbon cap at a national level. Various conclusions emerge from this thesis. First, the penetration of methanol and electric vehicles are slow, achieving market shares of 4% and 1%, respectively. Despite the lower methanol cost compared to gasoline, the penetration of the technology is slowed down by the higher cost of methanol vehicles compared to conventional vehicles as well as the delays associated with introducing new fuels, new vehicles, and new refueling infrastructure, none of which are completely compatible with the incumbent technology. This shift also results in an increase in greenhouse gas emissions compared to the business as usual scenario but a decrease in emissions of nitrogen oxides, carbon monoxide, and hydrocarbons. Instituting a gasoline tax has a greater impact than existing Chinese vehicle subsidy policies on methanol and electric vehicle penetration. However, the gasoline tax still results in modest methanol and electric vehicle penetration, achieving a market share of 6% each by 2050. Setting a carbon cap under an accelerated effort scenario impacts the vehicle trends most dramatically, completely driving down the use of methanol vehicles and allowing electric vehicles to achieve an 11.47% market share. Finally, these results are used to present various policy recommendations depending on China's existing provincial policy structures, its national objectives, and future goals.

Thesis Supervisor: William H. Green
Title: Hoyt C. Hottel Professor of Chemical Engineering

Thesis Reader: Wai K. Cheng
Title: Professor of Mechanical Engineering

Acknowledgments

My time at MIT has come to a bittersweet end. I could not be happier or more content with the experiences I have been blessed to have in the past two years. They have challenged me personally and professionally, and have allowed me to learn and grow with the support of people I am extremely grateful for.

First and foremost, my immense gratitude goes to Professor Green for his faith in me and my capabilities, specially at moments of doubt that accompanied research work. His dedication to my learning experience and growth while at the same time providing me with the autonomy to explore research work have only made me more confident in my abilities to push the boundary. Professor Cheng, thank you for your support in my pursuit of a second degree, and for your guidance on the thesis direction. Sergey and Henry, thank you for all the effort and time you put in helping me learn EPPA, debug code, and make progress. I am very appreciative of your help and could not have done it without you. Barb, thank you for your advice and joyful spirit, always bringing life to TPP, and for the comforting words you always seem to be able to find.

My journey at MIT has been made great by intellectually stimulating, yet extremely humble, people I have met at this institution who challenged my thinking on all levels, from the academic to the spiritual. Lisa, thank you for being my number one partner and supporter in this research endeavor. From our struggles over EPPA to our words of encouragement, you have been there in the highs and lows. Amn and Arfa, thanks for our stimulating chats over chai and for always being there for me; I have gained two sisters during my time at MIT. To Esther, Arun, Denis, Dhivya, Jieun, Mark, Titan, and Lauren, thank you for having my back, I am grateful to have gained such amazing friends from all over the world. To my Toronto buddies, Mina, Maher, and Noura, thank you for your words of encouragement and for being there even across the border.

Most importantly, my gratitude goes to my incredibly supportive family. Sharif and Fatma, you brighten my days with your jokes and always manage to cheer me up when I am down. Your faith in me and my capabilities have only pushed me to always try my best in all I do. Mama and Baba, I am so blessed for the two of you. Thank you for supporting me and giving me the freedom to always pursue my passions and follow through my 12-year-old dream of studying in the US. Thank you for pushing me to think critically in all aspects of life and for reminding me to always be proud of my origin yet continually try to explore the world and look beyond differences, from Dubai to Toronto to now Boston. All I am I owe to you, I love you.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

China has achieved rapid economic growth, industrialization and urbanization in the last few decades. This growth, while resulting in a GDP increase of 8 to 9% per year and lifting about 400 million people out of poverty, has also been associated with increasing resource constraints and environmental pressures, specifically associated with achieving energy independence and reducing the negative impacts of air pollution [8]. The January 2013 smog incident in Beijing reflected the magnitude of the problems posed by vehicles in China. In this incident, the concentrations of particles with a diameter of 2.5 microns or less (PM 2.5) hit 40 times the level the World Health Organization (WHO) deems to be safe [19]. This suggests that there is a mix of objectives that need to be satisfied within the light duty vehicle transportation sector that addresses the local pollution problems in China, improves China's energy security by minimizing oil imports, and addresses China's international commitment to climate change goals.

An area of growth within the light duty vehicle sector in China is the use of methanol as an alternative transportation fuel. The use of methanol has risen heavily in China due to the abundance of coal in the country and the ability to use it as the feedstock for methanol production in China. The conversion of coal to methanol also provides a cleaner pathway for using coal at a time of increasing concerns about emissions from the power sector. China is not a country abundant with natural gas and it has prioritized the natural gas utilization within the country in urban use such as heating and cooling and in industrial use such as combined heat and power generation. In fact, China has prohibited the expansion of existing methanol production capacity with natural gas as feedstock or use of natural gas as an alternative to coal for methanol production [22]. Therefore, the two leading options for obtaining methanol are producing it from locally available coal or importing it from countries in the Middle East which are producing methanol in Mega Methanol plants, through the shipment of methanol in tankers. Additionally, the high price of gasoline in China has made methanol attractive economically, further encouraging its use on the customer end.

This thesis analyzes the light duty private passenger vehicle sector in China and answers the question of whether methanol vehicles are likely to achieve a substantial market penetration in China when competing with conventional vehicles and electric vehicles. Through the use of the MIT Economic Projection and Policy Analysis (EPPA) model, a computable general equilibrium model of the world economy, the penetration rates and market shares achieved by methanol, electric, and conventional vehicles in China are obtained. This, in turn, leads to quantifying the associated economic and environmental impacts, in the form of greenhouse gas emissions and particulate emissions, with the transition.

On the policy side, this thesis analyzes the policy landscape in China with respect to light duty vehicles. It then simulates the impact of instituting a gasoline tax in China on vehicle penetration and associated emissions as well as the potential impact of existing policy plans in China with regards to speeding up the penetration of methanol vehicles and electric vehicles. Additionally, a policy scenario in which methanol imports are banned is tested to understand the impact on the national penetration of methanol vehicles. Finally, varying levels of carbon dioxide reduction policy efforts are simulated to examine the impacts of instituting national carbon dioxide emissions caps on the light duty vehicle transportation sector.

This thesis is organized as follows: Chapter 2 provides a background on the transportation sector in China and the motivation for this thesis. Chapter 3 details methanol use in transportation, describing the methanol production process, the modifications required for allowing a vehicle to run on methanol, and the associated infrastructure changes needed. Chapter 4 describes Computable General Equilibrium modelling and introduces the EPPA model. Chapter 5 explains the additional structures added to the EPPA model to create a more representative view of the private passenger vehicle sector in China. Chapter 6 describes the base case scenario model results and associated sensitivity analysis. Chapter 7 tests various policy scenarios and provides policy recommendations based on the results of the analyses. Chapter 8 concludes.

Chapter 2

Background

Achieving sustainable transportation globally is a challenging task that requires a combination of different solutions that are each suitable for the intended geographies at hand and that still allow for economic growth in emerging countries. The solutions are numerous; they include the rise in sharing schemes in transportation, such as car sharing or governmental implementations of bike share programs, the development of new forms of transportation, examples of which are electric bikes or electric scooters, and the commercialization of advanced drive-trains such as electric vehicles and hydrogen fuel cell vehicles. However, as attractive as these solutions seem on the surface, their implementation is not always feasible due to unfavorable economics, the mismatch of the new technology requirements with existing resources in the country, or the lack of cultural fit of the technology with the mentalities of the potential end users of the technology. In these cases, there exists value in analyzing the existing options that are pushed for by interest groups or local governments in order to either advocate for them and provide recommendations for speeding up their implementation or to outline the negative aspects of the options in cases where the economic and environmental costs are too high.

2.1 Transportation in China

The Chinese auto-market is segregated due to the nature of the country's economy, often having inconsistent national and local policies, with prevailing policies favoring the advancement of local markets over the national Chinese market. A recent example is the group of policies set by the national and various regional Chinese governments to encourage the development of the electric vehicles market in China with the aim of reducing negative impacts from pollution and increasing economic competitiveness by making China a leader in electric vehicles manufacture. Specifically, Beijing and Shanghai currently do not adopt the national Ministry of Industry and Information Technology (MIIT) catalog for local subsidy qualification, thereby creating an advantage for locally produced electric vehicles over foreign and other domestic vehicles [17]. This negatively impacts consumer perception as it creates ambiguity among consumers on distinguishing between car models that are included under existing subsidies from ones that are not.

Local policies also vary for alternative fuels. China is the largest user of methanol for automotive fuel, with methanol contributing about 8% of China's transportation fuel pool [32]. This corresponds to about 4 billion gallons of methanol used in China annually to fuel cars, trucks, and buses. For reference purposes, in 2015, the United States consumed 140.43 billion gallons of gasoline for transportation [2]. The five Chinese provinces that have been promoting methanol usage are Shanxi, Shaanxi, Zhejiang, Guizhou, and Heilongjiang, following previous successful methanol fuel pilots which have led the Chinese Ministry of Industry and Information Technology (MIIT) to expand its M100 methanol vehicle program. These provinces are shown in Figure 2-1 and in those provinces, M15 (gasoline blended with 15 volume percent methanol) is widely used. These provincial governments promote methanol use in a variety of ways. For example, 40 M85-M100 refueling points were created in Shanxi province in addition to 1,000 gasoline stations there which have been converted to include M15. Shanxi also plans to convert 2,000 additional refueling stations within the next five years [38]. Moreover, about 70,000 taxis in Shanxi had been converted to run on M100 and M85 by 2012 [31]. The Shanxi government has also set a target for *new energy* vehicles, which include methanol-fueled vehicles, to account for a minimum of 30% of new purchases by government agencies in three of its cities [4]. Table 2.1 displays the available methanol blend pilot programs in various Chinese cities and provinces.

Table 2.1: Chinese provinces and cities with programs promoting use of methanol blends as motor fuel [4]

Provinces	**Cities**	**Available Blends**
Shanxi	Taiyuan, Yangquan, Linfen, Pucheng, Datong, Shuozhuo	M15, M30, M85, M100
	Xinzhou, Puzhong, Changzhi, Yuncheng, Luliang	
Shaanxi	Xi'an, Baoji, Hanzhong	M15, M25, M85, M100
Zhejiang	Quzhou, Hangzhou, Huzhou, Jiaxing, Taizhou, Jinhua	M15, M30
Guizhou	Guiyang, Qiannan, Qianxi, and Tongren	M15, M85, M100
Gansu	Pingliang, Lanzhou	M85, M100

The Chinese government has been pursuing methanol as an energy-security option because of the abundance of coal in China (and the relative scarcity of petroleum and natural gas). China has the world's third largest proven reserves of coal, at 114.5 billion tons, or 13.3% of the global total at the end of 2010 [11]. Demonstration programs in the provinces have been conducted as a pathway for eventually developing national standards for methanol-fueled vehicles. However, developing these national standards is a challenge, in part because of the misalignment of incentives among different Chinese provinces.

While the model being used for this thesis, the MIT Economic Projection and Policy Analysis (EPPA) model, does not have China disaggregated into its different provinces, and thus does not allow for the analysis of impacts at the provincial level, outlining the existing policy scene in China is important for two reasons. First, it explains the limitations of this study, since the reported results will be applied to the country as a whole, and not specifically to the regions where methanol vehicles are likely to penetrate as a result of local policies. Second, it provides an opportunity for further refinement of the EPPA model through the disaggregation of China into its different regions depending on different factors, such as variations in average income levels of different regions, urban and rural distinctions, and differences in existing natural resources in different provinces.

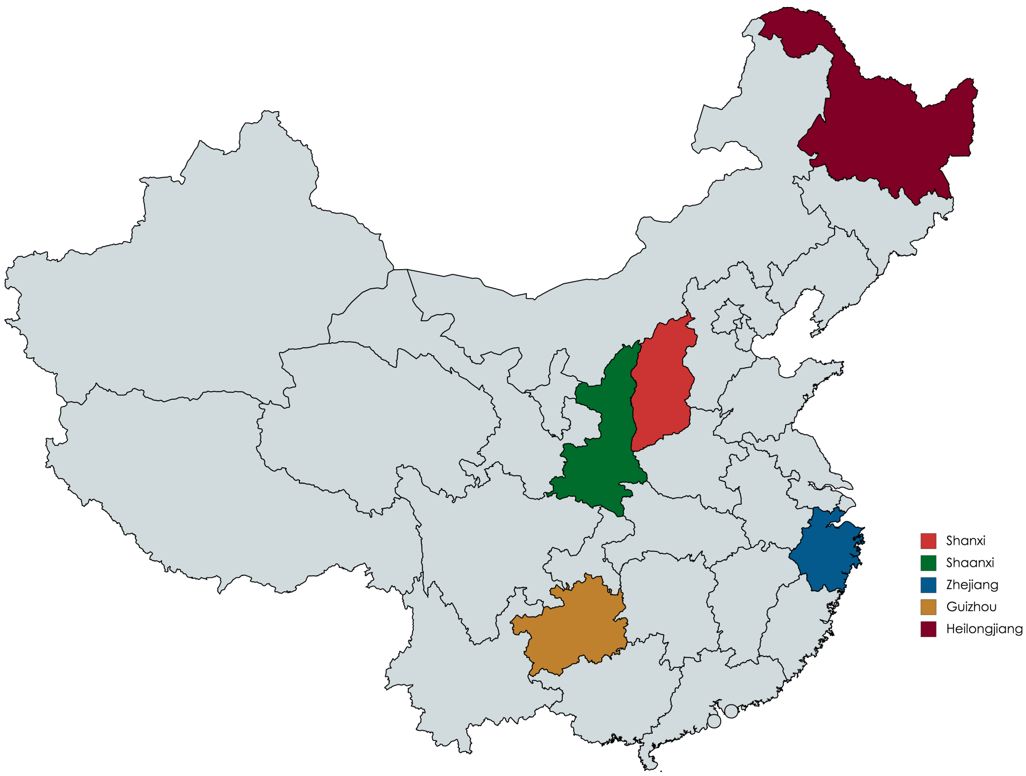


Figure 2-1: Chinese provinces leading the methanol transportation fuel market (created with mapchart.net)

2.2 Motivation

As the Chinese economy grows and energy consumption grows, issues of energy security, air quality, and climate change impacts become more urgent. On-road transportation is a major source of emissions in China and is undergoing major growth. Vehicle purchases in China increased from 2 million vehicles per year in 2002 to 13.6 million vehicles per year in 2009. Figure 2-2 shows that in 2014, China was responsible for 10% of global carbon dioxide emissions in the transport sector, following the United States and the European Union. In 2010, road transport contributed 5.1% of

China's carbon dioxide emissions, 46% of which were due to light duty vehicles [39]. This percentage is likely to grow with the economic growth in the country and the rise of vehicle ownership.

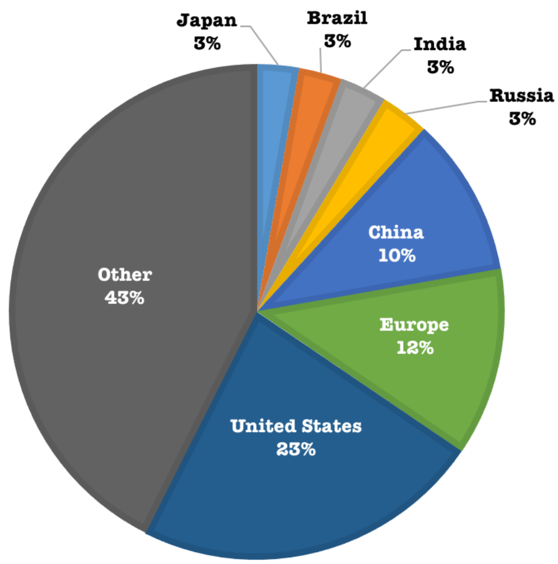


Figure 2-2: Carbon dioxide emissions from the transport sector in 2014 [56]

From an energy security perspective, the preference is relying on local resources and reducing crude oil imports to avoid being reliant on foreign countries or susceptible to blockades. From an economic perspective, governments are focused on creating local industries, providing jobs for citizens by making use of local resources, and reducing trade imbalances. However, given that coal is the most abundantly available local energy resource in China, achieving these energy security and economic goals comes at the expense of increasing emissions and opposing progress towards achieving climate change goals.

2.3 Thesis Goals

The major pathway that is considered for this thesis is the use of methanol in dedicated methanol vehicles in the form of M85 (85% methanol, remaining gasoline blend) and M100 (100% methanol). The advantage of this pathway is the lack of need for an entirely new fueling infrastructure. Rather, modest modifications to the existing fueling infrastructure enable the handling of the new chemical properties of methanol. The main questions this thesis attempts to answer are:

1. What market shares will methanol vehicles and electric vehicles take up in China from now until 2050?
2. What impact will the penetration of methanol vehicles and electric vehicles have on greenhouse gas, carbon monoxide, hydrocarbon, and nitrogen oxide (NOx) emissions?
3. What impact will existing policies set by the Chinese central and local governments on advancing the state of methanol and electric vehicles have throughout the next 35 years?
4. What impact will setting a carbon cap have on the transportation sector in China?

Chapter 3

Methanol Usage in Transportation

3.1 Methanol as a Fuel

Any hydrocarbon source, such as coal, petroleum, biomass, and coke, can be converted to methanol. At a large scale level, methanol (CH_3OH) can be made from both natural gas and from coal. It can also be made renewably from carbon dioxide and hydrogen, resulting in zero carbon emissions. The carbon dioxide to methanol process is based on technology developed by Carbon Recycling International (CRI). In 2012, the first commercial plant producing methanol by reducing carbon dioxide using hydrogen made from water produced using electrolysis from renewable sources opened in Iceland, called the George Olah facility. This facility provides experience in the area to help improve plant economics and allow for building larger plants that would benefit from economies of scale [45]. Moreover, in Europe, the Netherlands has an operating bio-methanol plant, producing methanol from glycerol produced from vegetable oils at a production rate of 550 metric tons/day. Sweden also has plans for developing a 300 metric tons/day bio-methanol plant [74]. Figure 3-1 displays the current pathway for methanol production from coal and shows the potential future state in which methanol is produced using the hydrogenative recycling of carbon dioxide from industrial exhaust or even from air itself. Methanol can be used directly as a fuel or converted to other fuel forms like gasoline, ethanol, and dimethyl-ether, and is used heavily in the chemical industry for the production of acetic acid and formaldehyde.

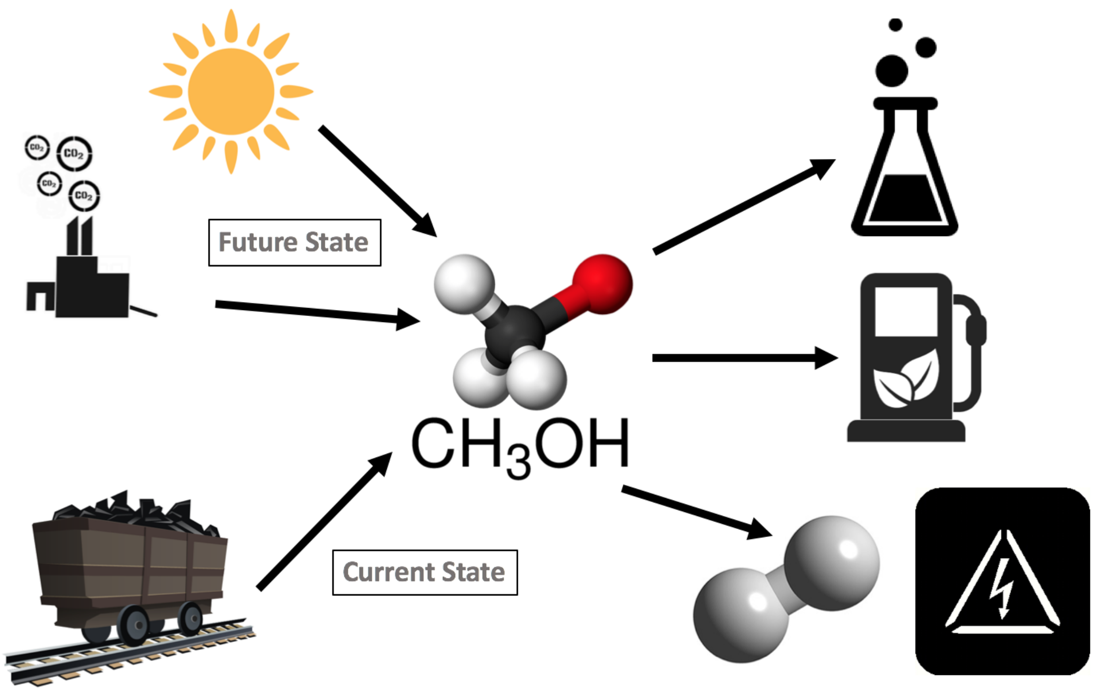


Figure 3-1: Methanol economy

This chapter will delve into the details of using methanol in transportation, from detailing out the properties of methanol as a fuel to outlining the economics of methanol-fueled vehicles and the resulting environmental impacts of their usage. The key takeaways are that low methanol proportions of 5-15% can be used directly with conventional gasoline vehicles. Higher proportions and specifically methanol proportions greater than 85% require dedicated methanol vehicles or the retrofit of existing gasoline vehicle engines. However, retrofits are inexpensive at around USD 200. Moreover, infrastructure costs are small relative to those associated with Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), or electric vehicles. The downside of methanol usage is that it is no better for the environment than petroleum fuels, indeed if the methanol is made from coal, its greenhouse gas emissions are higher than those associated with conventional gasoline.

3.1.1 Methanol Production Technologies

Methanol can be produced from a variety of different feedstocks; these include fossil fuels like coal and natural gas, renewable natural gas from animal waste or landfill gas, or cellulosic biomass such as switch-grass, willow, crop residues, and forest residues. Methanol can also be synthesized using renewable energy by reacting carbon monoxide or carbon dioxide with hydrogen. In China, the two leading options for obtaining methanol are producing it from locally available coal or importing it from countries in the Middle East which are producing methanol in Mega Methanol plants, through the shipment of methanol in tankers. Mega Methanol plants (with capacities of at least 1 million tonnes of methanol per year) are found in countries that have large reserves of natural gas, and are currently under operation in Qatar, Saudi Arabia, and Trinidad and Tobago [67]. Globally, methane from natural gas accounts for the majority of methanol production through the methane steam reforming process. Methanol is produced from natural gas in a series of reactions in which natural gas is first thermochemically converted to synthesis gas, followed by the catalytic conversion of the synthesis gas to methanol. Methanol can then be converted to gasoline, though not commonly done since it is less efficient and more costly, or to dimethyl ether which can be used to fuel modified diesel engines [1].

The process by which methanol can be produced from coal is simplified into two steps. Coal is first gasified to form synthesis gas, or syngas. Generally, gasification consists of three chemical reaction processes: pyrolysis, combustion and gasification. In pyrolysis, the volatile materials are released from coal. In combustion, oxygen is burned with the volatile gas generated from pyrolysis in an exothermic reaction. The generated heat is then supplied to the endothermic gasification reaction for converting the solid fuel to syngas. The syngas, mainly composed of hydrogen and carbon monoxide, is then converted to methanol over a catalyst. The steps can be described by the equations below [75][25]:

Coal gasification to form syngas

$$C + \tfrac{1}{2}O_2 \longrightarrow CO \quad \Delta H_r^o = -110.5 \text{ kJ/mol}$$

$$C + CO_2 \longrightarrow 2\,CO \quad \Delta H_r^o = +172.0 \text{ kJ/mol}$$

$$C + H_2O \longrightarrow CO + H_2 \quad \Delta H_r^o = +131.4 \text{ kJ/mol}$$

$$CO + \tfrac{1}{2}\,O_2 \longrightarrow CO_2 \quad \Delta H_r^o = -283.1 \text{ kJ/mol}$$

$$CO + H_2O \longrightarrow CO_2 + H_2 \quad \Delta H_r^o = -41.0 \text{ kJ/mol}$$

Methanol synthesis

$$CO + 2\,H_2 \xrightleftharpoons{CuO-ZnO} CH_3OH \quad \Delta H_r^o = -90.79 \text{ kJ/mol}$$

$$CO_2 + 3\,H_2 \xrightleftharpoons{CuO-ZnO} CH_3OH + H_2O \quad \Delta H_r^o = -49.50 \text{ kJ/mol}$$

As for the production of methanol from natural gas, it can be described by the reactions shown below [41]. Methane can be converted to syngas through either steam reforming or partial oxidation, with steam reforming being the traditionally dominant route. In steam reforming, methane is first reformed to form syngas, part of the carbon monoxide formed reacts consequently with steam in a water gas shift reaction to form hydrogen and carbon dioxide. Steam reforming is highly endothermic, and therefore part of the natural gas feedstock is burned to obtain the heat supplied to the system [67]. With partial oxidation, the process is exothermic. In the end, methanol is formed in the synthesis stage.

It is worth noting that the conversions of hydrogen, carbon monoxide, and carbon dioxide can be estimated by solving for the equilibrium reaction expressions of the steam reforming expression and the methanol synthesis expression. This allows one to determine the carbon dioxide emissions associated with the methanol production process from either coal or natural gas, the details of which are described in Section 3.4.1.

Steam reforming

$$\text{Steam reforming: } 2\,CH_4 + 2\,H_2O \xrightleftharpoons{Ni\,/\,800\,^\circ C} 2\,CO + 6\,H_2 \quad \Delta H_r^o = +205.43 \text{ kJ/mol}$$

$$\text{Water gas shift reaction: } CO + H_2O \xrightleftharpoons{Ni\,/\,800\,^\circ C} CO_2 + H_2 \quad \Delta H_r^o = -41 \text{ kJ/mol}$$

Partial Oxidation

$$CH_4 + \tfrac{1}{2}\,O_2 \rightleftharpoons CO + 2\,H_2 \quad \Delta H_r^o = -35.98 \text{ kJ/mol}$$

$$CO + \tfrac{1}{2}\,O_2 \rightleftharpoons CO_2 \quad \Delta H_r^o = -282.84 \text{ kJ/mol}$$

$$H_2 + \frac{1}{2} O_2 \rightleftharpoons H_2O \quad \Delta H_r^o = \text{-241.42 kJ/mol}$$

Methanol synthesis

$$CO + 2\,H_2 \xrightleftharpoons{CuO-ZnO} CH_3OH \quad \Delta H_r^o = \text{-90.79 kJ/mol}$$

$$CO_2 + 3\,H_2 \xrightleftharpoons{CuO-ZnO} CH_3OH + H_2O \quad \Delta H_r^o = \text{-49.50 kJ/mol}$$

Overall

$$CO_2 + CO + 5\,H_2 \xrightarrow{[Cu-Zn]} 2\,CH_3OH + H_2O + \text{heat}$$

Methanol (CH_3OH) is a simple chemical and has approximately half the energy density as gasoline and is a stable liquid at ambient conditions [16]. This means that 2 liters of methanol contains the same energy as 1 liter of gasoline. The lower energy density of methanol means that a larger tank is needed to cover the same range as when gasoline is used. However, when engines are optimized for methanol, efficiency improvements can be achieved to partially offset the decrease in miles per gallon from the lower energy density of methanol [13]. This is due to methanol being an alcohol fuel and having a higher octane rating, with a blending Research Octane Number (RON) of 127-136 and a blending Motor Octane Number (MON) of 99-104 [10]. The higher octane rating means that the fuel/air mixture can be compressed to a smaller volume before it is ignited. This allows the engine to run at a higher compression ratio (10-11 to 1 against 8-9 to 1 for gasoline engines), leading to a higher engine efficiency when used in engines optimized for alcohols [67]. However, this efficiency increase is partially negated when methanol is used in flex-fuel vehicles which use low compression engines suitable for conventional gasoline.

3.1.2 Methanol Fuel Economics

In China, the main reason consumers use methanol in the place of gasoline is because in certain instances, depending on methanol and gasoline prices and applied taxes, methanol results in lower costs to the consumer compared to gasoline. There is no need for subsidies or handouts for making the choice economical. To better understand the trends, a comparison of the fuel costs in Yuan/mile were calculated for both gasoline and methanol, in both existing engines and alcohol engines[1], for the purpose of comparison. This analysis takes into account the fact that 1 gallon of methanol has 49% of the energy of one gallon of gasoline [16]. Additionally, the analysis takes into account the taxes applied on gasoline in China between the years 2007 and 2014. Thus far, the Chinese government has not taxed methanol, and therefore the prices of methanol exclude taxes.

The results are shown in Table 3.1. Overall, gasoline fuel costs have been increasing due to the increase in the average gasoline price in China. Methanol fuel costs are on a decreasing trend due to the overall decrease in methanol prices in China for the chosen time period and the increase in fuel economy in new cars, with two sharp price decreases existing in 2009 and 2010. The prices of gasoline and methanol in Yuan/Liter are shown in Table 3.2. Fuel costs in recent years show the competitiveness of methanol with gasoline when compared on a Yuan per mile basis, with methanol costing significantly less on a per mile basis than gasoline.

Table 3.1: Fuel costs for new Light Duty Vehicles (LDVs) (gasoline taxes applied in China are included in this analysis)

Year	**New LDVs Fuel Cost (Yuan/mile)**		
	Gasoline	**Methanol - Existing Engine**	**Methanol - Alcohol Engine**
2007	0.51	0.55	0.52
2008	0.59	0.52	0.49
2009	0.61	0.27	0.25
2010	0.68	0.34	0.32
2011	0.77	0.44	0.42
2012	0.74	0.41	0.39
2013	0.71	0.42	0.40
2014	0.69	0.41	0.39

[1] Alcohol engines are assumed to result in a 5% engine efficiency improvement.

Table 3.2: Methanol and gasoline prices used for obtaining the new LDV fuel costs [47][69]

Year	Prices (Yuan/Liter)	
	Gasoline	**Methanol**
2007	4.24	2.23
2008	4.92	2.12
2009	5.30	1.14
2010	6.07	1.49
2011	6.72	1.88
2012	6.90	1.87
2013	6.76	1.96
2014	6.66	1.92

Figure 3-2 displays the variation in prices for energy commodities between 2009 to early 2016. As can be seen from the graph, gasoline prices are higher in China compared to the United States, partially explaining why the potential for using methanol from coal as a transportation fuel is greater in China than in the United States. The chart shows that if there is no tax on methanol, methanol has been cheaper to the consumer than gasoline since about 2008. From available data for Chinese gasoline prices, one can observe that historical methanol and gasoline prices, reported in US Dollars/MMBTU of energy, in China have followed similar trends and fluctuations as gasoline prices in the United States.

In March 2013, China started a new fuel pricing system with a closer link to global prices of crude oil [70]. As can be seen from Figure 3-2, the prices of gasoline in China in 2015 and the first quarter of 2016 were still higher than that of the United States, but matched the downward trend experienced in the United States, displayed in green. Overall, gasoline price fluctuations have a great impact on the potential for using methanol as a transportation fuel, particularly in 2009 due to the recession and in the past few years due to increases in crude oil supply. This, as a result, leads to a lack of stability in the demand for methanol for its use as a transportation fuel where the demand is more elastic compared to its use in the chemical industry sector where the demand is more inelastic.

Figure 3-2 also shows that there are strong fluctuations in methanol sales prices even though the price of producing methanol from coal is approximately constant since the majority of the cost is attributed to capital costs. One explanation is that the demand for methanol varies with the economic cycle, just as the demand for gasoline and oil prices fluctuate with the economic cycle. Since methanol is considered a substitute for gasoline, its price follows that of gasoline across economic cycles. Moreover, the prices of gasoline shown for China and the US for the last two quarters show that China has maintained a level of oil price even though the price of oil has dropped.

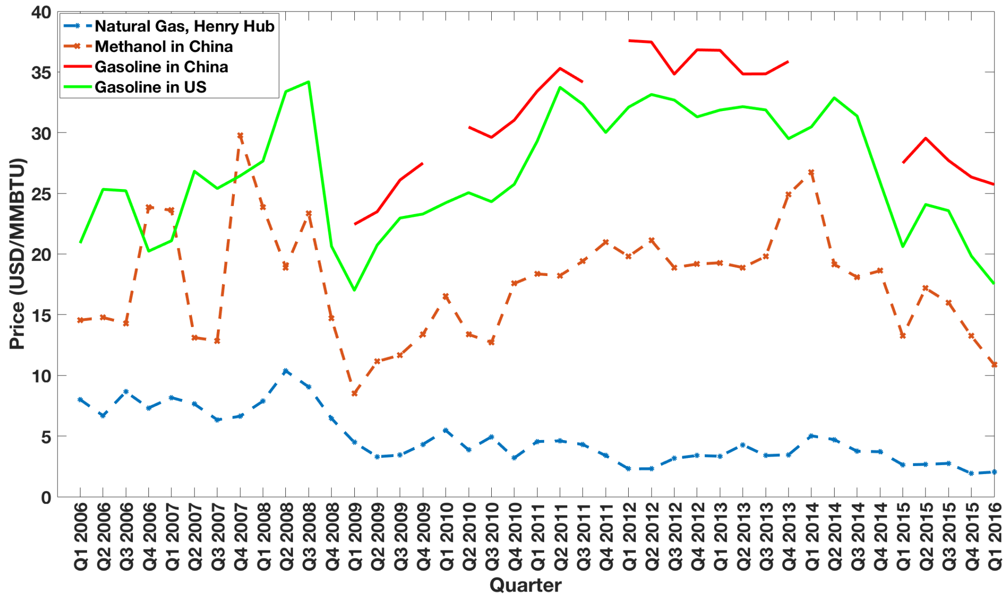


Figure 3-2: Variation in energy commodity prices. Data from China National Bureau of Statistics, Bloomberg, and EIA and converted at prevailing exchange rates (gaps in the graph are due to lack of available data) [3] [70] [47]

3.2 Methanol Vehicle Options

Several Chinese automakers have been involved in the mass production of methanol capable vehicles. These include the FAW Group, Shanghai Huapu, Geely Group, Chery, Chang'an, Shanghai Maple Automobile, and SAIC [38]. In February 2016, Geely Auto, the first automaker in China conducting research and development work on methanol vehicles, developed methanol vehicles that ran on pure methanol and set them on a trial in Iceland after having been tested in the Shanghai, Shanxi, and Guizhou provinces [54]. There are various possibilities through which methanol can be used in vehicles. The following list describes these possibilities:

1. Existing gasoline vehicle being run on up to 15% methanol blends. This can increase fuel efficiency by one to two percent [44] without engine modifications because engine peak power is increased due to evaporative cooling. This suggests that even though the theoretical energy content of methanol is about 50% of typical gasoline on a volume basis, the gasoline and methanol blend performs as though methanol contains energy equivalence of about 60% of typical gasoline

energy content. However, because of the disruption of the hydrogen bonding in methanol when it is mixed with a hydrocarbon, the mixture of gasoline and methanol has a high vapour pressure, which can cause stalling, engine hesitation, and difficulties with hot starts [15]. The high vapor pressure also increases evaporative emissions and photo-chemical smog.

2. Flex fuel vehicles in which two separate tanks are used for methanol and gasoline, such as M85 vehicles. In this case, the fuel efficiency of the vehicles was comparable to that of gasoline vehicles on a heating value basis [12].

3. Dedicated methanol (M85 or M100) vehicles with modified engines that are designed to make use of methanol's high octane number, low heat of combustion, and high heat of vaporization. This allows higher compression ratios, a faster and more stable combustion and efficiency gains of up to 20% [15][79]. The increase in efficiency allows for an increase in the number of miles travelled per unit of energy of methanol compared to gasoline.

3.2.1 History and Policy of Methanol Vehicles

The use of methanol as a transportation fuel was increasing within the United States in the 1980s and 1990s. Flex-fuel vehicles running on neat or near-neat methanol (M85) during that period demonstrated the potential of methanol as a cleaner burning fuel and its technical soundness. However, in the mid-90s, the demand for methanol in the United States decreased due to a drop in the price of gasoline which made methanol noncompetitive, coupled with the lack of subsidies for methanol, which hurt adoption because of the availability of subsidies for ethanol [67] [57]. Thus within the United States, methanol has failed in gaining market traction as an alternative fuel, highlighting the challenges associated with achieving large scale market penetration of alternative fuel and vehicle technologies in the transportation context.

Methanol vehicles were first introduced in China in 1995 with the aid of the Sino-

American Scientific Collaboration. Methanol usage in transportation was advocated by the Chinese government until 2008. After 2008, national methanol projects in China were discontinued but provincial initiatives took their place. In 2009, the Chinese government announced a national standard for M85 and M100. However, a national standard for M15 currently does not exist. This is to deter the acceptance of nation-wide methanol blending. Since about 2009, methanol has been economically competitive with gasoline in China and does not require engine changes when used in small quantities such as in the case of M15. One can speculate as to the various reasons that have stood in the way of the implementation of a national standard for M15. The first reason could be that methanol promoters fear M15 will grab the whole methanol fuel market, and thus preventing M85 or M100 from succeeding. The second reason could be because car manufacturers do not want negative performance impacts of their cars due to the usage of M15 in place of gasoline. The third reason could be that the Chinese government wants to avoid promoting methanol due to its greenhouse gas and evaporative emissions, and it requiring additional capital costs due to requiring the building of additional methanol production facilities. Finally, both the Chinese oil companies as well as the provinces where oil businesses provide jobs and profits have incentives to dampen the reach of methanol since it substitutes for petroleum fuels and lowers the market reach of the oil companies and as a result, reduces the number of available jobs in that industry.

However, the lack of an official M15 standard has not deterred private gasoline stations in China from illegally blending gasoline with methanol without the knowledge of customers and directly profiting as a result because of selling the illegal blend at the same price as gasoline [80]. This defrauds the customers since methanol has a lower energy density than gasoline. In fact, methanol is blended in 26 of China's 31 provinces, with the deepest penetration being in Shanxi province, the center of the coal industry in China.

3.2.2 Public Perception and Safety

In the United States, methanol's reputation has been associated with being a toxic or dangerous fuel, particularly due to its association with contamination incidents that involved Methyl Tertiary Butyl Ether (MTBE). MTBE is an additive to gasoline and in the United States, contaminated groundwater from leaks in tanks, resulting in an unpleasant taste in water [67]. Unlike MTBE, methanol is biodegradable in aerobic and anaerobic environments and has a half-life in ground and surface water of one to six days. However, one danger with M100 is that it burns invisibly [39]. Also, pure methanol lacks the volatility to start a cold engine. However, both issues are resolved when gasoline is added, forming M85 methanol blends. The addition of 15% gasoline to methanol also solves another concern regarding the high flammability of methanol. At standard temperature and pressure, the equilibrium air-fuel mixture formed from methanol vapour above the liquid in a tank is ignitable because of pure methanol's low vapour pressure. Adding 15% gasoline to the mixture moves the flammability limit temperatures to a safer range closer to that of gasoline vehicles [71].

3.2.3 Methanol Vehicle Economics

The extent to which methanol is used in powering a vehicle dictates changes in the economics of the vehicle relative to a conventional Internal Combustion Engine (ICE) vehicle. Currently, M15 methanol gasoline blends (consisting of 15% methanol) are used widely in present gasoline engine vehicles in China. These vehicles do not require additional costs to be able to run on methanol [7]. Flex fuel operation, in which the vehicle could run on either gasoline or on methanol (M100 or M85), would require an additional production vehicle cost or aftermarket cost ranging from $200 to $300 [1]. Table 3.3 shows the cost details associated with upgrading a gasoline vehicle and making it a methanol compatible vehicle. As can be seen from the table, the majority of the cost is attributed to the fuel pump and larger tank required because of the lower energy content in methanol relative to gasoline to provide the same range of operation. Moreover, modest changes to the materials used in the engine are required since methanol is an alcohol and is more corrosive than gasoline. A preventative method for reducing the corrosive effects of methanol is using corrosion inhibitor additives and specially formulated engine oils [12]. M100 or M85 would best be used in methanol-optimized cars with higher engine compression ratios, downsized engines, increased turbocharging and direct injection, resulting in an increased engine efficiency that would partially compensate for methanol's low energy density [39].

Table 3.3: Costs for converting a gasoline vehicle into a flex-fuel vehicle [12]

Component	**Total (in USD)**
Fuel sensor	20
Fuel system materials	50
Fuel pump/larger tank	120
Catalyst	–
Evaporative system	20
Total Estimated Costs	210

3.3 Methanol Distribution and Refueling Infrastructure

The refueling infrastructure that methanol requires is modest, mainly because methanol is a liquid fuel that is easily transported using inexpensive tanks, resulting in an inexpensive distribution process. Additionally, methanol's refueling time is almost the same as that of gasoline. Modest changes to the fueling infrastructure are needed since methanol is hygroscopic, but in most cases methanol fueling capacity could be added to existing retail gasoline outlets at modest cost. Extending the methanol distribution infrastructure in China would require the involvement of independent fuel distributors, methanol suppliers, and oil companies.

When comparing capital investments for retail service stations, methanol retail outlets cost a small fraction of those required for Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), and hydrogen. CNG stations for example cost about ten times the cost of a methanol station because of the high costs associated with the needed compressors. LNG stations, although having lower capital costs compared to CNG stations because of not requiring compressors, still have significant capital costs because of the need for super-insulated storage tanks [57]. Moreover, the extent to which existing refueling stations would need to be refurbished to include a methanol pump for refueling dedicated methanol vehicles would depend on the penetration of methanol vehicles encouraging infrastructure development as well as national or provincial policies encouraging the development of the stations. In Shanxi, more than 1,200 service stations offer methanol blends [31]. Still, investors are hesitant to make the capital investments for building the infrastructure due to the relatively small size of the fleet of methanol fueled vehicles. Governmental support either through instating a methanol mandate or providing stations subsidies can speed up the rate of infrastructure penetration.

3.3.1 Station Description

The components required for a methanol fueling station include a double-walled fuel storage tank to avoid leakages into underground water sources (or of groundwater into the methanol tank), particularly if the storage tank is stored underground, a fuel dispenser, a vapor recovery system that recovers emitted vapors during vehicle refueling and the filling of storage tanks, and associated pipes and fittings. Moreover, material changes are required to ensure that the materials used for the station are compatible with the chemical properties of methanol to avoid the dissolution of metals and leaching of plasticizers considering that methanol is more corrosive than its gasoline counterpart. With storage tanks for example, acceptable materials include carbon steel (which requires fiberglass coating for corrosion prevention), stainless steel (which is expensive), or fiberglass [73]. Two scenarios exist for developing methanol refueling stations. The first is adding methanol capacity to existing stations, and the second is displacing a fraction of the existing gasoline storage capacity with methanol.

The detailed cost estimates of the two options are found in Appendix D. As expected, adding methanol capacity to stations is more expensive, at a range of about $79,000 to $89,000 for 10,000 gallons of capacity, than displacing a fraction of the existing gasoline storage capacity with methanol, at a range of about $27,000 to $44,000.

3.4 Environmental Impacts of Methanol Fuel

This section explains the environmental impacts associated with the use of methanol fuel, focusing on the well-to-wheel greenhouse gas emissions, and changes in hydrocarbon, carbon monoxide, and nitrogen oxide emissions associated with the switch from gasoline to methanol as a fuel.

3.4.1 Well-to-Wheel Greenhouse Gas Emissions

Analyzing the well-to-wheel (WTW) greenhouse gas (GHG) emissions of various fuels is useful for estimating the potential advantages or disadvantages that can result from shifting to an alternative fuel form, having a more complete understanding of emissions since WTW analyses take into account the entire life cycle of the fuel, and examining areas of potential target by industry and academia for reducing emissions. With the chemical structure CH_3OH, methanol is the simplest alcohol and has the lowest carbon content and highest hydrogen content amongst liquid fuels. Figure 3-3 displays the WTW greenhouse gas emissions for various fuel and drivetrain combinations [28]. Methanol has a greater amount of WTW GHG emissions per kilometer of distance travelled compared to gasoline, with methanol produced from coal leading to greater overall greenhouse gas emissions compared to methanol produced from natural gas.

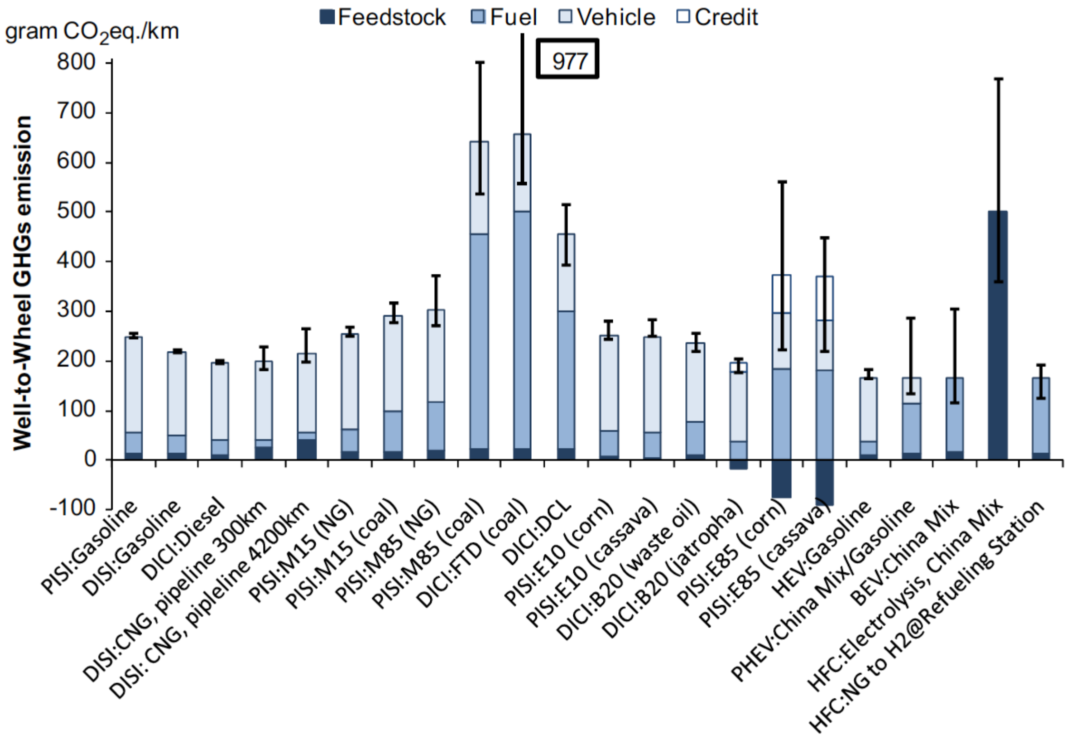


Figure 3-3: Well-to-wheel greenhouse gas emissions for various alternative fuels and gasoline [28]

In Figure 3-3[2], the dark blue bars represent feedstock excavation and the transport of feedstock to fuel conversion facilities. The medium blue bars represent the stage for fuel conversion and delivery. Together, the dark and medium blue bars constitute the well to tank step. The light blue bars represent the tank to wheel step[3] [28].

As can be seen from Figure 3-3, on a gram of carbon dioxide equivalent per kilometer basis, methanol produced from natural gas has slightly higher emissions than gasoline used in conventional vehicles. Moreover, the well to wheel greenhouse gas emissions associated with using methanol made from coal in an existing engine is

[2]Note that Figure 3-3 overstates total greenhouse gas emissions for synthetic fuels in the case where synthetic plants export the electricity produced on-site, as this can displace other fossil fuel electricity. In Reference [28], the energy conversion efficiency used for methanol from natural gas was 57% and the energy conversion efficiency used for methanol from coal was 38%.

[3]With biofuels, the carbon stored in the biomass is treated as carbon dioxide credit that is subtracted from the greenhouse gas emissions of the feedstock stage. This is indicated in the diagram using a white bar, in which the bottom boundary of the white bar represents the total greenhouse gas emissions

almost three times higher than existing gasoline run vehicles. This is assuming that the plant is only making dedicated methanol. One way to reduce this value is by combining methanol production with electricity generation, thereby increasing plant efficiency, corresponding to lower greenhouse gas emissions per unit of fuel energy produced [71]. Combining methanol production with electricity generation can lead to efficiency gains of up to about 25%[4]. For determining the WTW greenhouse gas emissions for electricity and hydrogen produced using electrolysis, the Chinese electricity supply mix in 2010 was used in Figure 3-3. In 2010, 76.8% of the electricity in China was supplied by burning coal, followed by 16.2% supplied through hydro, 1.7% supplied through natural gas and the remaining through residual oil, biomass, wind, and others [28]. Appendix A.3.2 goes into the details of obtaining the overall emissions values.

To summarize, methanol and gasoline vehicles have similar GHG emissions per kilometer traveled. However, methanol production emits more GHG than gasoline production. GHG emissions during methanol production are very large if one starts with coal as the feedstock, making coal based methanol a very undesirable fuel from a GHG point of view.

3.4.2 Carbon Monoxide Emissions

Methanol use also impacts carbon monoxide emissions. Carbon monoxide is produced as a result of incomplete combustion due to either low temperatures and pressures or shortages of oxygen during the combustion process. Whether or not methanol results in an increase or decrease of carbon dioxide emissions depends mostly on how the vehicle engines are run. If the engines are run with high air/fuel ratios to maximize efficiency, carbon monoxide emissions are expected to be lower compared to gasoline vehicles. If the vehicles are run with air/fuel rations at stoichiometric levels, as with gasoline, carbon monoxide emissions should be similar to levels achieved by

[4]In this case, instead of vehicles using coal methanol emitting 3 times as much greenhouse gases as gasoline, in an optimal case it might be less than 2 times.

gasoline vehicles with two possible variations. One variation is that carbon monoxide could even be higher if the vehicle faces starting problems due to the use of methanol blends [78]. Another variation is that the carbon monoxide emissions could be lower, because methanol has a simpler molecular composition with no carbon-carbon bonds and therefore undergoes simpler reaction kinetics compared to gasoline [15]. A study conducted by the Beijing Institute of Technology in 2011 shows that carbon monoxide emissions from methanol-fueled vehicles during the driving process were significantly lower than those from gasoline-fueled vehicles, at approximately 0.8 g/km and 1.25 g/km respectively [30].

3.4.3 Hydrocarbon Emissions

The effect of using methanol in gasoline blends on hydrocarbon emissions is not easily determined because the constituents of the unburned fuel are different for methanol compared to gasoline. There exists evidence that use of methanol blends can decrease hydrocarbon emissions slightly, but the decrease is minimal compared to that of carbon monoxide emissions [15]. With dedicated methanol vehicles, tests measuring emissions of hydrocarbons yielded different results depending on whether hot start or cold start tests were used. During hot start emissions tests, the emissions of hydrocarbons were lower for dedicated methanol vehicles compared to gasoline vehicles. The opposite was true during cold start tests because of the longer warm-up time period [15]. Hydrocarbon compounds have varying levels of reactivity in the atmosphere. Methanol is low on the reactivity scale compared to other compounds found in gasoline. The rate constant for reaction with hydroxyl radical of methanol is $0.148*10^{-4}$ (1/ppm)(1/min) compared to $4.9*10^{-4}$ (1/ppm)(1/min) for trimethyl benzene[5] [55].

The lower reactivity of methanol exhaust emissions results in less ozone generation, which is important in the case of China where major cities suffer from extreme

[5]Since trimethyl benzene has about 2 times the heating value of methanol, less trimethyl benzene will be emitted. If one corrects for this difference, the rate constants differ by a factor of about 16.6

amounts of smog created due to emissions of reactive hydrocarbons. According to the California Air Resources Board (CARB), the ozone forming reactivity of methanol, a measure of the potential to form smog, is 41% of gasoline emissions [78]. Even though methanol emissions may be the same quantity as gasoline emissions from a car's tailpipe, the reactivity of the emissions in the atmosphere is less[6]. Therefore, for a given amount of emissions, less ozone is formed. However, this reduction also depends on the adequate control of formaldehyde emissions, which are considerable when technologies for controlling formaldehyde emissions are not used. Generally, the evaporative emissions of methanol vehicles vary greatly depending on the type of vehicle used. If the vehicle used is a dedicated methanol vehicle, then the evaporative hydrocarbon emissions are lower because of the low vapor pressure of methanol. In cases where flex-fuel vehicles are used, the vapor pressure and resulting evaporative emissions vary greatly because the mixture in the tank can vary greatly from being filled completely with gasoline to being filled completely with methanol, and anything in between [55]. Finally, the extent to which switching to methanol from gasoline will result in a reduction in smog will depend on the atmospheric conditions in the area. Ozone formation is limited by nitrogen oxides in areas with high concentrations of reactive hydrocarbons relative to nitrogen oxides. In these areas, the benefits obtained by the lower hydrocarbon emissions of methanol will not be realized in smog reduction [78]. In summary, methanol poses somewhat different hydrocarbon emission challenges than gasoline, but overall the smog due to hydrocarbon emissions are expected to modestly improve if methanol replaces gasoline.

3.4.4 Nitrogen Oxide Emissions

The usage of methanol blends results in varying impacts with regards to nitrogen oxide emissions depending on the vehicle in which it is used and the operation of the vehicle. In an unmodified vehicle operating at or near stoichiometric conditions, methanol blends have resulted in a decrease in nitrogen oxide emissions because of the

[6]Given that almost twice as much methanol is used to travel the same distance as gasoline, this emissions reduction is reduced to half.

lower combustion temperature of methanol. This is because the reaction producing NOx from oxygen and nitrogen is an endothermic reaction that moves forward at a greater rate at higher temperatures. However, for vehicles operating fuel rich, the usage of methanol blends have resulted in an increase in NOx emissions. In dedicated methanol vehicles, the NOx emissions have been lower [15]. Reports from Shanxi in China mention a 20% decrease in CO, NOx, and benzene emissions and a 70% reduction in particulate matter. However, there was also an increase in formaldehyde associated with the switch to methanol, specially at cold starts [31]. Another study conducted by the Beijing Institute of Technology found that M15 blends reduced Volatile Organic Compound and Carbon Monoxide emissions by 10 to 15%, and that particulate matter emissions in the vehicle exhaust could be reduced by over 70% [24]. Researchers at Ghent University report reductions of exhaust NOx levels of 5 to 10 g/kWh in gasoline engines they have converted to allow for operation on alcohol [79].

3.5 Trends in Technology Development

Existing technology involves the use of methanol in Internal Combustion Engines. Future trends are moving towards the use of methanol in fuel cell vehicles or as a fuel for electric power generation. An ideal renewable future would be the case in which methanol is produced from hydrogen produced from water electrolysis using solar energy and carbon dioxide from the atmosphere. The usage of methanol in fuel cell vehicles is attractive because of its fit in terms of fuel processor mass/volume and overall thermal efficiency [74]. It would also overcome the difficulty of achieving massive scale of hydrogen refueling infrastructure. Methanol has the potential of acting as an alternative energy carrier for fuel cells and has modest refueling infrastructure requirements.

In addition to the use of methanol in light duty vehicles, another route for utilizing methanol is by dehydrating it into Dimethyl Ether (DME) via catalytic dehydration where two molecules of methane react to form one molecule of DME and one molecule of water. Dimethyl ether has high potential as a substitute for diesel in heavy duty trucks due to its cost effectiveness, high cetane number, and requiring modest changes to the diesel base engine [34]. It is also easy to store and transport as pressurized storage tanks similar to ones used for propane handling can be used for its distribution and storage. In terms of stations, costs are modest and similar to costs of Liquefied Petroleum Gas (LPG) filling stations. Finally, it is much cleaner burning than its diesel counterpart and eliminates the need for diesel particulate filters [34]. However, use of DME requires changing the fuel tank and fuel injection system on the truck.

Chapter 4

EPPA: A Computable General Equilibrium Model

This chapter provides a background on the model used in this thesis, the Economic Projection and Policy Analysis (EPPA) model which has been developed throughout the years at MIT. It first provides a background on Computable General Equilibrium (CGE) models, then dives into the details of the EPPA model itself, and ends by describing how household transportation is represented in the model.

4.1 Background on CGE Modelling

The use of Computable General Equilibrium (CGE) modelling is motivated by the need for efficient scare resource allocation within different sectors of the economy. One can view resource allocation as a trade-off issue, with the resource either exported to support imports, or set aside for domestic supply. This trade-off issue becomes more complex when we consider the various agents in an economy, such as households, firms, and the government. Moreover, imports and domestic supply of goods can either be consumed directly by households, which determines the welfare of the society, or they can be used as intermediate inputs, which can contribute to an increase in output. One way to determine an efficient allocation of the resource among various agents under given resource and technology constraints is using the price mechanism, which involves optimizing for the behaviour of economic agents under given constraints using market prices [33].

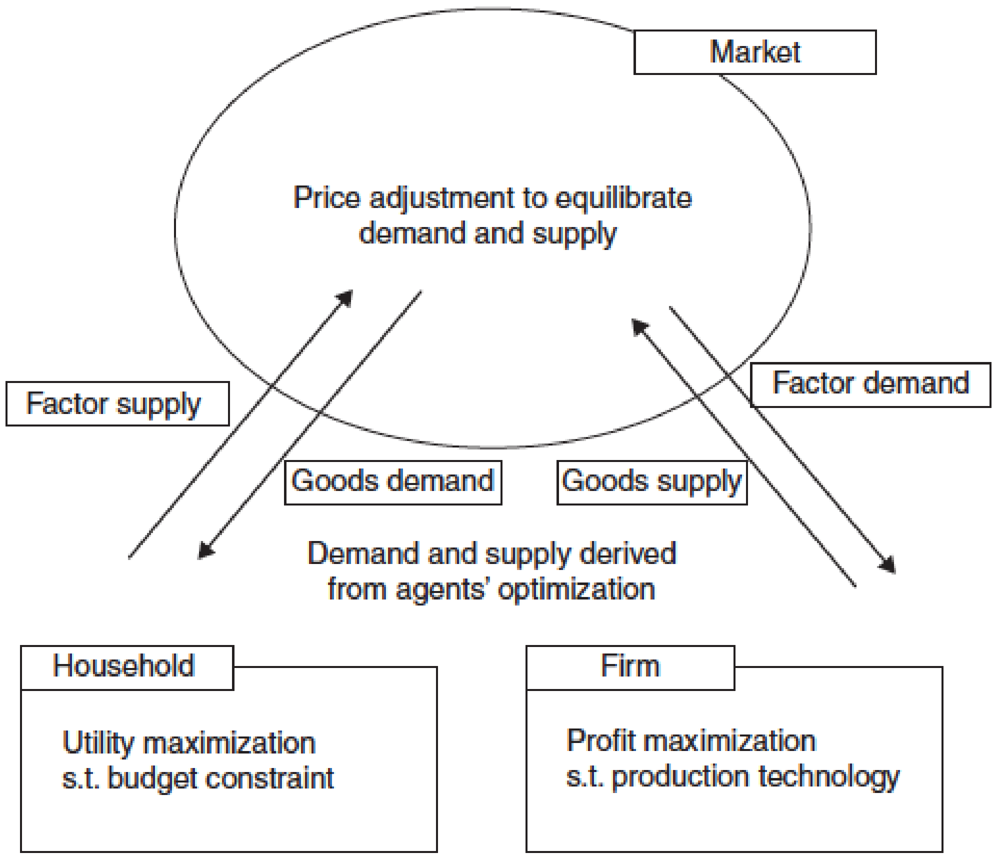


Figure 4-1: Representation of a simple economy [33]

Figure 4-1 displays a representation of a simple economy with one firm and one household. As can be seen, the behaviour of the agents is optimized by having households maximize their utility subject to their budget constraints and firms maximize their profit subject to technological constraints. The equilibrium prices are determined by adjusting the prices of goods and services until the supply for the good or service matches the demand for it. This price mechanism allows CGE models to depict economies in a quantitative manner. This brings forth the point that CGE models are not meant to be predictive models of future trends of technology penetration or agent expenditures. Rather, they are meant to provide the means for quantifying and evaluating the outcomes of setting various kinds of economic policies particularly related to resources allocation issues, thereby providing us with tangible rationale as to why certain policies are worth setting into place and why others are not best suited for addressing the goals the policy was intended to achieve. CGE models can be applied in analyzing policies in different sectors, including international trade policies, transport policies such as the impact of investing in a new highway, environmental policies such as introducing a new carbon tax, and labour policies such as deregulating the electric power sector [33].

4.1.1 Advantages and Disadvantages of CGE Models

CGE models have two main advantages compared to standard econometric models. First, they have relatively small data requirements, mostly using macroeconomic data obtained from input-output tables and trade statistics. This allows CGE models to analyze changes in countries and regions where data is not as widely available and is likely to undergo drastic changes, as is the case with China's fast growing economy. Second, CGE models allow for the incorporation of various sectors, which would require very large data sets in econometric models.

However, CGE models also have some shortcomings. All price calculations in the model are done relative to a base year, resulting in model outputs in the form of price indices. This means that the choice of base year has large implications in terms of the end model output, specially in the case where the reference year data are skewed in one direction due to a one-time event. Additionally, typical CGE models do not incorporate financial aspects or deal with the absolute prices in an economy. Thus, they do not deal with inflation or exchange rate policies as examples [33]. Finally, equilibrium models start by ignoring the time lags, frictions, and irrationality present in the real world. To make the model more realistic, those have to be added in, often in a rather ad hoc manner.

4.2 Background on the EPPA Model

The MIT Economic Projection and Policy Analysis (EPPA) model is a multi-region and multi-sector recursive dynamic Computable General Equilibrium (CGE) model of the global economy. The recursive approach suggests that production, consumption, saving, and investment are determined by current period prices. The model's foundation is based on a general equilibrium representation of the world economy, and the various details on resources and environmental implications have been added throughout the years of model development. The EPPA model uses data from worldwide input-output (IO) tables and trade database prepared by the Global Trade Analysis Project (GTAP) at Purdue University [33]. In addition to the two agents, households and producers, outlined in the previous section, EPPA also has a third type of agent in each region: the government. The household provides owned factors like capital, labor, and natural resources to producers and earns income for the services it provides. The income is used for daily consumption of goods and services, and the remnant is assigned to savings. Producers create goods and services from primary and intermediate inputs, and sell these goods and services to households, other producers or the government in exchange for money. Producers maximize profit level using the cost-minimizing mix of inputs for a given output level. Production functions are defined for each sector and describe the substitutability of different inputs into the sector. The government acts as a passive entity that collects taxes for government consumption [52].

Rather than predicting the mix of energy sources and uses in the future, the model provides us with the means to study the impacts of different policies and assessing the prospects for existing or new technologies under different scenarios and in different geographical locations. In this thesis, the methanol vehicle representation is added to the latest version of the model, EPPA 6. The intended purpose of using the EPPA model is capturing the long-term dynamics resulting from the interactions of different variables within the model, such as income changes, changes in commodity prices, and technology advancements. As a result, a limitation of the EPPA model is that it is not able to capture the short term market changes or incidences of sudden one-time events. EPPA 6 is solved at 5 year intervals from 2010 up to 2100. For this thesis, the model will be run until the year 2050 as uncertainties in policies, technology advancements, income levels and commodity price variations, and changes in transportation modes make results beyond 2050 quite uncertain. The base data for the model is based on the year 2007. The model outputs include Vehicle Miles Traveled (VMT) by different vehicle technologies, greenhouse gas emissions, and air pollutant emissions [52].

The EPPA model is composed of a static component and a dynamic component. Within the static component, three conditions must be satisfied. The first condition is the zero-profit condition in which marginal costs must equal marginal benefits. The second condition is the market clearing condition where the price level is determined based on market supply and demand. If the supply of a good or service is greater than the demand, then the price of the good or service equals zero. If the demand for the good or service is greater than the supply of the good or service, then the price will continue to increase until the market is clear. The third and final condition is the income balance condition, which requires that for each agent (including any government entities), the value of income must equal the returns to factor endowments and tax revenue. For a representative household, the total household income consists of net labor income, net capital income, resource rents, and the tax payment. Household expenditure is divided into purchasing utility and spending on government output. Government output is exogenously determined and is assumed to increase proportionally to GDP growth since the government is treated as a passive entity in EPPA [52]. As for the dynamic component of the model, it is determined by both exogenous and endogenous factors. The exogenous factors include projections for Gross Domestic Product (GDP) growth, labor growth, and autonomous energy efficiency improvement. The endogenous factors include savings, investment, and fossil fuel resource depletion [52]. Additionally, the *technology specific factor* is specified in the model which sets the time lags associated with the penetration of new technologies.

4.2.1 EPPA Regions and Sectors

EPPA 6 disaggregates the global economy into 18 regions. These regions are the United States, Canada, Mexico, Japan, Australia-New Zealand-Oceania, Europe, Eastern Europe, Russia, East Asia, South Korea, Indonesia, China, India, Brazil, Africa, Middle East, Latin America, and Rest of Asia [52]. Disaggregated regions in EPPA reflect the increasing importance of their economic activities and greenhouse gas emissions in the global economy. EPPA 6 also consists of 14 sectors; these include both energy and non-energy sectors. Table 4.1 describes these 14 sectors. The main sectors impacted by the addition of methanol vehicles are the transport and refined oil sectors. The transport sector is divided into household transport and non-household transport. Within the household transport block, choices are divided into own-supplied transport, in the form of an individual owning his/her own vehicle, and other forms of household transport. Moreover, gasoline is represented in EPPA through the refined oil sector since the refined oil sector is not disaggregated into the different oil products at this stage.

Table 4.1: EPPA 6 sectors [52]

EPPA6 Acronym	**Description**
CROP	Agriculture - crops
LIVE	Agriculture - livestock
FORS	Agriculture - forestry
FOOD	Food products
COAL	Coal
OIL	Crude Oil
ROIL	Refined Oil
GAS	Natural Gas
ELEC	Electricity
EINT	Energy-intensive Industries
OTHR	Other Industries
DWE	Ownership of dwellings
SERV	Services
TRAN	Transport

4.2.2 Capital Representation in EPPA

Since methanol production from coal is very capital intensive, it is valuable to understand how capital is represented in EPPA. In EPPA, savings are used as investments to meet the demand for capital goods. EPPA distinguishes between malleable and vintaged, or non-malleable, capital [63]. Malleable capital is mobile between sectors and technologies while non-malleable capital is not. EPPA tracks levels of vintages for non-malleable capital to represents the irreversibility of investments in a technology in specific periods of time. The portion of capital that is vintaged at each period is determined by the malleable capital in the previous period, the investment rate in capital, and the depreciation rate of capital. In EPPA 6, it is assumed that the physical productivity of installed vintage capital does not depreciate until it reaches the final vintage. This is because a physical plant in reality can produce the same level of output without the need for further investment [52]. On the other hand, the malleable portion of capital undergoes continuous depreciation and therefore takes into account the short term replacement of plant parts. This is valuable because it allows the substitution response in EPPA due to a change in relative prices to account for both long-run and short-run substitution possibilities. The long-run possibilities depend on the output level of malleable capital, allowing capital to move between sectors in pursuit of higher rates of return, and the short-run possibilities depend on the output level of vintage capital [26].

4.3 Household Transportation Representation in the EPPA Model

Various researchers have already conducted work on including new transportation technologies into the EPPA model. Examples include work on modelling the impacts of heavy duty liquefied natural gas vehicles [81], modelling the prospects for hydrogen powered transportation [72], examining the implications of natural gas light duty vehicles in the United States [42], and modelling the prospects for plug-in hybrid electric vehicles in the United States [40]. These works have, to some extent, a similar methodological foundation of adding a new vehicle technology into the model. This methodological foundation is described in Figure 4-2, which shows the representation of EPPA as a top-down economic model.

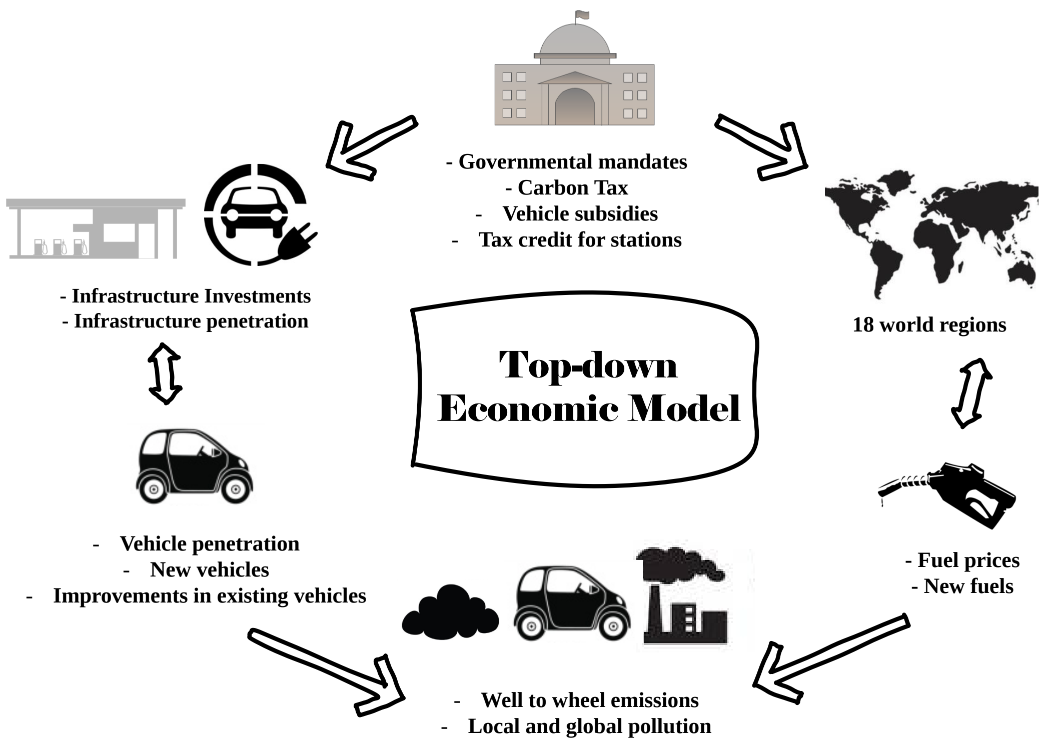


Figure 4-2: EPPA representation as a top-down economic model

Different governments across the world institute different policies to address their transportation challenges, with the balance of power between the private and the public sector differing in different countries. These different policies dictate investments in infrastructure supporting new vehicle technologies, which in turn impacts new vehicle penetration, since customers are unlikely to invest in new vehicles that lack supporting refueling stations, due to the inconveniences associated with them and the range anxiety that can result with technologies that have shorter range capabilities compared to existing technologies. On the fuel side, refined oil, being a homogeneous commodity that is easily and inexpensively transported across oceans, undergoes dramatic price fluctuations due to changes in supply and demand. In the absence of carbon prices, changes in refined oil prices determine the end customer's inclination to choose refined oil for powering their vehicle compared to alternative fuels. In addition, research is continuously paving the path for both the creation of new fuels and improvements in existing fuels. The same is true for the case of vehicles, where technological advancements are not only occurring with new technologies, but also with improving the efficiency of existing internal combustion engines as an example. Together, the types of fuels and vehicles used determine the well to wheel emissions, and the resulting levels of local and global pollution. Again, the cycle is repeated whereby the levels of local and global pollution spur governmental actions in terms of mandates, tax implementations, or subsidies to address the externalities at hand.

Chapter 5

Implementation of Methanol Transportation in the EPPA Model

Technological change can be represented in EPPA in several ways. The first way is the price-driven substitution of factor inputs like capital, labour, and fuel. The prices projected by the model determine an equilibrium point in which an agent can spend more on capital investment to increase efficiency for example in the place of fuel costs when fuel costs are high. The reverse is true when fuel costs are low. The second way to represent technological change in EPPA is through the specification of the Autonomous Energy Efficiency Improvement (AEEI) parameter, which specifies the magnitude of reduction of energy input for a given process due to technological advancements or process improvements [81]. The third way is the implementation of backstop technologies, which is the task completed for this thesis since we are specifying a completely new pathway for satisfying the transportation demand.

Methanol transportation can be added to the EPPA model through the addition of backstop technologies. Backstop technologies are new or alternative technologies to existing ones that are usually, but not necessarily, more expensive to operate at the base year [52]. Backstop technologies endogenously penetrate the market in cases where fossil fuel prices increase, making the backstop technology economically competitive, or when policy interventions dictate the penetration of the backstop technologies. The addition of the methanol transportation backstop technology can be broken down into the addition of three separately defined, new production blocks. These production blocks are: methanol-based vehicles, methanol production from natural gas, and methanol production from coal. This chapter will describe the details associated with the addition of these three production blocks in EPPA.

5.1 Methanol-Based Vehicles Production Block

A production function describes the relationship between inputs and outputs in an economy. It describes the maximum output that can be produced from different combinations of inputs of a given technology. Figure 5-1 represents a simplified nesting structure for methanol-based vehicles. Household transportation can be satisfied through the use of various transportation modes. In EPPA, the two modes are using personal owned transportation, one's own car, or other household transportation modes, which can include using public transportation, taxis, or bikes and other modes of transportation. The substitution elasticity, which defines the responsiveness of the end consumer of the transportation good or service to the price changes in its substitutes (measured as the percentage change in factor proportions resulting from a unit change in the marginal rate of technical substitution), between the two is 0.2. This is because there are limitations imposed on the individual due to the lack of personal owned transportation. In addition, the availability of personally owned transportation provides individuals with a certain level freedom that impacts one's daily choices on transportation modes. Personal owned transportation in EPPA at this stage is satisfied using three types of vehicles: conventional vehicles running on gasoline, methanol fueled vehicles, and electric vehicles, which are omitted from the figure for simplicity. The substitution elasticity between household conventional vehicles and methanol vehicles is set to infinity, indicating perfect substitutability between the two options and that they are only competing on a cost basis. Inherent in this choice of elasticity is the assumption that end customers do not experience changes in quality when using a methanol-based vehicle compared to when using a conventional vehicle.

There exist four inputs into methanol-based vehicles. These are the methanol fuel, vehicle services (including operation and maintenance costs), miscellaneous inputs that do not fit under the fuel and service inputs, and the technology specific factor. The technology specific factor is used to model the penetration of methanol-based vehicles, by specifying that the supply of the backstop technology is limited when the technology is in the earlier stage of introduction. Therefore, there is a time lag association with the penetration of the new technology into the marketplace.

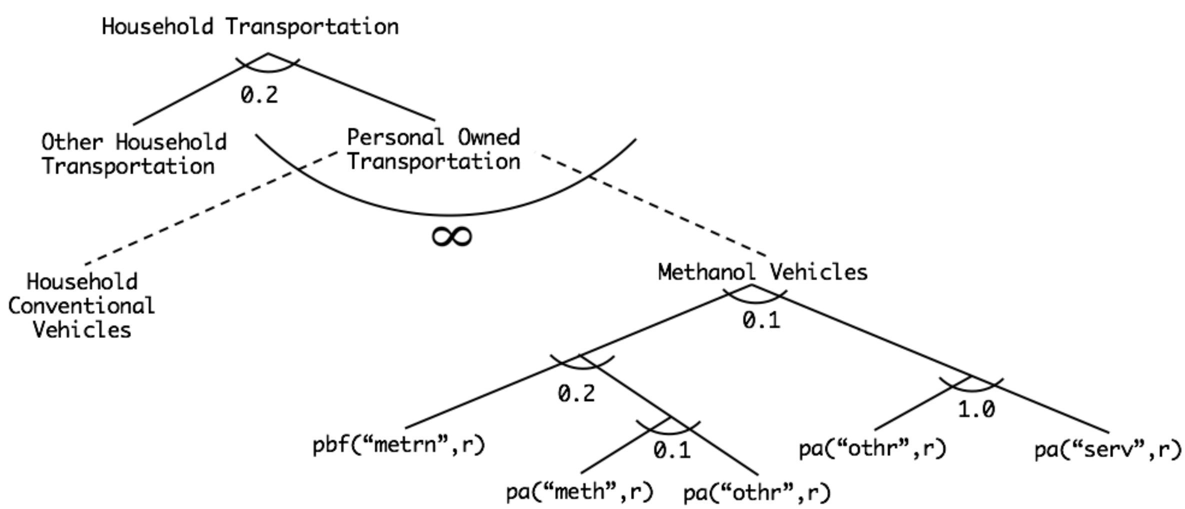


Figure 5-1: Methanol-based vehicles nesting structure

5.1.1 Defining Input Shares

Defining the input shares for methanol-based vehicles in China is first based on calculating the household transportation input shares for conventional Internal Combustion Engine (ICE) vehicles. This involves obtaining annual expenditures in China on refined oil, new vehicles, and services directly related to privately owned transportation. For China, details on these expenditures are further described in Appendix A. The relative proportion of each of the three factors is shown in Table 5.1 for the years 2007 to 2014. Throughout the chosen time period, there are modest increases in the refined oil input share caused by the rise in oil prices until 2014 and a corresponding modest decrease in the vehicle input share.

Table 5.1: Conventional ICE vehicle input shares

Year	**Refined Oil**	**Vehicle**	**Services**
2007	0.0254	0.7762	0.1984
2008	0.0452	0.7825	0.1723
2009	0.0398	0.8095	0.1508
2010	0.0488	0.7921	0.1591
2011	0.0609	0.7697	0.1694
2012	0.0666	0.7449	0.1885
2013	0.0648	0.7508	0.1844
2014	0.0662	0.7553	0.1784

To obtain the input shares for methanol (M85 or M100) vehicles, we assume that the household personal transportation expenditures on vehicle purchase and services remain the same as in the case of Internal Combustion Engine (ICE) vehicles [1]. Therefore, the difference lies in the variation in fuel expenditure resulting from the switch to the methanol fuel. In the case where a vehicle is designed to run on methanol, the change in fuel consumption results from the different energy density of methanol compared to gasoline, difference in prices between methanol and gasoline, and the engine efficiency improvement associated with methanol vehicles. Appendix A describes the details on calculating methanol vehicle expenditures. Table 5.2 displays the final input shares for methanol vehicles in the case of China. For modelling purposes, the input shares for 2014 are used due to being the most recent values and best reflecting the household expenditures on private vehicles.

[1]The difference in price between a conventional ICE vehicle and a methanol vehicle is reflected through the use of a vehicle markup. The vehicle markup is defined and computed in detail in Appendix A. Additionally, the fuel economy (Lower Heating Value (LHV) MMBTU Fuel/km) difference between a methanol vehicle and a conventional vehicle is reflected both in the input share value described in this section and the fuel markup value, also defined and computed in detail in Appendix A.

Table 5.2: Methanol vehicle input shares [16]

Year	Methanol	Vehicle	Services
2007	0.0202	0.7804	0.1995
2008	0.0316	0.7937	0.1747
2009	0.0140	0.8312	0.1548
2010	0.0197	0.8164	0.1639
2011	0.0281	0.7967	0.1753
2012	0.0298	0.7743	0.1959
2013	0.0310	0.7780	0.1911
2014	0.0316	0.7834	0.1850

5.1.2 Defining Substitution Elasticities

The elasticity of substitution defines the responsiveness of the end consumer of the transportation good or service to the price changes in its substitutes, and is measured as the percentage change in factor proportions resulting from a unit change in the marginal rate of technical substitution (MRTS) [50]. Simply, the substitution elasticity addresses the extent to which two goods or services can be substituted for one another under a given level of output when the relative price of the two inputs changes. If the production function has two inputs, x_1 and x_2, the elasticity of substitution, σ_{21}, between the inputs of the production function $f(x_1, x_2)$ can be defined as follows:

$$\sigma_{21} = \frac{dln(\frac{x_2}{x_1})}{dlnMRTS_{12}}$$

$$= \frac{dln(\frac{x_2}{x_1})}{dln(\frac{df}{dx_1}/\frac{df}{dx_2})}$$

$$= \frac{\frac{d(x_2/x_1)}{x_2/x_1}}{\frac{d(\frac{df}{dx_1}/\frac{df}{dx_2})}{\frac{df}{dx_1}/\frac{df}{dx_2}}}$$

In our modeling scope, we assume constant elasticity of substitution. This means that the technology has a constant change in input proportions due to a change in the rate of substitution. Therefore, the ratio of the inputs demanded depends on their relative prices, and not on the scale of production. The substitution elasticity between methanol fueled vehicles and conventional gasoline run vehicles is set to be infinity, representing the perfect substitutability between the two, mainly because the performance of the methanol vehicle is approximately completely homogeneous in the eye of the end user as that of a gasoline fuelled vehicle in terms of operation, range, fuelling time, and fueling supply. The difference in energy content and prices between methanol and gasoline has already been taken into account in the calculation of input shares of methanol vehicles compared to gasoline vehicles. As for the elasticity of substitution between service and other, it is set to 1, that of a Cobb Douglas production function. This reflects the possibility of shifting the expenditures between the vehicle capital costs and the vehicle operating costs. A consumer has the option for example to switch to a more expensive vehicle that has lower operating and maintenance costs, or leasing a vehicle rather than buying it. Finally, the substitution elasticity between the methanol resource and other is chosen to be 0.1. This reflects the existing technical limitations associated with being able to reduce fuel usage by increasing maintenance expenditures. A larger value would reflect a greater possibility of additional maintenance expenditure reflecting in lower end fuel needs.

5.1.3 Defining Vehicle Markups and Technology Specific Factors

The vehicle markup is the ratio of the new methanol vehicle price relative to a conventional ICE vehicle price, the mature corresponding technology. The values used in our simulation are described in Appendix A. The technology specific factor determines the penetration rate of a new technology added to EPPA. The supply of the technology-specific factor goes up when the investment for the backstop technology goes up as a result of an increase in demand for the technology [52]. Because methanol vehicles have not yet penetrated the Chinese market, it is not possible to rely on past methanol vehicle penetration data for parameterizing the technology-specific factor. For our purposes, we use the technology-specific factor parametrized by Karplus, developed to represent the penetration of plug-in hybrid electric vehicles in the United States [40]. Moreover, the depreciation rate of the technology specific factor is set to 5%/year based on past work by Morris et al. on representing advanced technologies in energy-economy models [68]. Additionally, the substitution elasticity between the technology specific factor and other inputs is set at 0.3, based on past work on the penetration of nuclear power during its rapid expansion period. The expression defined in EPPA for the supply of the technology specific factor includes depreciation of the technology specific factor. This assures that if the technology disappears for some period of time, it would require another period of time to rebuild the capacity to expand the technology [68].

5.2 Methanol Production Block

Currently, EPPA does not include methanol as a commodity. As such, the addition of the methanol production block allows us to create the commodity in EPPA and specify its various inputs. Figure 5-2 displays the nesting structure for natural gas to methanol pathway. The corresponding structure for the coal to methanol pathway is shown in Figure 5-3. The difference between the two is in the source of methanol production used and the variation in the input shares depending on the percentage of costs attributed to different factors. The inputs to methanol are the fuel source, the fixed resource factor, and the value added intermediates. The substitution elasticity between the fuel source and the other inputs is 0.01, implying that the factors of production will be used in fixed, predetermined proportions as there is essentially no substitutability between the factors. The fixed resource factor, represented by the price index *pbf*, is used to represent limitations on the expansion of the methanol production technology due to the prioritization of the usage of the natural gas feedstock in other sectors such as the power sector. The value added intermediates include the fixed capital costs of producing methanol, the fixed labour costs associated with plant operation, the cost of electricity required for running the plant, costs associated with energy intensive activities within the plant, and the cost of shipping the end methanol product to its intended destination. These value added intermediates are related with a substitution elasticity of 0.5, which indicates that the the inputs are considered to be complementary and substitutable. As an example, labour costs can be reduced by increasing automation through investments in capital costs.

In EPPA, both methanol produced from natural gas, *methgas*, and methanol produced from coal, *methcoal*, are designed to yield one methanol price. This is the uniform price which methanol is sold at in the Chinese market regardless of whether it is produced from coal or natural gas. This price is used as the input to methanol vehicle to link the two structures together and allow the model to project vehicle penetration depending on the trade-off between methanol and refined oil, and ICE vehicles and vehicles adapted to run on methanol. EPPA is then able to make a choice between producing methanol from coal locally or importing methanol produced from natural gas.

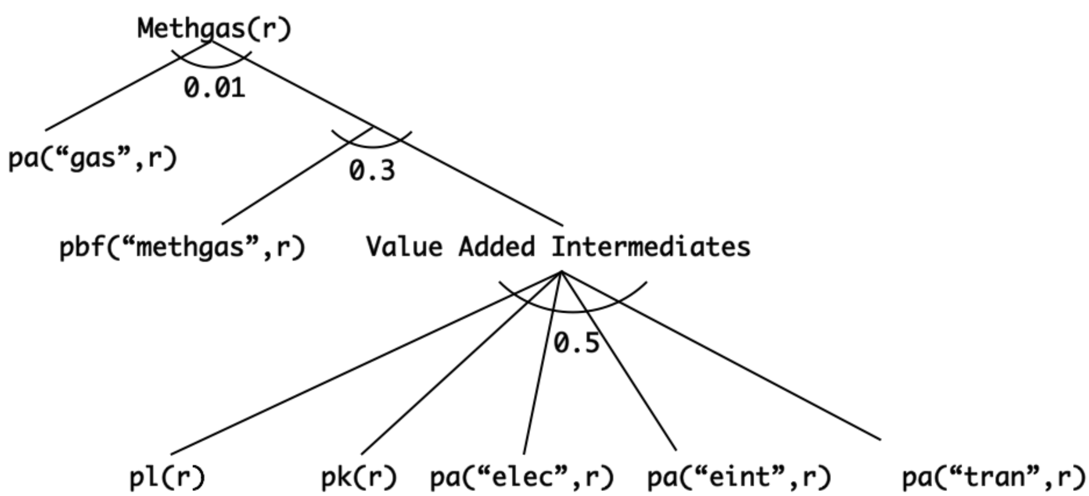


Figure 5-2: Natural gas to methanol production nesting structure

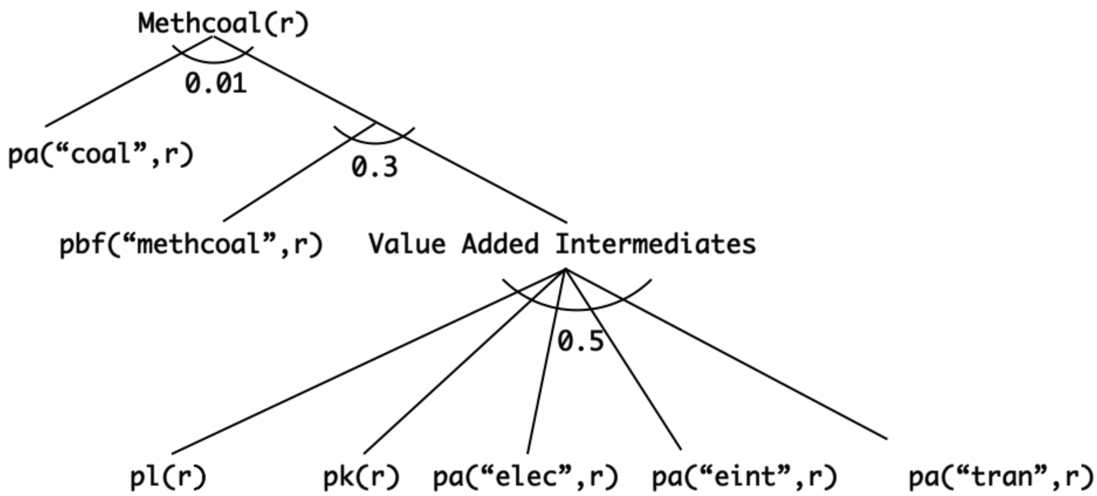


Figure 5-3: Coal to methanol production nesting structure

5.2.1 Defining Substitution Elasticities

The substitution elasticities are the same in the nesting structure for natural gas to methanol production and the nesting structure for coal to methanol production. Between the base fuel resource, gas or coal, and the other inputs, the substitution elasticity is chosen to be 0.01. In reality, the structure is Leontief. A Leontief produced function refers to a fixed proportions production function in which the factors of production are used in fixed proportions, since there is no substitutability between the factors, implying an elasticity of substitution of 0 between the factor inputs. This is because it is realistically not possible to substitute the fuel input with any of the other inputs. The choice of inputting the value of 0.01 is decided upon to avoid numerical problems. The backstop fixed factor substitution elasticity is chosen to be 0.3 between the price index for the technology specific factor and that of the value added intermediates, which include labour, capital, electricity, energy intensive activities, and transportation. This indicates a degree of substitutability between the two, in that investments in the other inputs allows in more efficient or faster production processes. An example of such investment is in training the workforce to be more productive in their daily tasks. This, in turn, results in an increase in the supply of the technology specific factor, thereby increasing the speed of technology penetration.

Finally, the substitution elasticity between the five value added intermediates is set to be 0.5, indicating an intermediate degree of substitutability, with a 50% change in factor proportions relative to a 100% change in the marginal rate of technical substitution.

5.2.2 Defining Output Shares

Methanol output shares define the percentage of methanol used in transportation compared to other energy intensive activities in China. In 2010, China used about 7 million tons of methanol as transportation fuels [38]. Table 5.3 displays the shares of methanol usage in China based on the actual consumption in 2010[2]. It is worth noting the the demand for methanol used in energy intensive activities is more inelastic compared to the demand for methanol used in transportation, mainly due to the greater availability of substitutable fuels for transportation.

Table 5.3: Shares of methanol usage in China [38]

	Consumption of Methanol
Energy Intensive Activities	69.16%
Transportation Fuel	30.84%

5.2.3 Defining Input Shares and Markups

Methanol input shares defined the cost shares attributed to the different inputs to the methanol production process. The first input is the fuel source, which is either coal or natural gas for the purposes of our analysis. The second input is the electricity used for powering the plant, which is assumed to be 10% of the fuel since electricity is generated within the plant itself [3]. Other inputs include energy intensive

[2]In the model, because an explicit production function for the use of methanol in energy intensive industries, such as the chemical industry, is not considered, the share of produced methanol being used as a substitute for gasoline is assigned a value of 1. This is a reasonable assumption because EPPA allows for an increase of production capacity of a given fuel to match an increase in consumer demand for the fuel.

[3]It is worth noting that because the methanol synthesis process is highly exothermic, the excess heat of reaction is usually recovered to make steam to drive turbine compressors, and some methanol

activities in the plant, capital expenditures, variable labor costs, and transportation costs associated with shipping the methanol to its end use location, which is in the form of larger tankers in the case where methanol is imported from Mega Methanol plants but could also take the form of pipeline shipments with methanol produced from coal if the infrastructure is available.

In 2009, global methanol production was dominated by China, Saudi Arabia, Trinidad and Tobago, and Eastern Europe [80], and interest in methanol fuelled vehicles exists in China, Israel, Sweden, Poland, Trinidad and Tobago, and Azerbaijan [39]. China has more than 200 methanol production facilities nationwide [31]. Table 5.4 displays methanol production input shares depending on whether methanol is produced from low-cost natural gas in plants in the Middle East or locally from available coal reserves. Methanol plants producing methanol from natural gas or coal are nearly self sufficient. Moreover, EPPA already takes into account the variation in natural gas prices across different regions, which is important in the case of China as it lacks in local natural gas reserves, but is able to make use of the lower priced natural gas in the Middle East by importing the methanol produced there.

Table 5.4: Methanol production input shares [43]

Component	**Methanol from Coal**		**Methanol from Natural Gas**	
	Cost ($/gal)	**Share**	**Cost ($/gal)**	**Share**
Fuel	0.234	0.140	0.513	0.418
Electricity	0.026	0.016	0.057	0.046
EINT	0.090	0.054	0.030	0.024
Capital	1.035	0.620	0.460	0.375
Labor	0.150	0.090	0.070	0.057
TRAN	0.134	0.080	0.097	0.079

Overall, methanol production from natural gas is less expensive, at 1.23 dollars per gallon of methanol ($/gal), compared to methanol production from coal, at 1.67 $/gal

plants generate excess electric power. For the purpose of this analysis, we ignore electricity production by methanol plants.

of methanol. The difference between the two is a result of two main factors. The first factor is that coal-based methanol production requires higher capital investment and has lower plant thermal efficiency and lower plant availability [74]. Second, natural gas generally has higher cost per million British Thermal Units (MMBTU) relative to coal. For obtaining the cost estimates, the coal price used is \$2.14/MMBTU and the natural gas price used is \$6.13/MMBTU. However, this comes at the cost of the natural gas route being subjected to greater operating cost changes because of the greater price volatility of the natural gas feedstock. Figure 5-4 displays the large level of variation that natural gas spot prices at the Henry Hub terminal in Louisiana have undergone in the last 10 years. The range is large, with the lowest price over the last 10 years being 1.7 USD/MMBTU in March 2016 and the highest price over the last 10 years being 12.68 USD/MMBTU in June 2008, highlighting the impact of advancements in fracking, which dramatically expanded gas reserves, on the price of natural gas.

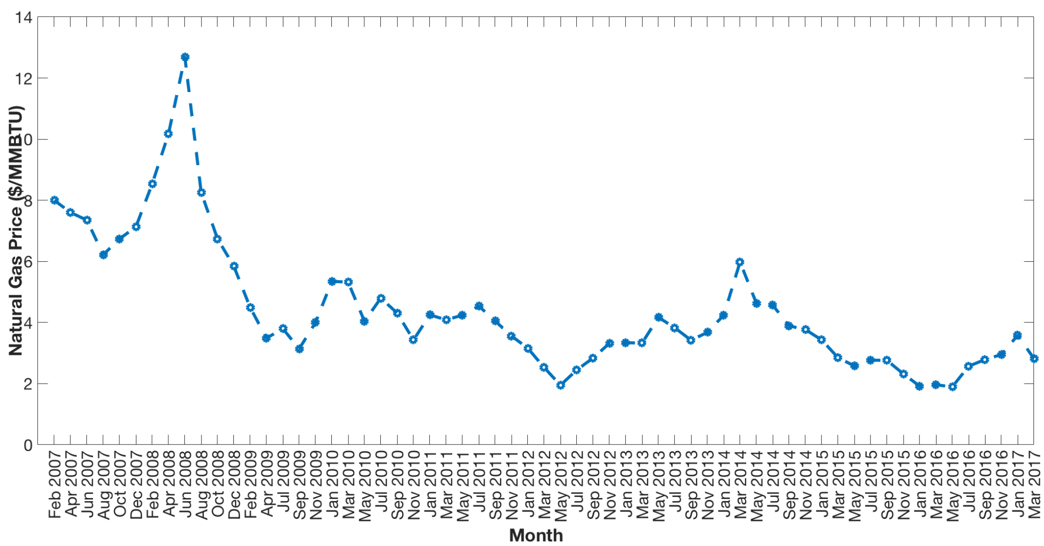


Figure 5-4: Natural gas spot price at the Henry Hub terminal in Louisiana [47]

In terms of the fuel markup, a detailed analysis is presented in Appendix A that determines the relative price of methanol to gasoline on a per mile traveled basis. Finally, it is worth noting that there are uncertainties associated with the estimates obtained for methanol production processes, and that these estimates vary depending on project specifics such as location, construction costs, labour market conditions, changes in feedstock costs, and changes in government policy and incentives.

5.2.4 Feedstock Price Impact on Methanol Prices

In order to better understand the impact of price differences of coal and natural gas on the end methanol price, a simple cost analysis was conducted to understand the natural gas prices at which the production of methanol from coal is cheaper than the production of methanol from natural gas. Figure 5-5 displays the results of the analysis for the case which does not include a carbon price and a range of cases which include a variety of carbon prices. The carbon prices chosen are based on estimates provided by the United States Environmental Protection Agency (EPA) on the social cost of carbon. The social cost of carbon represents a measure of the long-term damage done by a ton of carbon dioxide, or alternatively the value of the benefit resulting from a reduction in carbon dioxide emissions [6]. The case where coal is used for methanol production is represented with constant methanol prices due to the lower variation in coal prices compared to natural gas prices. Therefore, fixed coal feedstock prices were used for obtaining the methanol prices for the case in which it is derived from coal. The graph shows that as the carbon price increases, the intersection point of the coal and natural gas lines shifts to the right, meaning that higher natural gas prices can be tolerated economically due to the higher carbon price penalty incurred by methanol production from coal.

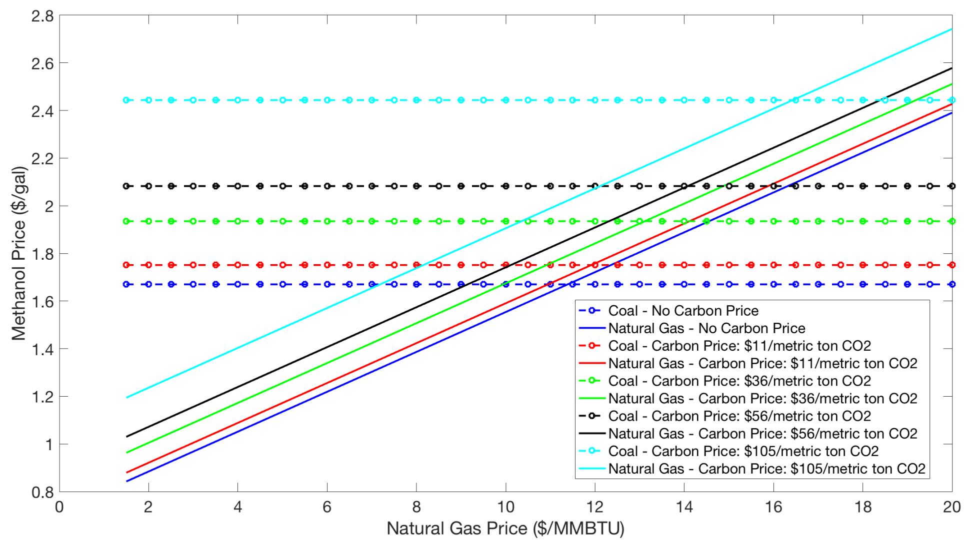


Figure 5-5: Variation in natural gas feedstock price impacts the point at which methanol from coal is a cheaper option compared to methanol from natural gas

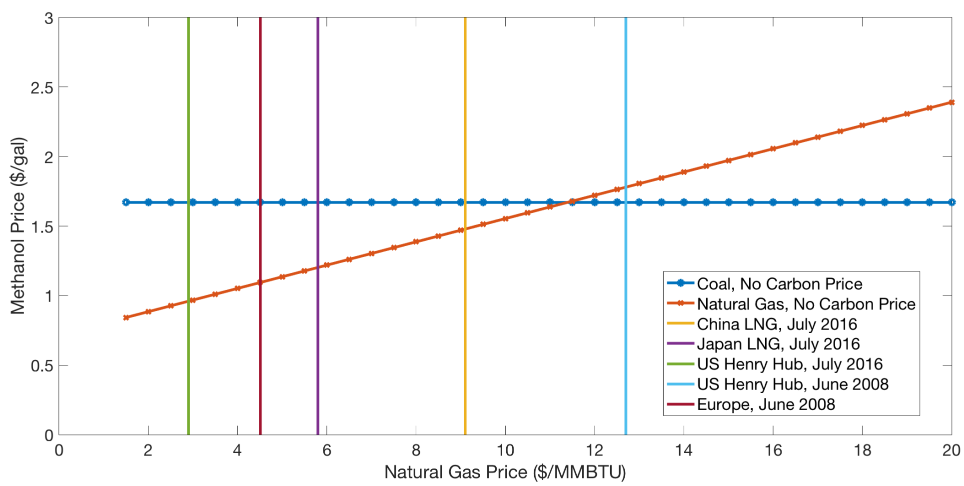


Figure 5-6: View of natural gas prices across the world [47]

Additionally, Figure 5-6 displays a snapshot of natural gas prices across different locations in the world during different times. Since natural gas is not considered to be a homogeneous commodity, these fluctuations are expected. In all cases, methanol production from natural gas is the cheaper option, except back in June 2008, when natural gas prices in the United States were at a high of 12.7 USD/MMBTU. Additionally, in July 2016, natural gas prices in China led to methanol production in the country using natural gas being more economical than its production using coal. However, despite the favorable economics, the prohibition of local natural gas usage for methanol production by the government due to the shortage of the local resource prevented natural gas utilization for methanol production.

5.3 Estimating Associated Emissions

Estimating the emissions associated with the use of methanol fueled vehicles involves using data from well-to-wheel analyses of fuel life cycle emissions. Well To Tank (WTT) data and Tank To Wheels (TTW) data are used to estimate emissions from the distance travelled by vehicles. The details of the values used for obtaining overall emissions are shown in Appendix A.

Chapter 6

Model Results

This section outlines the results of running the EPPA model with the addition of the new structures for methanol. It presents the market penetration of methanol vehicles and electric vehicles in China compared to conventional light duty private vehicles. It then describes the underlying rationale behind the market shares achieved by describing the controlling factors and the underlying energy commodity prices. Then, it describes the associated emissions with the base case scenario, both for greenhouse gas emissions and criteria pollutant emissions. Finally, it presents that results of a sensitivity analysis conducted to determine the impact of varying the engine efficiency of methanol vehicles on the penetration of the vehicles on a large scale.

6.1 Base Case Scenario

The base case scenario represents the case where the transportation sector does not undergo any changes in policies. For our purposes, the base case scenario is run for the case of China from the base year of 2007 to the year 2050. Despite the fact that EPPA is able to solve for the vehicle mix up to the year 2100, the analysis is limited to the year 2050 due to the limitations in predicting mobility trends beyond 2050. Realistically, one is unable to confidently prescribe changes in technology advancement and changes in mobility trends beyond a certain point.

Changes in mobility trends include changes in transportation mode choices associated with an increase in urbanization, advancements in autonomous driving, and the rise of sharing schemes within the transportation context.

6.1.1 Base Case Market Shares

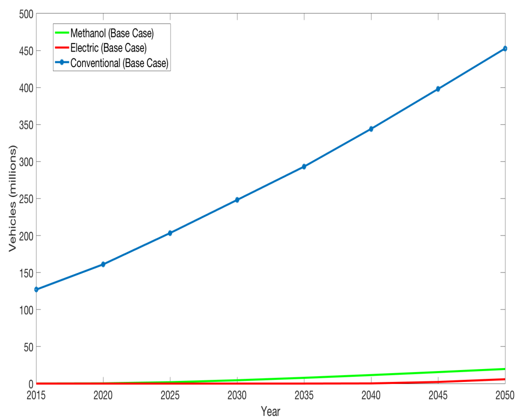
The first parameter to examine is the vehicle stock attributed to each vehicle type. Vehicles in EPPA include both passenger vehicles and commercial vehicles. Within passenger vehicles, a proportion are considered to be private vehicles. Private vehicle stock is our main concern for this analysis. The base case scenario results for private vehicle stock in China are shown in Figure 6-1[1]. It is worth noting that electric vehicles in this case refer to advanced Battery Electric Vehicles (BEVs) and not Hybrid Electric Vehicles or Plug-in Hybrid Electric Vehicles. Both methanol vehicle and electric vehicle production structures are activated in the year 2015[2]. The results show that both methanol and electric vehicles do not achieve significant market penetration by the year 2050. By the year 2050, methanol vehicles only achieve a 4% market share and electric vehicles reach a mere 1% market share. Moreover, large scale penetration of methanol vehicles does not take place until the year 2020 and electric vehicles do not penetrate on a large scale until 2040. The lag in the penetration of vehicles is due to the additional cost of buying an electric vehicle or methanol vehicle or converting an existing vehicle to be able to run on methanol[3]. These are reflected in markups greater than one for electric and methanol vehicles compared to gasoline vehicles. For methanol and electric vehicles, the economic advantage resulting from the lower fuel prices is minimal in having a large-scale impact because the fuel price

[1] The natural gas resource setting in EPPA has been modified to allow for regional trading, thereby resulting in more stable price changes for natural gas. In the initial setting, the price of natural gas was increasing by more than two-fold due to the strict limitation imposed in EPPA that disallowed regional trading, resulting in great increases in price due to the increase in demand not being matched by the supply

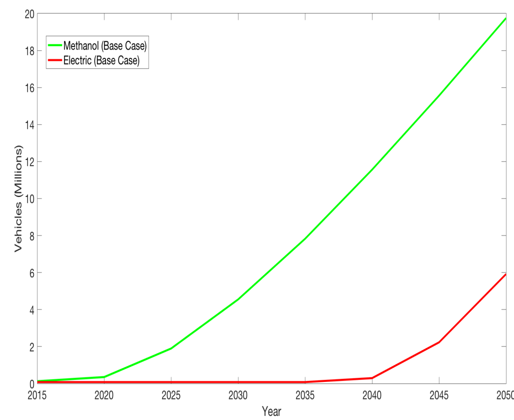
[2] The stock of methanol vehicles in 2015 in China was 130,000 vehicles and the stock of electric vehicles in 2014 in China was 83,198 vehicles [5].

[3] The service input share of electric vehicles is higher than that of gasoline vehicles, mainly because the expenditure on electricity is lower for electric vehicles, leading to a smaller fuel input share for electric vehicles. This results in a larger service input share for electric vehicles even if the expenditure for electric vehicles services is the same.

constitutes a small percentage of the overall price. Another parameter that plays a significant role is the technology specific factor specified in the model, which defines the penetration rate of a new technology added to EPPA. The technology specific factor goes up when the investment for the backstop technology goes up as a result of an increase in demand for the technology.



(a) Base case scenario

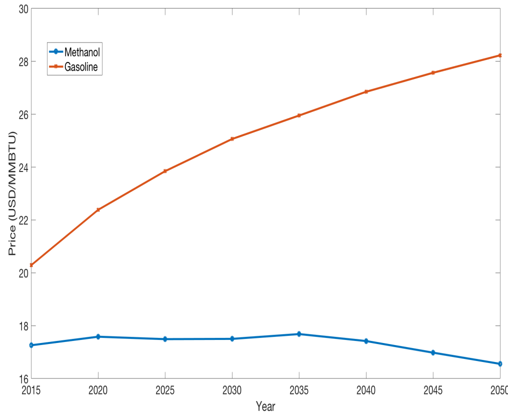


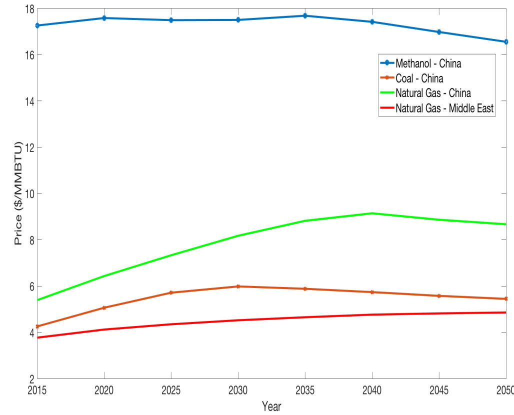
(b) Base Case Scenario: limited to vehicles running on methanol or electrically

Figure 6-1: Passenger private vehicle stock in China by vehicle type for the base case scenario

6.1.2 Base Case Fuel Prices

To understand the underlying reasons for the results, one parameter worth examining is the change in the prices of the commodities in the different years. EPPA reports prices in the form of price indices which are ratios of the price of the commodities in any given year relative to the price of the commodities in the base year. The conversion of the price indices to actual prices is described in detail in Appendix B. Figure 6-2 displays the prices of the various commodities for the different years. The graph on the left shows that methanol prices are consistently lower than gasoline prices and are also more steady. However, despite the lower price of methanol compared to gasoline, penetration is slow due to the limitations imposed by converting existing vehicles and establishing the required infrastructure.

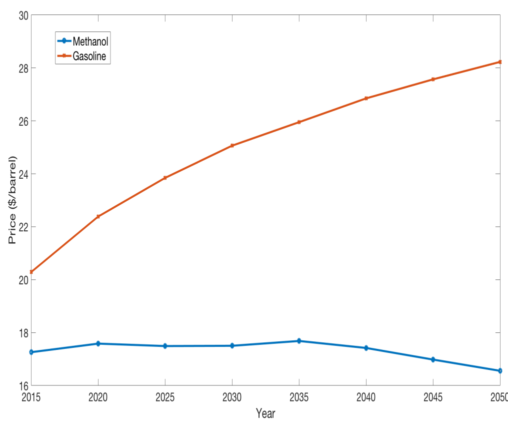


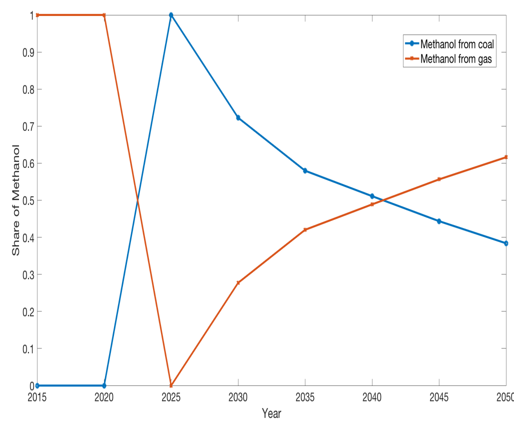


(a) Comparison of methanol and gasoline prices in China ($/MMBTU)

(b) Comparison of the price of methanol in China and the prices of its feedstocks

Figure 6-2: Prices of relevant commodities in EPPA





(a) Comparison of methanol and gasoline prices in China ($/barrel)

(b) Methanol shares used as a fuel coming from coal or natural gas

Figure 6-3: Methanol and gasoline prices in China ($/barrel) and shares coming from coal or natural gas

The graph on the right in Figure 6-2 displays the projected price of methanol compared to its two chosen feedstock sources[4]. The price of coal is more stable

[4] The methanol production sectors introduced in EPPA are designed to have a single output price for methanol regardless of whether it is produced from coal or natural gas since the end product is homogeneous regardless of whether coal or natural gas is used for its production. The methanol price projections do not include taxes. The gasoline price projections include existing taxes on refined oil

and only increases from \$4.26/MMBTU in 2015 to \$5.44/MMBTU in 2050. On the other hand, the price of natural gas in China experiences a greater increase, from \$5.39/MMBTU in 2015 to \$8.67/MMBTU in 2050. Additionally, natural gas from the Middle East is even cheaper than coal prices in China and experiences minimal changes across the years. The relative economics of producing methanol from natural gas and coal determine the shares of methanol being produced from each source at a given year. Figure 6-3 displays the share of methanol used as a fuel coming from coal or natural gas. The higher capital costs associated with methanol production from coal result in methanol used in transportation being imported in the years 2015 and 2020. In the year 2025, the methanol production completely shifts to coal due to the price gap between natural gas and coal increasing to a point where methanol production from coal is favored in spite of the higher capital costs associated with methanol production from coal. Post 2025, the increase in demand for methanol use in transportation due to the increase in methanol vehicle penetration as well as favorable economics of methanol produced from natural gas leads to a mix of methanol produced from both coal and natural gas. This mix depends on the relative prices of the feedstocks and the costs associated with building and operating the additional capacity needed to satisfy the methanol demand for use in transportation. In the year 2050, EPPA predicts that 38.4% of methanol used in methanol vehicles will be produced from coal sources and the remaining 61.6% will be satisfied through methanol produced from natural gas[5] Finally, in order to gain a sense of comparison on where EPPA's projections of commodity prices compare with that of other sources, the crude oil prices calculated by EPPA from the years 2015 to 2050 are compared to the crude oil projections of the Annual Energy Outlook until 2050. A graph comparing the prices from the two sources in shown in Appendix E.2. The crude oil price projections by EPPA closely match that of the Annual Energy Outlook's

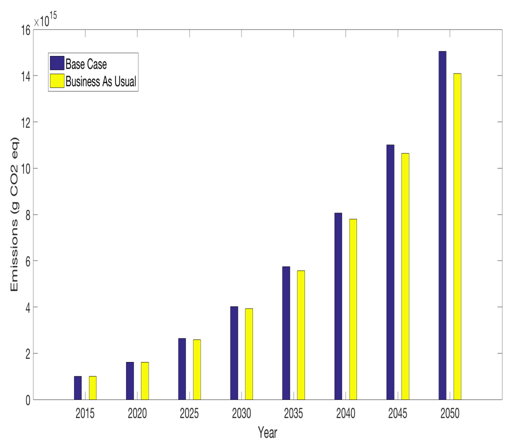
in China.

[5]In the simulations, methanol is allowed to be produced from natural gas in China in addition to imports from locations with cheaper natural gas resources. The natural gas input to the methanol production structure relies on the Armington assumption. This takes into account the variation of prices between natural gas in different countries, allowing the model to decide on whether to produce the methanol from local natural gas resource or to import it from other locations based on the price differences.

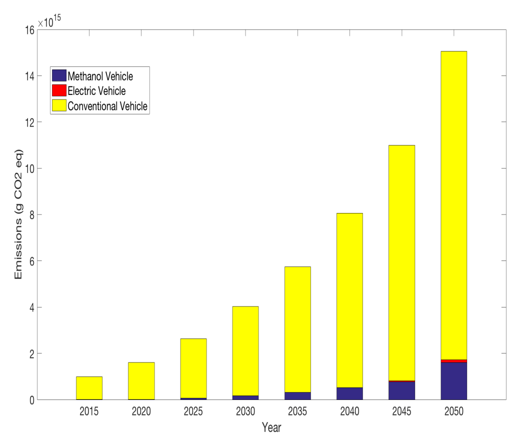
reference oil price scenario.

6.1.3 Base Case Greenhouse Gas Emissions

Figure 6-4 displays a comparison of greenhouse gas emissions in grams of carbon dioxide equivalent between the base case scenario and the scenario assuming the increase in transportation demand is satisfied by conventional transportation schemes [6]. Part A displays that that the base scenario is associated with an increase in total emissions in China, mainly due to the higher greenhouse gas emissions associated with using methanol derived from coal. Greenhouse gas emissions are 3.18% higher in the base case scenario compared to the business as usual scenario. Part B displays that methanol vehicles result in a considerable increase in emissions compared to electric vehicles, even after accounting for the different in market shares achieved by both.



(a) Emissions comparison between business as usual trajectory and base case trajectory



(b) Emissions breakdown in base case scenario

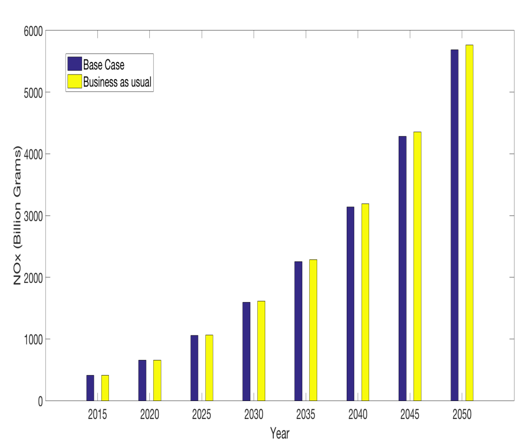
Figure 6-4: Comparison of greenhouse gas emissions from private passenger vehicle transportation fleet in China between the business as usual and base case scenarios

6.1.4 Base Case NOx Emissions

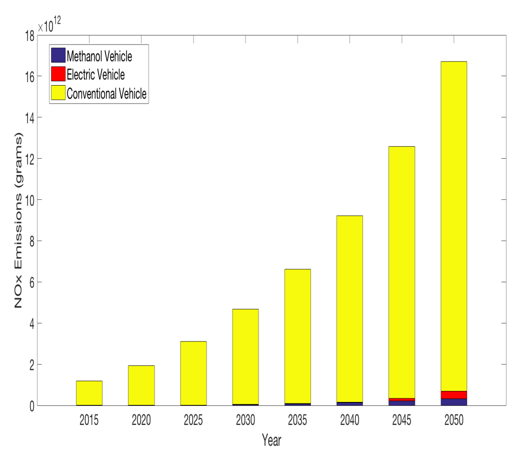
Similar to evaluating greenhouse gas emissions, the NOx emissions of the base case were evaluated against the business as usual trajectory. Figure 6-5 displays the

[6]This is assuming existing technologies and emission standards stay the same.

results, with the base case scenario resulting in NOx emissions that are 1.32% lower compared to the business as usual scenario. It is worth noting that NOx emissions in this case are aggregated on the entire country of China. In reality, the impact of NOx emissions is very specific to certain geographic locations. Still, it is worth conducting this analysis to understand if the policies at hand are addressing the goals they are intended for, and whether there are any unintended consequences associated with the implementation of the policies. In this case, we observe decreases in overall NOx emissions if policies encouraging methanol vehicle and electric vehicle penetration are implemented. On a distance travelled basis, methanol vehicles emit less NOx compared to their gasoline vehicle counterparts. As for Battery Electric Vehicles, they are associated with higher NOx emissions compared to gasoline vehicles. Currently, due to advancements in three way catalysts that effectively control for NOx emissions as well as the use of ultra-low sulfur gasoline fuel, gasoline vehicles are associated with lower NOx emissions than electric vehicles. For the case of electric vehicles, two factors that contribute to their higher NOx emissions are the use of fossil fuels for power generation and the lack of flue gas control in these power plants [21][27]. Future trends in comparing NOx emissions will depend on the relative improvements in tailpipe emissions control and power plant emission control.



(a) Emissions comparison between business as usual trajectory and base case trajectory



(b) Emissions breakdown in base case scenario

Figure 6-5: Comparison of NOx emissions from private passenger vehicle transportation fleet in China between the business as usual and base case scenarios

6.1.5 Base Case Carbon Monoxide and Hydrocarbon Emissions

In addition to comparing NOx emissions, local pollution impacts from carbon monoxide emissions are also compared[7]. Figure 6-6 provides a comparison of carbon monoxide emissions between the business as usual and base case scenarios. The gap increases throughout the years up to 2050, with greater emissions reductions resulting mostly from the increase in the share of electric vehicles. In 2050, the total carbon monoxide emissions are 2.72% lower in the base case scenario compared to the business as usual scenario.

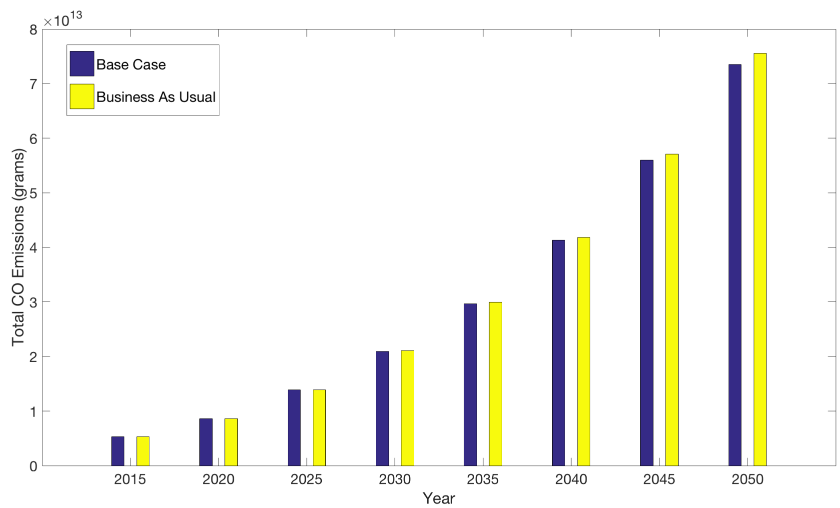


Figure 6-6: Carbon monoxide emissions comparison between business as usual trajectory and base case trajectory

Additionally, local pollution impacts from hydrocarbon emissions are also compared[8]. Figure 6-7 provides a comparison of hydrocarbon emissions between the business as usual and base case scenarios. Emissions reduce until the year 2050, in which the hydrocarbon emissions are 3.71% lower in the base case scenario compared to the business as usual scenario.

[7]Due to the fact that electric motors do not emit any carbon monoxide emissions during the driving process, the value for carbon monoxide emissions for electric vehicles is set to 0.

[8]The value for hydrocarbon emissions for electric vehicles is set to 0. Additionally, data used for methanol vehicle emissions are based on M100 vehicles since there are greater uncertainties with estimating emission levels for methanol blends.

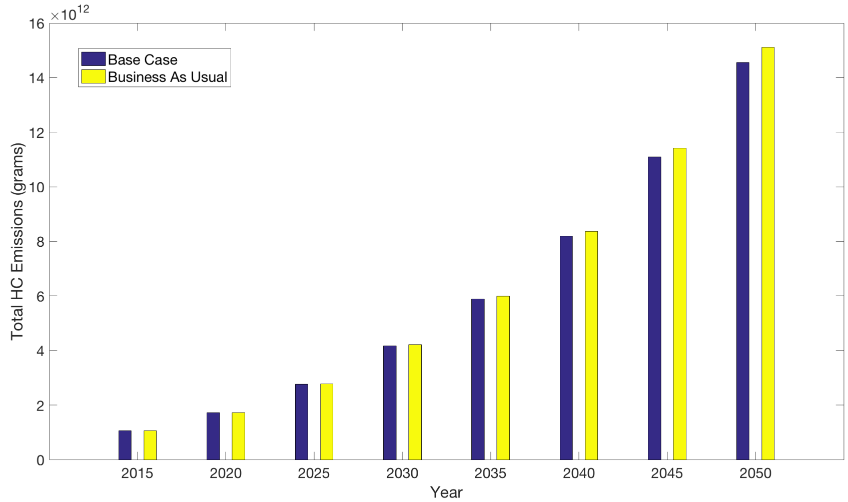


Figure 6-7: Hydrocarbon emissions comparison between business as usual trajectory and base case trajectory

6.2 Sensitivity Analysis

To be able to evaluate how significant the change in the fuel economy of methanol vehicles is on methanol vehicle penetration on a large scale, a sensitivity analysis is conducted in which the value for the methanol vehicle engine efficiency is varied. Increases in engine efficiency favor methanol vehicle economics. The next section explores whether improvements in methanol vehicle economics due to engine efficiency increases is likely to be significant.

6.2.1 Effect of Engine Efficiency

As highlighted previously, a benefit of M85 and M100 vehicles is their ability to achieve better fuel economy compared to gasoline vehicles due to their use of higher compression ratios. To understand the significance of the fuel economy changes from using methanol vehicles, we run a sensitivity analysis that compares the methanol vehicle penetration under different assumptions of vehicle fuel economy. The fuel economy of a vehicle is the fuel efficiency relationship between the distance traveled and the amount of fuel consumed by the vehicle. Changes in the fuel economy are modelled by assuming various gains in engine efficiency from using methanol vehicles. The efficiency levels vary from experiencing no gains to experiencing up to 30% gains in efficiency levels. Table 6.1 displays changes in the methanol vehicle input shares resulting from the variations in the efficiency level. The input shares at every efficiency level serve as inputs to the EPPA model for every simulated run. As the engine efficiency level increases from a level of no efficiency gain to 30%, two major trends are observed. The input share for the methanol fuel decreases, resulting in an increase in the vehicle and services input shares. Additionally, the fuel markup decreases steadily, because a smaller volume of fuel is needed to satisfy the same distance travelled.

Table 6.1: Input share variations associated with different engine efficiency levels

Efficiency Level	**Input Shares**		
	Methanol	**Vehicle**	**Services**
No Gain	0.0377	0.7785	0.1839
5%	0.0359	0.7799	0.1842
10%	0.0343	0.7811	0.1845
15%	0.0329	0.7823	0.1848
20%	0.0316	0.7834	0.1850
25%	0.0304	0.7844	0.1853
30%	0.0292	0.7853	0.1855

Figure 6-8 displays the methanol vehicle penetration under different assumptions of engine efficiency levels. As can be seen from the figure, the impact of engine efficiency on overall vehicle penetration is modest. There exists a divergence in the graph at the point where the assumed engine efficiency improvement is 20%. With lower engine efficiency improvement values, the vehicle penetration of methanol vehicles reaches about 14.8 million vehicles by 2050. With an efficiency improvement value of 20%, the number of methanol vehicles reaches 18.5 million vehicles by 2050. Improving the engine efficiency beyond the 20% mark results in minor increases in the number of methanol vehicles on the road by 2050. Increasing the engine efficiency to 30% results in increase of about 585,000 additional methanol vehicles on the road by 2050 compared to the 20% improvement in engine efficiency scenario.

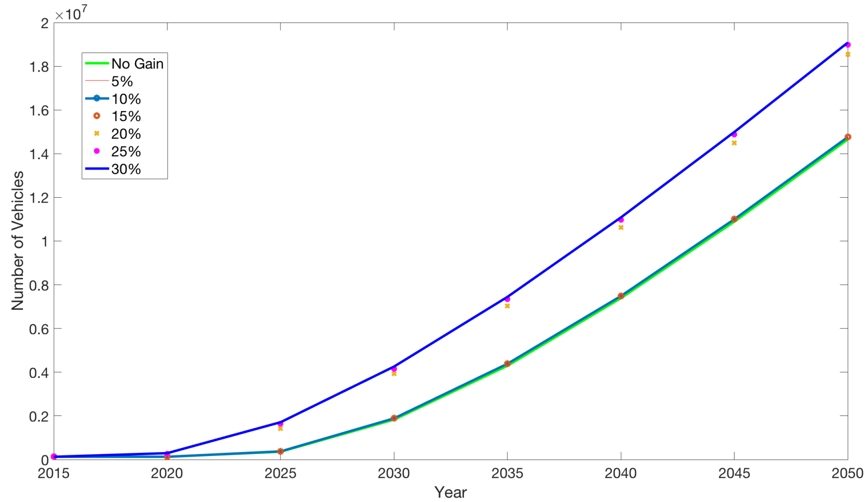


Figure 6-8: Methanol vehicle penetration under different assumptions of engine efficiency levels

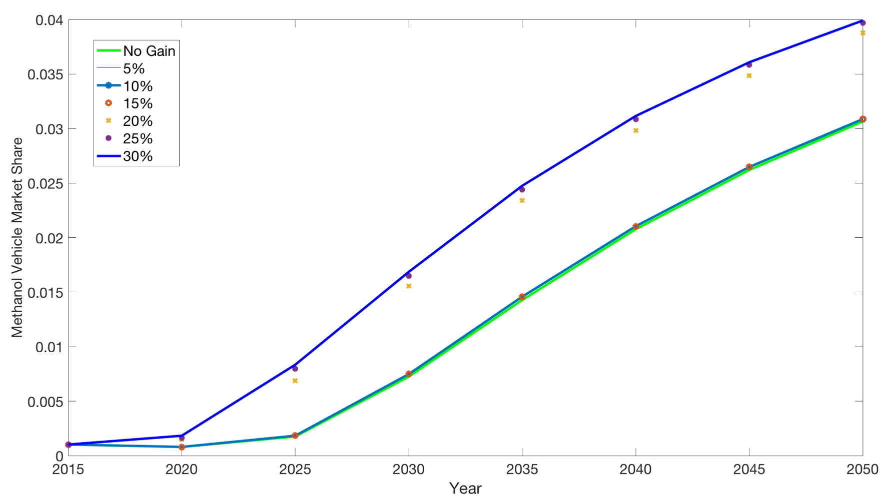


Figure 6-9: Market shares achieved by methanol vehicles under different assumptions of engine efficiency levels

Figure 6-9 displays the market shares achieved by the methanol vehicles. The divergence in the middle is due to it being the point at which the cost increase due to the vehicle markup being greater than one balances out the cost decrease due to the fuel markup being less than one. It is worth noting here that the vehicle markup divergence from 1 is much smaller, at 1.017, than the fuel markup, at 0.873. However, the cost impact also takes into account the variation in input shares, with vehicles taking up about 78.34% of the methanol vehicle input and the methanol fuel taking up about 3.16% of the methanol vehicle input. Achieving an additional 10% efficiency gain from 20% for an overall 30% improvement in engine efficiency only results in a 0.11% increase in methanol vehicle market share.

Chapter 7

Policy Implications

Governmental policies, whether at the local or the national level, play a big role in determining the penetration of different types of vehicles. In the case of China, the implementation of policies encouraging or discouraging the use of different types of light duty passenger vehicles could be motivated from mainly adhering to international commitments on emissions or increasing energy security through reducing oil imports by making use of domestic fuels. This chapter describes some of the policies that could be implemented as well as existing policy plans in China with regards to methanol and electric vehicles. The policies tested in EPPA include a gasoline tax, methanol vehicle subsidies, electric vehicle subsidies, and the implementation of a carbon cap.

7.1 Gasoline Tax

An externality is a cost or benefit that results from an activity or transaction and affects a third party who did not choose to incur the cost or benefit. Externalities can be positive or negative depending on the nature of the impact on the third party, and can create a situation of market failure in which the market fails to produce the efficient level of output. Within the transportation context, conventional vehicles produce various negative externalities. These include congestion and environmental externalities like air pollution and climate change. The existence of these negative externalities results in a market failure where the social marginal benefit is lower than the private marginal benefit, resulting in a socially optimal consumption quantity that is lower than the competitive market equilibrium. The over-consumption of the gasoline results in a dead-weight loss. The dead-weight loss can be addressed by instituting a gasoline tax that corrects for the negative externality by increasing the cost of the gasoline and as a result, pushing for lowered use of gasoline, thereby correcting for the inefficient market outcome.

7.1.1 Existing Gasoline Tax in China

The retail price of oil can be broken down into three components: the crude price, the industry margin, and the tax level imposed by the oil consuming nation. The main cause of the oil price gap between the United States and China is because total taxes and dues are higher in China compared to the United States. China's oil price includes value-added tax (VAT), consumption tax, city maintenance and construction tax, and education surtax [60]. Fuel consumption tax accounts for more than half of the total taxes and dues levies on oil products in China [77]. In 2009, China started a reform of its fuel tax, raising the fuel consumption tax from 0.2 Yuan per liter to 1.0 Yuan per liter for gasoline [46]. At the time of the reform, with oil prices being low, the tax increase had minimal impact on consumers. As oil prices rose until mid-2014, the impact of the tax increased in terms of causing consumers to shift their demand for fuel use to other fuels, methanol being one of them. The tax rates thus far have been modest compared to countries like Turkey and the Netherlands. Figure 7-1 displays the values of gasoline tax in dollars per gallon in various countries. The data is based on 2012 reported values, except for Canada which is based on 2013 reported values and the United States which is based on 2016 reported values. As can be seen from the chart, in 2012, China had set its tax rates on gasoline use on the road at 0.64 USD/gallon and ranked 35th on tax levels ranked on a decreasing scale. More recently, the gasoline consumption tax in China in early 2016 was reported to have increased to 0.944 USD/gallon [20].

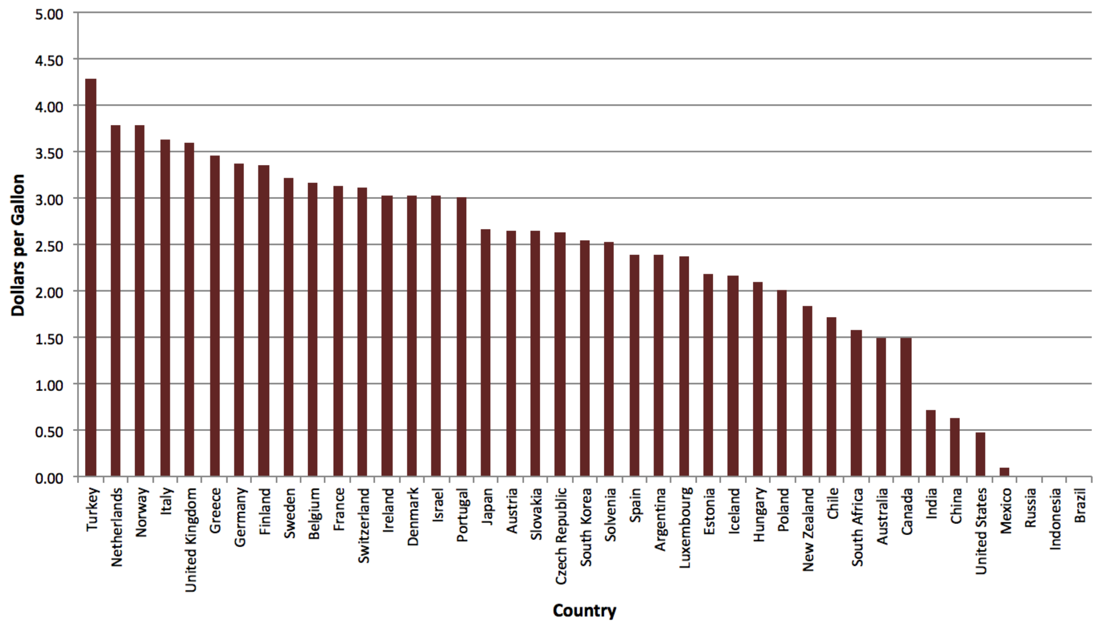
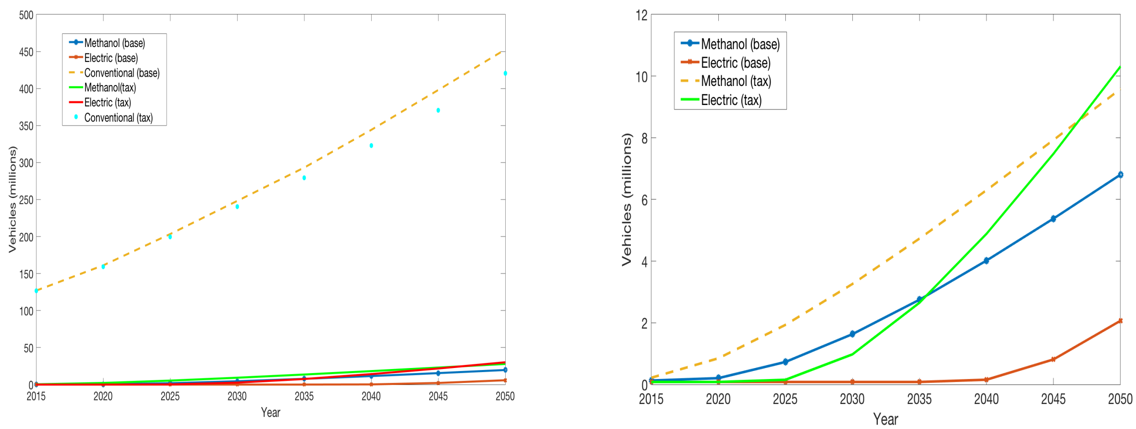


Figure 7-1: Gasoline use tax by country (This is domestic consumption tax on fuels and excludes other fees. Data for all countries are based on tax rates in 2012, except for the United States where the gasoline tax is the total of state and federal taxes as of May 2016) [76]

Increasing the gasoline tax helps achieve the objectives of addressing the negative environmental externalities associated with the use of gasoline and help reduce dependence on foreign oil imported from OPEC. However, it is worth noting that a gasoline tax only serves as a second best policy. Parry and Small mention that a tax on emissions would better address local air pollution and a tax on peak-period driving would better address congestion [65]. However, these two options are associated with high implementation costs and only address one objective at a time. Ultimately, the best option with taxation is directly addressing the end objective, whether it is achieving economic growth, local pollution reduction, or growth in certain types of vehicles at the expense of others. If the best option is difficult to implement on a large scale, then second place policies come into play.

7.1.2 Impact of Gasoline Tax on Vehicle Penetration

The commodity price data used in EPPA is based on data reported by the Global Trade Analysis Project (GTAP). The GTAP dataset includes existing taxes. Therefore, an additional tax rate imposed on the consumption of gasoline in the transportation sector should take into account existing tax values. The gasoline tax imposed in EPPA in this study is the optimal gasoline tax value for China calculated by Lin and Zen, at \$1.58/gallon, which is 2.65 times greater than the current tax level. Figure 7-2 displays the market shares achieved by the different vehicle technologies when this higher gasoline tax is implemented in China.



(a) All three vehicle types

(b) Expanded view of electric and methanol vehicles

Figure 7-2: Private passenger vehicle stock in China by vehicle type for the gasoline tax scenario

The figures show that, as expected, implementing the gasoline tax results in increases in the market shares of both methanol vehicles and electric vehicles. The graph on the right shows that electric vehicles take longer to penetrate the market on a large scale, with large scale penetration only taking place in 2035, 5 years earlier than in the base case. However, by 2050, electric vehicles achieve the same market share as methanol vehicles, 6%, and together the alternative vehicles make up a 12% market share of all vehicles in China. Despite the seemingly small market share achieved, the magnitude of the transition is actually large since the 12% market share achieved by both vehicle types translates to around 20 million vehicles on the road. Another factor that determines the overall effectiveness of the gasoline tax but is beyond the scope of this thesis is the areas in which the tax revenue can be invested in by the government. The revenue can be used for paying for transportation infrastructure, such as roads and bridges or extensions of transit lines. It can also be used in the form of research and development investments in cleaner transportation technologies such as advancements in battery technologies as an example.

7.1.3 Impact of Gasoline Tax on Gross Domestic Product

The implementation of a gasoline tax impacts government revenue and also has an impact on the Gross Domestic Product (GDP), which is a measure of a country's economic activity. The GDP takes into account all forms of public and public consumption, government expenditures and investments, and exports and imports within the single country. For our purpose, to understand the impact of instituting a gasoline tax on the GDP, we examine the changes in the macroeconomic consumption since we are assuming no changes in government investment or trade. Figure 7-3 displays the impact of the gasoline tax on the aggregate consumption in China. the magnitude of the difference is very small, but there exists a slight reduction in aggregate consumption due to the gasoline tax. Assuming all other factors are unchanged, this translates to a corresponding GDP decrease. Theoretically, tax cuts are associated with economic growth because it is assumed that reducing the taxes increases the amount of money available for individuals to spend money as they like, boosting economic growth. This is what is observed in this case because the increase in the penetration of the more expensive methanol and electric vehicles results in less consumption in the other sectors of the economy.

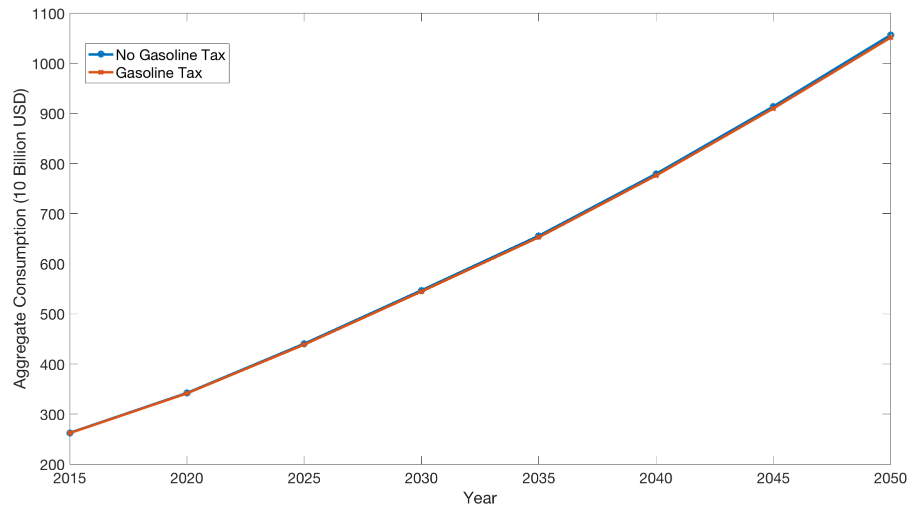


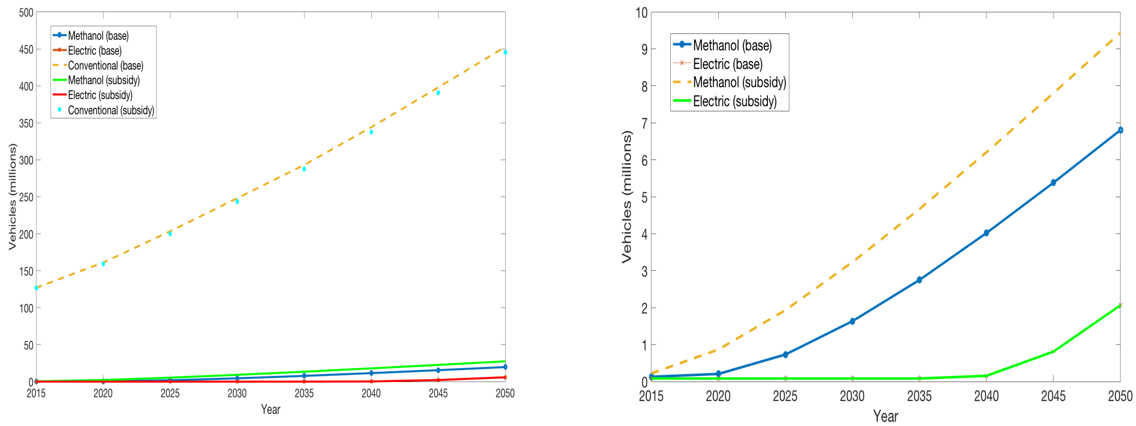
Figure 7-3: Impact of gasoline tax on aggregate consumption (reported in 10 billion USD)

7.2 Vehicle Subsidy

A second way to change the price of goods and the resulting quantity consumed is through subsidies. Within transportation, both fuel and vehicle subsidies have been provided by different governments to individual consumers to reduce some of the burden associated with the purchase of a more expensive technology or the end costs incurred by the customer. Ideally, subsidies are instituted, like taxes, with the aim of increasing overall public interest by adjusting quantities of goods or services consumed to socially optimal quantities, and thereby reducing the dead-weight loss associated with the existence of externalities. However, often, the case is that subsidies are maintained for too long or do not reflect the amount required, resulting in inefficient outcomes.

7.2.1 Impact of Methanol Vehicle Subsidy

In 2013, China's methanol favoring Shanxi province finalized methanol car subsidies. The plan entailed a subsidy of 3,000 Yuan (equivalent to USD 436) given for the purchase of methanol-fueled (M85 and M100) cars for the first year, in addition to an annual subsidy of 1000 Yuan (equivalent to USD 145) after the first year [53]. To test the impact of applying this policy on a national level, Shanxi's policy was applied across all of China in EPPA. Figure 7-4 displays the results. Additionally, methanol is not currently taxed in China, also explaining the price differential between gasoline and methanol in China [51].



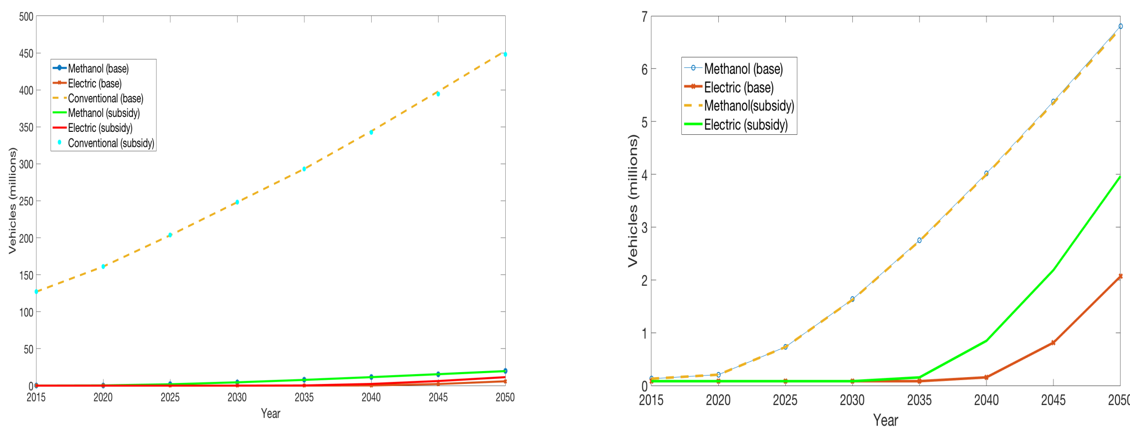
(a) All three vehicle types (b) Expanded view of electric and methanol vehicles

Figure 7-4: Private passenger vehicle stock in China by vehicle type for the methanol vehicle subsidy scenario

As can be seen from Figure 7-4, the addition of the methanol vehicle subsidy results in a faster increase in the number of methanol vehicles into the market. Methanol vehicles displace some of the conventional vehicles that would have otherwise existed in the mix. In terms of market shares achieved, the impact of instituting a methanol vehicle subsidy is similar to instituting a gasoline tax for methanol vehicles, reaching a market share of 6%. However, as expected, the methanol vehicle subsidy has no impact on electric vehicles, and their market share remains at the base case value of 1% market share in 2050.

7.2.2 Impact of Electric Vehicle Subsidy

Just earlier this year, the Chinese government changed its policies surrounding electric vehicles with the aim of pushing electric car manufacturers to improve the quality of their products. Subsidies on pure electric cars were set to decline by 20% and a cap was placed on subsidies at local government levels. Despite the short term pressure imposed on the electric car manufacturers, the goal of the policy changes is to help the industry grow strongly. The new policy limits central government subsidies for electric vehicles to 44,000 Yuan (equivalent to USD 6,333) for cars with a driving range of 250 kilometers and above. Additionally, subsidies at local-government levels are capped at 50% of the level offered by the central government [18]. To understand the impact of electric vehicle subsidies, three runs are conducted. These are implementing the electric vehicle subsidy only on a national level, implementing the subsidy on local-government levels, and implementing it on both national and local levels. The trends of the three scenarios are similar, with the magnitude of the impact differing depending on the total end amount of subsidies.



(a) All three vehicle types

(b) Expanded view

Figure 7-5: Private passenger vehicle stock in China by vehicle type for the electric vehicle subsidy scenario

Figure 7-5 displays the impact of implementing both central government and local government electric vehicle subsidies on the total vehicle stock. The impact of the subsidy is minimal, bringing the total electric vehicle market share to 2% from a base case of 1% market share in 2050. The reason for this minimal improvement in vehicle penetration is because even with the availability of subsidies, it is applied to the vehicle portion of the input structure of electric vehicles. In the case of electric vehicles, more than half of the input shares are dedicated to the service costs associated with electric vehicles, which include infrastructure investments, maintenance costs, and adjustments required on the consumer end, thereby hindering technology penetration within the market.

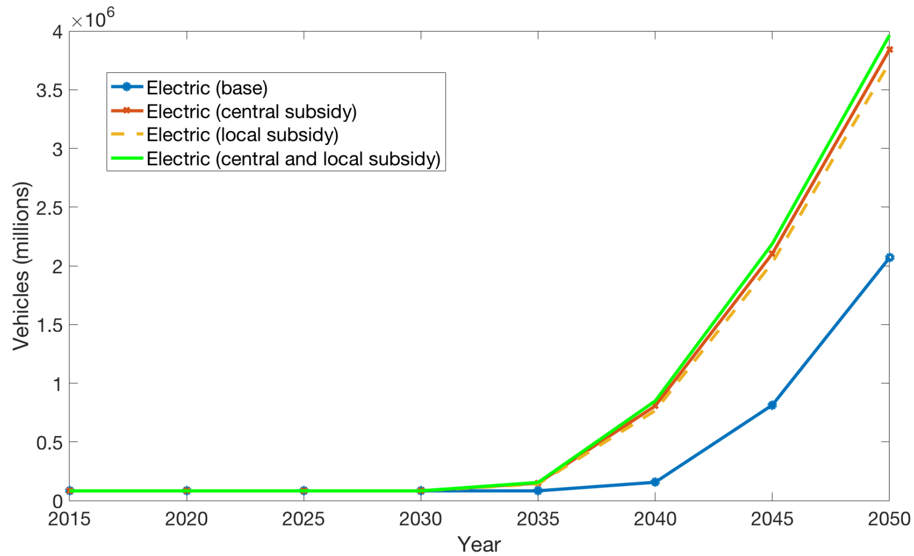
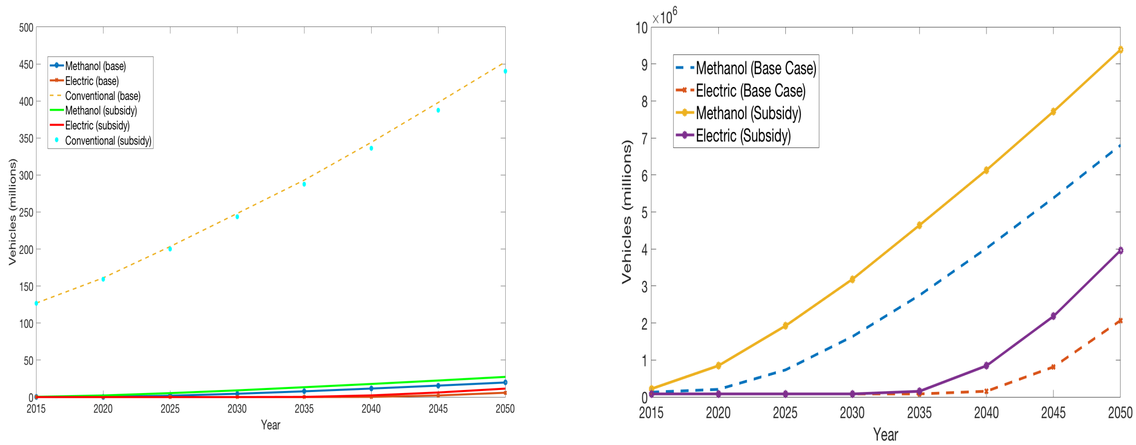


Figure 7-6: Difference of impact between central government and local government electric vehicle subsidies

Figure 7-6 affirms the initial hunch on model projection in terms of the magnitude of impact of different levels of subsidies. As mentioned, the addition of both subsidies results in minimal improvement in technology penetration. The subsidy is too small to make electric cars economical at early years and the penetration rate at later years is set by the technology specific factor, limiting technology penetration.

7.2.3 Impact of Both Methanol and Electric Vehicle Subsidies

The most realistic scenario, policy-wise, is that both methanol vehicle subsidies and central and local electric vehicles are going to be implemented simultaneously in China. Especially due to the minimal coordination in China on aligning local government incentives with incentives at the federal level, this scenario is very likely to take place due to the variation in incentives of the different stakeholders involved. Figure 7-7 displays the results of running both sets of subsidies simultaneously. Together, methanol and electric vehicles achieve an 8% market share, with 6% taken up by methanol vehicles. These results bring up questions on the effectiveness of existing policies in addressing the goals set by the Chinese government in increasing the share of alternative vehicle technologies in the marketplace. Additional infrastructure investments in terms of station development are required to bring down the service costs incurred by the end consumer. Additionally, more aggressive subsidies are needed to push consumers towards electric and methanol vehicles. Overall, across all policy options, the implementation of the optimal gasoline tax has the greatest impact on vehicle market shares. Even with the increase of the gasoline tax, the gasoline tax in China would still stand well below those of other countries, such as Turkey which stands at 4.29 USD/gallon of gasoline.



(a) All three vehicle types

(b) Expanded view of electric and methanol vehicles

Figure 7-7: Passenger private vehicle stock in China by vehicle type for the scenario with both methanol vehicle and electric vehicle subsidies

The application of vehicle subsidies also impacts the methanol consumption levels in China. Figure 7-8 displays the increase in methanol consumption from the application of the vehicle subsidies. In 2050, the amount of methanol consumed for transportation is 43.95% higher in the scenario where vehicle subsidies are applied for both methanol and electric vehicles compared to the base case scenario.

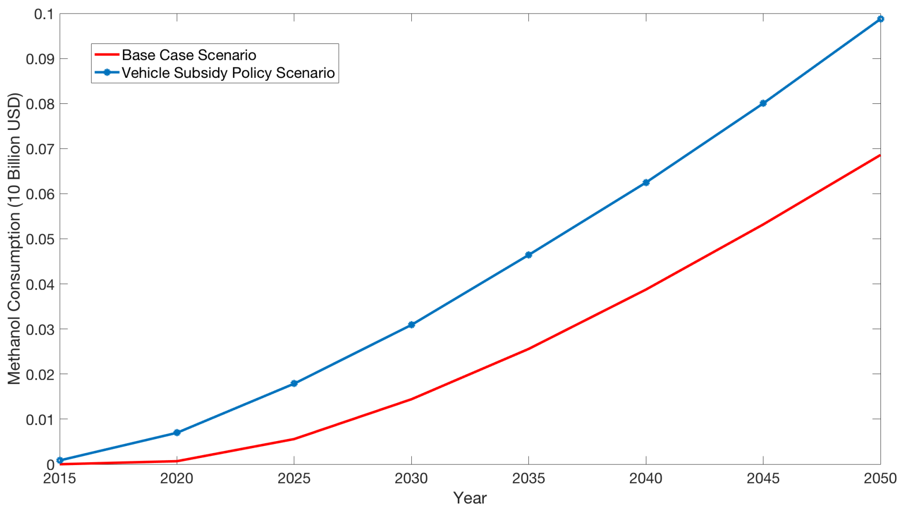
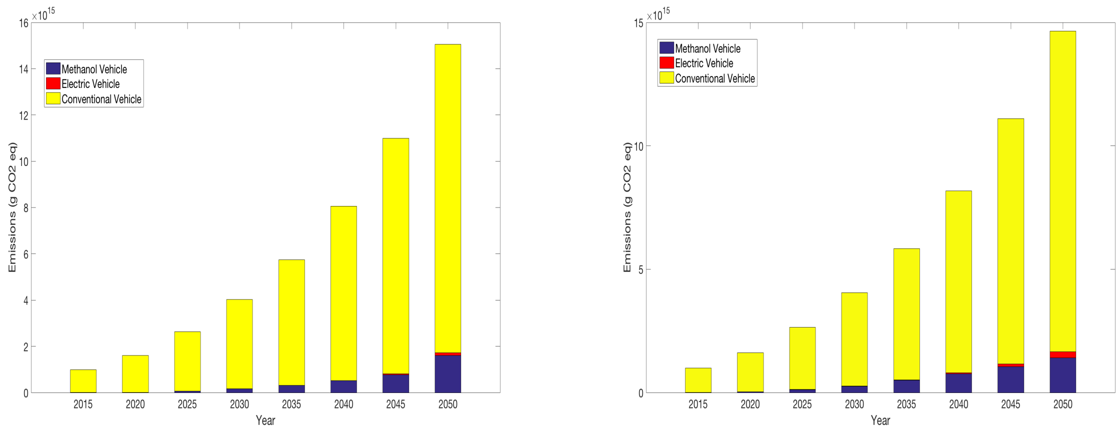


Figure 7-8: Increase in methanol consumption from the application of vehicle subsidies

7.2.4 Emissions Impact of Vehicle Subsidies

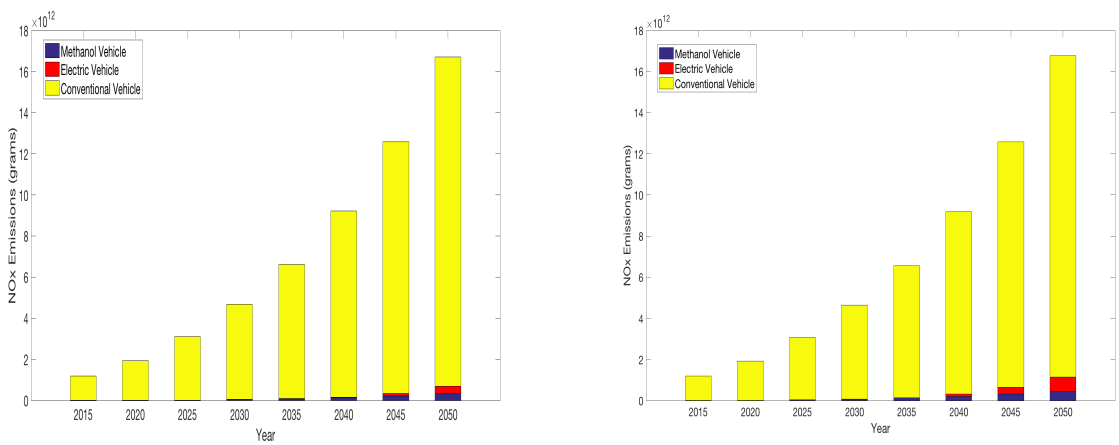
Figure 7-9 displays the impact of instituting vehicle subsidies on greenhouse gas emissions. This scenario accounts for both local and central electric vehicle subsidies. Overall, we see an increase in emissions overall in the policy scenario, mostly because of the increase of use of methanol vehicle and the larger emissions associated with their use. Despite the increase in use of electric vehicles, which result in lower emissions on a kilometer distance driven bases, the benefit is offset by the increase in emissions resulting particularly from use of methanol derived from coal.



(a) Base Case Scenario

(b) Policy Scenario

Figure 7-9: Comparison of greenhouse gas emissions from the private passenger vehicle transportation fleet in China between the base case and vehicle subsidy policy scenarios



(a) Base Case Scenario

(b) Policy Scenario

Figure 7-10: Comparison of NOx emissions from the private passenger vehicle transportation fleet in China between the base case and vehicle subsidy policy scenarios

7.3 Banning the Use of Methanol Imports as a Fuel

Existing regulations in China ban the use of natural gas in lieu of coal for local methanol production. The high natural gas prices in China are likely to continue the trend of limited methanol output in China from natural gas sources. Additionally, there exist multiple motivations for using coal for methanol production, including weak coal prices due to overcapacity and stricter environmental laws offering firms attractive margins for producing methanol from coal. Additionally, China currently meets more than 10% of its methanol demand through imports, about 40% of which are from Iran, 38% from the rest of the Middle East, and the rest from Southeast Asia, New Zealand and other countries [49]. If one views methanol fuel produced from coal from an energy security perspective, then a very plausible scenario resulting from this view is China banning imports of methanol for use as a fuel and continuing the existing trend of producing domestic methanol from coal. This scenario was simulated in EPPA by turning off methanol production from natural gas. The results show that the number of methanol vehicles are similar to that of the base case scenario because the cheap coal prices and the lower methanol prices relative to gasoline favor the building of additional coal to methanol plants to meet the required demand from the private vehicle transportation sector. Figure 7-11 displays the prices of the relevant energy commodities in the base case scenario compared to when methanol production is limited to the coal feedstock. The graph shows that methanol prices are slightly lower in the scenario where methanol imports are banned compared to the base case scenario. Additionally, there exists a shift in prices in 2025 due to the dip in the price of coal from the increased production of methanol in the previous period in 2020 and the decrease in gasoline prices due the lowered demand for gasoline in that period. As the penetration of methanol vehicles increases, the price of methanol deviates less from the base case scenario.

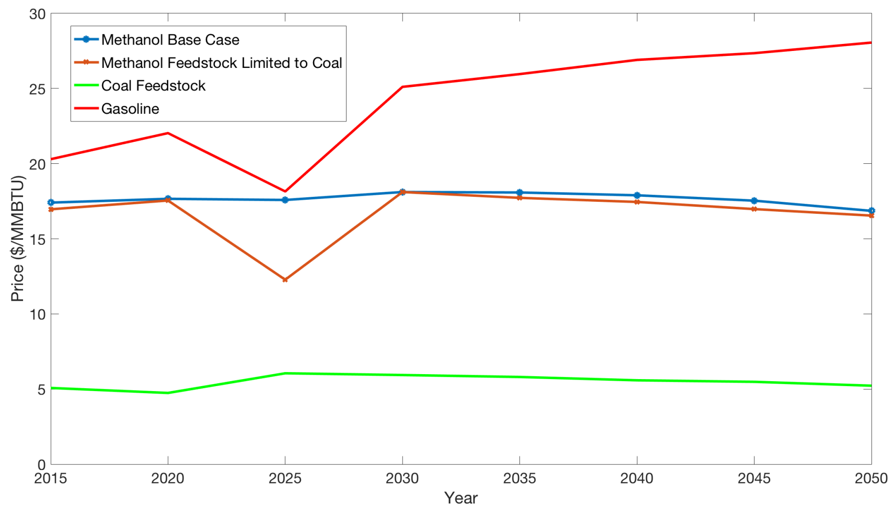


Figure 7-11: Variation of prices when turning off the ability to produce or import methanol produced from natural gas

Figure 7-12 displays the greenhouse gas emissions from methanol vehicles associated with the banning of methanol imports. As can be seen from the figure, greenhouse gas emissions from methanol vehicles are about twice the magnitude of that of the base case scenario. This is due to the higher carbon intensity of the methanol production process from coal, since the greenhouse gas emissions for methanol produced from coal is 432.9 g CO2 eq/km compared to 97.7 g CO2 eq/km for methanol produced from natural gas.

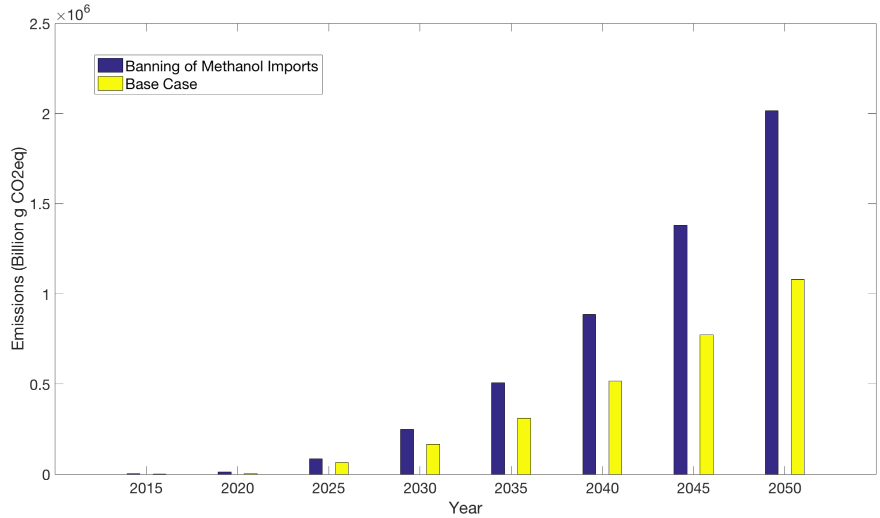
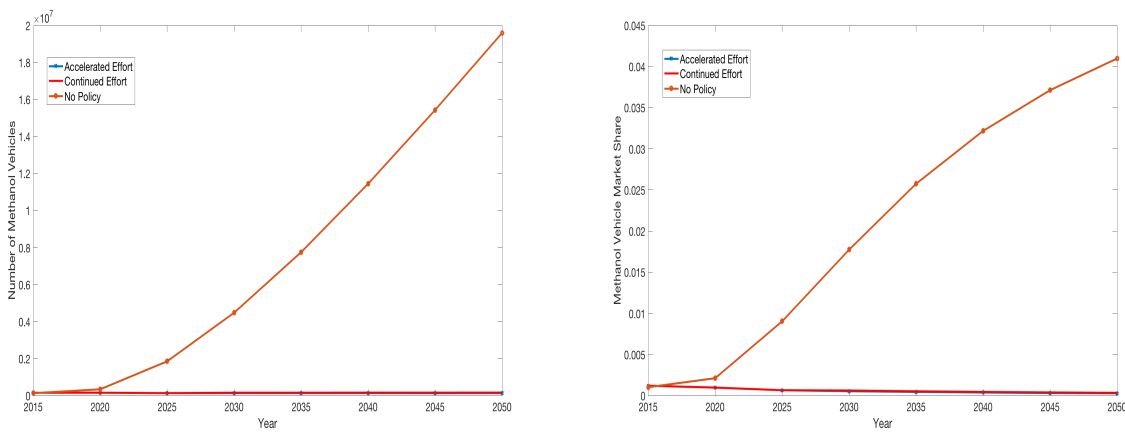


Figure 7-12: Increase in greenhouse gas emissions from methanol vehicles associated with the banning of methanol imports

7.4 Carbon Dioxide Emissions Cap

To understand the magnitude of impact on privately owned passenger vehicles that will come as a result of China's policy directives, various scenarios are run in which total yearly carbon dioxide emission levels are capped at different values. The carbon dioxide emission levels the scenarios are run at are based on work by Zhang et al. in which three levels of policy effort are simulated to understand their impact on the level of emissions from China. The first level is a continued effort scenario in which existing policies are extended beyond 2020. The second level is an accelerated effort scenario that reflects China's newly announced policy efforts. The final level is the result of a no policy scenario in which no effort is made to reduce total carbon dioxide emissions [29]. The exact emission values and the corresponding carbon dioxide intensity values (in terms of million metric tons of carbon dioxide per billion 2007 USD) used in the simulations are presented in Appendix A.4.

Figure 7-13 displays the penetration of methanol vehicles under the three carbon policy scenarios. It is clear that the greatest impact on methanol vehicle penetration results from the implementation of carbon caps. Under the no policy scenario, methanol vehicle penetration increases to 19.6 million vehicles. With the implementation of the continued effort and accelerated effort carbon cap limits, the growth in methanol vehicles declines, and the overall number of methanol vehicles declines due to the retirement of existing methanol vehicles and methanol vehicles obtained in 2015 and 2020 while the carbon cap impact is still minimal. In the no policy scenario, the market share occupied by methanol vehicles compared to the overall vehicle mix increases from 0.1% to 4.1%, an increase of 4%. With both the continued effort and accelerated effort policy scenarios, the market share occupied by methanol vehicles decreases from 0.1% to 0.03%.

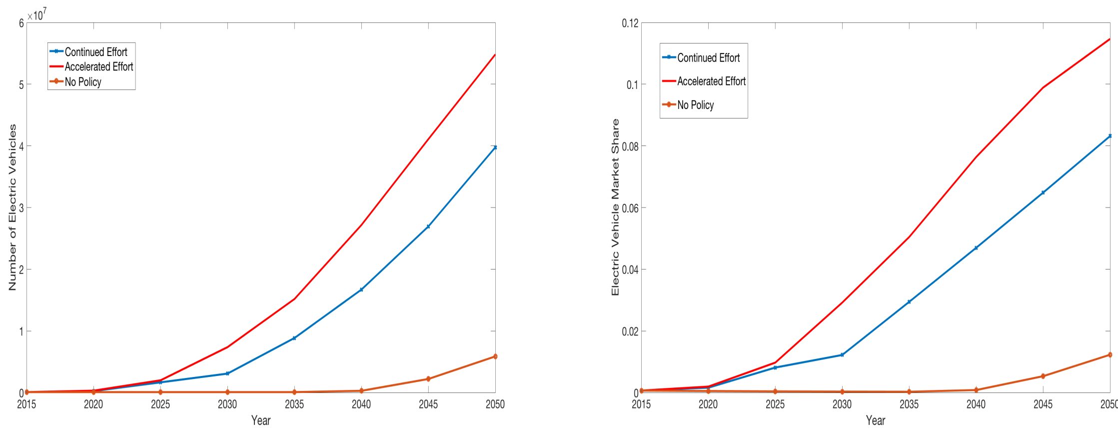


(a) Methanol vehicle penetration

(b) Methanol vehicle market shares

Figure 7-13: Methanol vehicle penetration and market shares achieved in China under different carbon cap levels

Figure 7-14 displays the penetration of electric vehicles under the three carbon policy scenarios. The magnitude of impact of the carbon policy scenarios is also large for electric vehicles. As can be seen from the graphs, the penetration of electric vehicles speeds up with increasing stringency of the carbon policies, as seen from the increase in the slopes of the electric vehicle market penetration lines. Under the no policy scenario, the number of electric vehicles reaches 5.87 million vehicles, achieving a 1.23% vehicle market share in 2050 from a 0.07% market share in 2015. Under the continued effort scenario, the number of electric vehicles reaches 39.8 million vehicles, achieving a 8.32% market share in 2050. Under the accelerated effort scenario, the number of electric vehicles reaches 54.8 million vehicles, achieving a 11.47% market share in 2050. Overall, it is easily seen from the graphs that instituting stringent national carbon caps have the greatest impact in terms of increasing the penetration of methanol vehicles and electric vehicles.



(a) Electric vehicle penetration

(b) Methanol vehicle market shares

Figure 7-14: Electric vehicle penetration and market shares achieved in China under different carbon cap levels

7.5 Policy and Regulatory Considerations and Recommendations

The results of this chapter suggest two policy extremes that the Chinese government could undertake. The first is a national security focused approach in which the use of methanol vehicles is heavily encouraged and imports of methanol from locations producing it more cheaply using natural gas sources is banned. The large coal reserves in China allow locally produced methanol to satisfy the demand for methanol vehicles projected by the EPPA model. This approach has detrimental GHG emission ramifications, as the high carbon dioxide intensity of coal-based methanol leads to large increases in GHG emissions, 6.88% in 2050. The second extreme is a full commitment to reducing greenhouse gas emissions, which entails either continued or accelerated effort in achieving set carbon dioxide emissions cap. This scenario completely dampens the reach of methanol vehicles, and speeds up the reach of electric vehicles in the place of conventional vehicles.

In between the two, less dramatic changes are seen with instating a gasoline tax or a methanol/electric vehicle subsidy. Both allow methanol and electric vehicles to capture some of the market shares currently satisfied by conventional vehicles, with the policies helping expand the reach of methanol vehicles at a greater level compared to electric vehicles. At their present state, electric vehicles are too expensive, specially due to the large infrastructure changes they require, and thus are heavily dependent on subsidies. China has decided to phase out electric vehicle subsidies by 2021. This will have a large impact on the vehicle mix. Electric vehicles can still capture part of the market if consumer attitudes towards electric vehicles become more favorable, prices of electric vehicles go down, and thus result in an increase in the demand for electric vehicles, pushing investments in electric vehicle infrastructure. If those factors play out in the opposite direction, methanol vehicle could potentially capture a small portion of the market share that would have otherwise been captured by electric vehicles. More likely though, conventional vehicles are likely to remain dominant.

A few policy recommendations emerge from this section. First, the Chinese government needs to determine its long-term goals in the light duty vehicle sector and fuel sector. This will allow policy-makers to introduce policies that fit those goals, and the policies can be designed to account for and minimize unintended externalities that can result. Second, the implementation of a carbon cap requires rapid changes in the light duty vehicle sector. If the Chinese government wants to meet the caps, heavy investment in electric vehicle infrastructure and research and development effort in battery technologies are needed to push the economics and consumer perception favorably towards electric vehicles and achieve the market shares projected by the EPPA model. Third, policy-makers need to be aware of the negative environmental impacts associated with the large scale increase in coal-based methanol vehicles. As such, cost benefit analyses are required to determine the extent of the benefits resulting from the use of local resources in terms of job creation and national security gains compared to the costs of environmental losses. These cost benefit analyses involve a lot of value judgment on the relative importance of different criteria, and therefore require the involvement of stakeholders coming from different backgrounds from academia, to the government, to the industry to allow for a more informed and inclusive decision-making process.

Chapter 8

Conclusions

This chapter provides a summary of the results obtained in this thesis and the insights they provide on a macroscopic level, highlighting the main factors impacting the market entry of methanol and electric vehicles, the associated economic and environmental impacts, and the importance of existing and potential future policies on the light duty vehicle sector in China. It then explains some of the limitations associated with the study, as well as potential areas for future work to improve upon the results and further expand the scope.

8.1 Overall Conclusion

The main reason for methanol's attractiveness in the marketplace is its economic advantage compared to gasoline. Other advantages include its potential for local production through the use of coal reserves and ability to help with air quality issues as it can reduce emissions of carbon monoxide, hydrocarbon, and nitrogen oxides. The results of this thesis show that M85 and M100 vehicles can achieve enough of a scale in China for them to warrant attention from both the industry and the government. The scale of M15 reach is less significant in its current state, as it currently only displaces 8% of the gasoline vehicle pool, but consumer losses due to the illegal blending of methanol with gasoline shows the urgent need for governmental intervention, either through stricter enforcement of existing gasoline standards, the implementation of a national standard for M15, or through the introduction of specific regulations on methanol use. Methanol use in M85 and M100 vehicles works economically with existing tax policies, with methanol vehicles achieving a market share of 4% by 2050 in the base case scenario. However, methanol vehicles are also associated with implementation challenges that prevent the expansion of their reach on a large scale. According to the EPPA model, the market penetration of methanol vehicles will be very slow despite the economic driver. The shift to methanol vehicles requires new vehicles or vehicle conversions, new methanol production plants, and new or converted tanks in gas stations. As long as China is able to buy oil on world markets, particularly at the existing prices, there lacks a strong enough economic driver to encourage much investment in these infrastructures. This negatively impacts the attractiveness of methanol vehicles from a consumer standpoint. In turn, the lack of support for methanol vehicles from a consumer standpoint deters investment in the required infrastructure for methanol vehicles, further contributing to the slow pace of this transition.

The impacts of large scale penetration of methanol vehicles on the environment is different depending on whether the methanol is produced from coal or natural gas. Methanol vehicles overall result in lower NOx and carbon monoxide emissions due to methanol being a cleaner fuel compared to gasoline when burned. However, in terms of GHG emissions, methanol vehicles running on methanol from natural gas result in modest increases in GHG emissions. On the other hand, methanol vehicles running on methanol from coal result in considerable increases in GHG emissions. Regardless of methanol feedstock, overall, methanol vehicles do not address the GHG challenge and China's commitments to reducing GHG emissions. This leads to the main reason supporting the large scale introduction of methanol vehicles in China, and it is that methanol helps achieve national security objectives in China by reducing China's reliance on oil imports and instead relying on local reserves for liquid fuel production. EPPA shows that the banning of methanol imports results in China expanding its local production of methanol from coal to satisfy the demand for methanol as a fuel.

While resulting in serious environmental consequences, methanol from coal does help China achieve national security gains, and this benefit could also be replicated in other countries with large natural gas reserves, such as the United States.

Finally, governmental policies play a big role in determining the magnitude and reach of both methanol and electric vehicles. The results of EPPA simulations show that both gasoline taxes and vehicle subsidies result in a decrease in the share of conventional vehicles and corresponding increases in shares of methanol and electric vehicles. However, the effects are small compared to the implementation of a national carbon cap that matches China's commitment to international efforts in reducing greenhouse gas emissions. The balance of interests between different Chinese provinces and the national government strongly affects which policies get implemented, and the resulting consequences can have strong implications in how China's future light duty vehicle sector grows in the next few decades as the rise in vehicle ownership continues.

8.2 Study Limitations

This section highlights some of the limitations associated with this thesis work. First, the structure for M15 as a substitute for gasoline needs to be introduced to EPPA to better reflect the realities of the existing Chinese transportation market. This will add further insight into the resulting impact on the demand for methanol use in transportation. Additionally, it is worth further considering the impact of fuel taxes on the vehicle penetration results. Currently, the fuel taxes in China favor methanol use. However, this is likely to change if methanol becomes widely used and the Chinese government considers taxing methanol as a source of revenue generation. Additionally, car manufacturers are continually investing in programs to improve the efficiency of the internal combustion engine in addition to new technologies. While the EPPA model used in this work accounts for technological advancements with an Autonomous Energy Efficiency Improvement (AEEI) parameter, it is of course difficult to accurately predict technology advancements up to the year 2050.

Shifting to using methanol as a fuel allows for gasoline replacement in the most compatible way, specially in terms of infrastructure. However, environmentally, there could exist greater potential in using natural gas in CNG or LNG forms. The addition of the CNG and LNG pathways in the EPPA model would allow for a more informed analysis in determining optimal choices that account for the trade-offs among performance, infrastructure, economics, and environmental impacts associated with each pathway.

A major limitation of the EPPA model is its inability to capture chicken-and-egg dynamics. In this work, a penetration factor was assumed based on trends observed with past technologies in the transport sector. While this rough approach is suitable for the aggregate analysis obtained through the use of a CGE modelling framework, a more specific city-level or even province-level analysis would require the involvement of system dynamics modelling that allows for the determination of the feedback effects between infrastructure development and vehicle penetration that can then be fed back into the EPPA model through modification of the technology specific factor. In the current model, it takes methanol many decades to penetrate the transportation fuel market even though it has an economic advantage over gasoline. It would be interesting to determine the factors that would have to change to significantly accelerate the fuel shift.

A major advantage of the EPPA model is its ability to endogenously calculate world oil prices depending on supply and demand dynamics globally. However, in reality, oil markets do not always behave competitively. Rather, monopolistic behaviour by certain member countries of the Organization of the Petroleum Exporting Countries (OPEC) results in shifts of prices, which greatly impact the transportation sector. One way to overcome this limitation is to exogenously set the price of crude oil in the EPPA model, based on assumptions of future monopolistic behaviour. However, this can yield unexpected results because the exogenous determination of crude oil prices in EPPA dramatically impacts prices of other energy commodities in different sectors. Therefore, one must exercise caution in simulating scenarios in which oil prices are an input and run sensitivity analyses to ensure that results are credible when prices in other sectors are being impacted.

8.3 Future Work

In the EPPA version used for this thesis, China is set up as one region. This simplifies the inputs needed for the model. However, it also prevents us from analyzing the detailed differences amongst China's different provinces. Disaggregating China in EPPA into different regions depending on their economic status would allow us to capture variation in results due to the urban-rural divide in the country as well as allow us to test the impact of local policies on the specific regions for which they are intended to target rather than applying them on China as a whole. Moreover, EPPA currently represents the vintaging of vehicles through a fixed structure in which at any given time, 40% of the private vehicle fleet is categorized as new (0-5 years old) and the remaining 60% of the private vehicle fleet is characterized as used (greater than 5 years old). While this distribution is plausible in developed countries like the United States, it is a big assumption for emerging economies like China in which new cars constitute a greater percentage of the vehicle mix. Refining the mix of vehicles will allow us to gain better results in terms of vehicle penetration rates.

CNG is already present in the past version of EPPA, EPPA 5. However, the work on CNG modelling in EPPA is limited to the United States region and its base year data is based on 2004. By updating the base year data and collecting input share data for CNG vehicles in the case of China, one could update EPPA 6 with CNG details. This would allow one to have a more complete picture of the light duty private vehicle mix in China, since there is an interest in China in pushing for the expansion of CNG vehicles since some regions in China, such as Sichuan province, are rich in natural gas and thus can help decrease oil consumption and reduce the country's dependence on imports of oil [37]. However, since China is overall not rich in natural gas, the government is simultaneously aggressively pushing for the increase of penetration of electric vehicles. However, electric vehicles in China are still dependent on subsidies. Therefore, conditions are likely to change during 2021, which is when China has decided to phase out electric vehicle subsidies. The phase out of electric vehicle subsidies could potentially have a significant impact on the vehicle mix, including both methanol and CNG vehicles, depending on the economics and advancements in the technologies in the next few years.

Additionally, the current version of EPPA assumes an income elasticity of demand of one for the household transportation sector [52]. In this case, the income elasticity of demand is the ratio of the percentage change in demand for private vehicles to the percentage change in income. An income elasticity of one has limitations because it does not take into account the extreme ends of the spectrum. One one end, the income elasticity value could be greater than one for countries with emerging economies in which many people are climbing into the middle class. On the other end, the income elasticity value could be less than one for developed countries in which most people are on the upper end of the middle class or in the upper class and who have saturated their income expenditures on personally owned vehicles. Adjusting the income elasticity values for household transportation so it is reflective of the differences in different regions will allow us to better quantify the expenditure levels.

Finally, there exists support in academia for turning to the *Methanol Economy* as the means for transitioning to a sustainable economy that accounts for increased energy demand in emerging economies, the limitations of energy supply, and the increasing pressure on reducing emissions to achieve climate change goals. Therefore, creating an additional methanol production pathway in EPPA in which methanol is produced renewably, using hydrogenative recycling of carbon dioxide to methanol from industrial exhausts, would be valuable to understand the cost and supply limitations that need to be overcome for this option to be economical and impactful.

Appendix A

EPPA Inputs

This appendix describes the details of the inputs used in the EPPA model. Section A.1 describes the details of private passenger vehicle expenditures on fuel, services, and the vehicle itself for both Internal Combustion Engine (ICE) vehicles and for methanol fueled vehicles in China. These expenditure values are used for obtaining the input shares of the vehicle structure that are used in EPPA. Section A.2 describes the method used for obtaining the markup values used in the model, which include both a fuel markup and a vehicle markup. Section A.3 explains the conversion factors used for obtaining energy usage values from the base year monetary values reported in EPPA as well as the emission factors used to obtain the carbon emissions resulting from methanol vehicles. Finally, Section A.4 presents the carbon dioxide emission levels in 5-year intervals used for the carbon cap no policy, continued effort, and accelerated effort scenarios.

A.1 Input Shares: ICE and Methanol Fueled Vehicles

Table A.1: Household transportation private passenger ICE vehicle expenditures (10^{10} Chinese Yuan)

Year	Refined Oil	Vehicle	Services
2007	2.65	81.1	20.7
2008	5.68	98.4	21.7
2009	7.18	146	27.2
2010	10.0	162	32.6
2011	13.3	168	37.0
2012	15.6	174	44.1
2013	17.4	202	49.5
2014	19.1	218	51.6

Table A.1 displays the household transportation private passenger ICE vehicle expenditures in China. The assumptions and values involved in obtaining these expenditures are as follows:

1. Reported household gasoline consumption in China is obtained from the yearly China Statistical Yearbook. We assume that 100% of the consumption is taking place in the household transportation sector [59].

2. Vehicle expenditures are the product of the average new vehicle prices in China, $17859 in 2010 for example, and the number of passenger commercial vehicles sold per year, which are obtained from Statistics Portal [35][66].

3. Service expenditures are obtained through a product of the average per capita annual consumption expenditure of rural and urban households on personal household transport, and the respective urban and rural populations [59].

Table A.2: Household transportation private passenger methanol vehicle expenditures (10^{10} Chinese Yuan)

Year	Methanol	Vehicle	Services
2007	1.23	81.1	20.7
2008	2.30	98.4	21.7
2009	1.44	146	27.2
2010	2.29	162	32.6
2011	3.46	168	37.0
2012	3.94	174	44.1
2013	4.70	202	49.5
2014	5.15	218	51.6

Table A.2 displays the household transportation private passenger methanol vehicle expenditures. The assumptions and values involved in obtaining these expenditures are as follows:

1. Energy equivalence: 1 gallon of methanol has 49% of the energy of one gallon of gasoline [16].
2. Methanol prices for China are obtained from Bloomberg [47].
3. Historical gasoline prices in China are obtained from Reuters for the years 2007 to 2012 [69] and from the National Bureau of Statistics of China for the years 2013 and 2014 [58].

A.2 Markup Values

Two sets of markups are used as inputs to the EPPA model. The fuel markup is the ratio of the methanol fuel cost to the existing gasoline fuel cost. The vehicle markup is the ratio of the new methanol vehicle cost relative to the conventional ICE vehicle cost and includes infrastructure changes in fueling stations. Along with the input shares defined in the model, the markups influence the cost of the technology at any given year. In EPPA, every input share is multiplied by its respective markup to obtain the overall expenditure share for the fuel and vehicle inputs to the methanol vehicle sector. The next two sections describe the details of obtaining the markups and the values used in the simulations.

A.2.1 Fuel Markup

The fuel markup is the ratio of the fuel cost on a Yuan/mile traveled basis for the new backstop technology, in this case methanol vehicles, to the fuel cost on a Yuan/mile traveled basis for the existing technology, conventional vehicles. The fuel markup used in our base case simulations is 0.87[1].

A.2.2 Vehicle Markup

The vehicle markup is calculated by taking two factors into account; the increase in cost of a methanol-run vehicle compared to a conventional vehicle as well as the infrastructure investments required to satisfy the demand for methanol vehicles. Table A.3 displays the cost estimates used for obtaining the methanol vehicle markup. The infrastructure cost is obtained by assuming that 50% of the stations are refurbished using the lowest cost option outlined in Appendix D and the cost of the remaining 50% of the stations is the average of the three other options for station upgrades. The estimate for the infrastructure cost per vehicle is obtained using the assumptions for station refueling capacity shown in Table A.4. It is assumed that customers are filling tanks for 16 hours out of the 24 hours in a day.

[1]This is a conservative value as even though the base year (2007) fuel markup is slightly greater than one, the fuel markup value has been continuously on the decline since then, down to 0.6 in 2014, so 0.87 provides a good mid-point in between. Additionally, simulations have been conducted that go down to fuel markups of 0.65, with minimal impact in increasing vehicle penetration due to the limits imposed by the technology specific factor.

Table A.3: Parameters used for obtaining the methanol vehicle markup

Parameter	Cost ($)	Markup
2007 vehicle price	20805	
Modification cost/vehicle	210	
Infrastructure cost	48894	
Infrastructure cost/vehicle	153	
Methanol vehicle cost	21167	**1.017**

Table A.4: Assumptions on station refueling capacity

Parameter	Value	Unit
Refueling capacity	20.000	vehicles/hour
	320.000	vehicles/day

A.3 Conversion Factors

A.3.1 Base Year Monetary to Energy Conversion Factor

EPPA's outputs are in the form of monetary units, and have units of 10 billion US Dollars. In order to convert the monetary output to the corresponding energy value in units of Exajoules, the conversion factor for methanol is calculated as follows for the base year in 2007:

1. **Monetary value of an energy unit of methanol fuel from either coal or natural gas in the base year:**

$$\frac{USD \quad 378.125}{1 \quad metric \quad ton} * \frac{1 \quad metric \quad ton}{1263.74 \quad liters} * \frac{1 \quad liters}{15.8 \quad megajoules \quad (LHV)}$$

= **$0.01894** per megajoule (MJ) of methanol fuel used

2. **Conversion factor between the methanol vehicle output in EPPA and energy consumption of methanol transportation in exajoules**

$$\$10^{10} \quad * \frac{1 \quad vehicle}{\$20805} * \frac{17,500 \quad km \quad traveled}{vehicle} * \frac{2.4 \quad MJ}{1 \quad km} * \frac{10^{-12} \quad EJ}{1 \quad MJ}$$

= **0.02019 exajoule of methanol per 10 billion US Dollars spent on methanol vehicle usage**

A.3.2 Greenhouse Gas Emissions

The greenhouse gas emissions for the different stages of relevant fuel and drivetrain combinations are shown in Table A.5. These values are obtained from work by Shen et al [28]. Note that the values used for gasoline are the average values for gasoline used in a Direct Injection Spark Ignition (DISI) engine and gasoline used in a Port Injection Spark Ignition (PISI) engine.

Table A.5: Greenhouse gas (GHG) emissions of different stages of methanol and gasoline used in vehicles [28]

GHG Emissions (g eq.CO2/km)	Feedstock	Fuel	Vehicle	Total
PISI:M85 (NG)	20.4	97.7	184.4	302.5
PISI:M85 (coal)	23.9	432.9	184.4	641.2
Gasoline	13.7	38.9	180.5	233

A.4 Carbon Cap Levels

Table A.6 displays the CO_2 emissions values in million metric tons per year for the No Policy (NP), Continued Effort (CE), and Accelerated Effort (AE) scenarios. This data is based on work by Zhang et al. on evaluating various levels of CO_2 emission limits in China [29]. The values represent the total CO_2 emissions for all of China, including sectors other than transportation. The corresponding CO_2 intensity values in million metric tons per billion 2007 USD are also presented. The CO_2 intensity values are the inputs to the EPPA model for the carbon cap scenarios.

Moving forward, the adoption of CO_2 emissions restrictions will lead to massive changes to China's electricity sector. If CO_2 emissions restrictions are adopted, China will have to diversify its electricity sources and move away from traditional power production using fossil fuels. These changes will impact the emissions per km travelled for electric vehicles, and will further push the case for the widespread penetration of electric vehicles from a CO_2 emissions reduction perspective.

Table A.6: CO_2 emissions levels (million metric tons per year) and CO_2 intensity (million metric tons per billion 2007 USD) [29]

Year	**CO2 Emissions**			**CO2 Intensity**		
-	**NP**	**CE**	**AE**	**NP**	**CE**	**AE**
2010	7382	7382	7382	1.57	1.57	1.57
2015	9561	8803	8674	1.43	1.31	1.28
2020	12249	10269	9738	1.3	1.1	1.04
2025	14511	11216	10072	1.19	0.93	0.84
2030	16491	11774	10158	1.08	0.78	0.68
2035	18000	12000	9875	0.98	0.66	0.55
2040	19370	12102	9497	0.89	0.56	0.44
2045	29359	12084	9049	0.8	0.48	0.36
2050	21057	12046	8565	0.71	0.41	0.30

Appendix B

EPPA Outputs

This appendix describes the steps taken to convert the relevant outputs in EPPA from expenditure values to values that are more meaningful for the transportation analysis context. The outputs of the vehicle production structures in EPPA are reported in the form of expenditures with units of 10 billion US Dollars for every 5 year interval. To be able to meaningfully interpret the results, the expenditure output for the vehicle structures must be converted to the number of vehicles and the corresponding kilometers travelled in China. The details of this conversion is described in Section B.1. As for energy commodities, they are reported in EPPA in the form of price indices. For every commodity, the price level in 2007 is normalized to one and the price index for every five year period thereafter is reported as a price index relative to the price index of one in the base year. In order to compare the prices across various commodities, the prices indices are converted to their respective average prices. This is described in further detail in Section B.2.

B.1 Number of Vehicles and Kilometers Travelled

The number of private passenger cars is obtained for China for the year 2015 using information published by the Ministry of Transport of China. In 2015, China had 127 million private passenger cars [61]. It is worth noting that the value for the year 2015 is entered as the base value for the number of vehicles in EPPA for years thereafter instead of the value for the number of vehicles in 2007 because of the large increase in the stock of private vehicles in China between 2007 and 2015. Accordingly, EPPA calculates the number of vehicles for subsequent years by assuming that the growth in China is proportional to the growth in expenditure on household transportation.

Similarly, the Vehicle Kilometers Travelled (VKT) is obtained for private passenger light duty vehicles for 2007. In China, the VKT value for private light duty vehicles was 17,500 km [23]. Similar to the growth in the number of vehicles, the growth in VKT is defined in EPPA as being proportional to the growth in expenditure on household transportation.

B.1.1 Limitations with VKT definition in EPPA

Defining the VKT in the manner described by the previous section is plausible. However, it associated with limitations. First, different Chinese cities have different average VKT levels. For example, in 2009, Chengdu had an average VKT value of 15,200 and Foshan had an average VKT value of 22,000 [23]. Since China is not currently disaggregated in EPPA, implementing different base VKT values is not possible, but is a valuable parameter to take into account when considering how to best disaggregate China in EPPA for the purpose of modeling different transportation trends. Second, VKT is currently represented as proportionally increasing with increases in household expenditure on transportation. In reality, two alternatives exist. One is the existence of a threshold at which VKT reaches a plateau due to the existence of limits on car usage based on need. Another is a scenario in which an increase in household expenditure on transportation corresponds to a decrease in VKT. This is a plausible scenario in the case where individuals have more than one car or rely on other modes of transportation. Realistically, this scenario is only likely to occur within a small fraction of the population with enough financial liberty to be able to make such expenditure choices and is unlikely to have a dramatic effect in the near term for the case of China where many individuals do not yet have cars and are likely to obtain one as their financial position improves with the growth of China.

B.2 Commodity Prices

Absolute prices cannot be obtained in CGE models because CGE models are represented as a system of simultaneous equations in which one of the equations, against the same number of endogenous variables, is redundant. Therefore, the prices are expressed relative to a chosen base value. To convert the price indices from 2010 and onwards into the actual commodity prices, the price level for the commodities of interest are first obtained for the year 2007. These prices are 17.87 $/MMBTU for gasoline, 2.80 $/MMBTU for coal, 3.47 $/MMBTU for natural gas, and 19.83 $/MMBTU for methanol [47][9]. For each price index, the price level in 2007 is normalized to one. Therefore, we can obtain the commodity prices for the different years by comparing the indices relative to the prices in the base year. This allows us to compare the prices of the different energy commodities on an energy unit basis. As an example, the base year price for gasoline in China[1] was obtained as follows [69]:

Base year gasoline price in China:

$$\frac{Yuan \quad 5980}{1 \quad tonne} * \frac{1 \quad tonne}{8.5 \quad barrels} * \frac{1 \quad barrel}{5.25 \quad MMBTU} * \frac{USD \quad 1}{Yuan \quad 7.5}$$

$$= \textbf{\$17.87 per MMBTU of gasoline}$$

Table B.1 displays a summary of the base prices for gasoline, coal, methanol, and natural gas in China for 2007 [47][70][36].

Table B.1: Energy commodity base prices in China for 2007

Energy Commodity	**Price ($/MMBTU)**
Gasoline	17.87
Methanol	19.83
Coal	2.80
Natural Gas	3.47

[1] Since refined oil is not disaggregated in EPPA, the price of gasoline in any given year is obtained by multiplying the price index of refined oil for China in that year with the base price of gasoline in China in 2007.

B.2.1 Limitations with Calculating Commodity Prices

It is worth noting that one limitation of using a CGE model is that the estimation of future prices are all done relative to that of the base year. Therefore, if the price in the base year is singularly high or low compared to its adjacent years, our estimation of future prices will, as a result, be scaled upwards or downwards since the actual prices are obtained relative to the base price. Typically, the choice of a base year for the CGE model takes into account this limitation and tries to overcome it by choosing a base year that had relatively steady prices and that was not associated with any big shocks that could have swayed the prices in one direction or another.

Appendix C

Fuel Cost Analysis

This appendix presents the details of the fuel cost analysis conducted to determine the viability of using EPPA as a model for understanding the dynamics of penetration of methanol fueled vehicles in China. Since EPPA is a computable general equilibrium model of the world economy and assumes that human beings are rational in their decision choices, we can generally get an intuition for model behaviour since the model makes choices by maximizing consumer utility and minimizing producer costs. As such, one can predict that advanced technologies with large markups relative to existing technologies are unlikely to penetrate the market in the near future, or at all if the markup is very high. In this case, the advanced technology, despite having a large markup, might still be worth implementing in EPPA to allow the modeller to test the policy implementations required to lower the cost of the technology for the end consumer or alternatively, the technology advancements required to take place for the technology cost to be lowered enough for it to penetrate.

Table C.1 displays the gasoline cost in Yuan/mile for China for the years 2007 to 2014. This is obtained using light duty vehicle fuel efficiency values in miles/liter and the yearly gasoline price in China. The gasoline prices for the years 2007 to 2012 are obtained from Reuters [69], while the gasoline prices for the years 2013 and 2014 are obtained from the National Bureau of Statistics of China [58]. The four sets of vehicles correspond to different levels of fuel efficiency: average light duty vehicle

(21.4 miles per gallon), short wheel light duty vehicle (23.2 miles per gallon), long wheel light duty vehicle (17.1 miles per gallon), and new light duty vehicle (36.4 miles per gallon) for 2014 [62]. For the time frame presented (2007-2014), the gasoline fuel cost in Yuan/mile has overall increased due to the increase in price of gasoline in China despite improvements in the efficiency of light duty vehicles.

Table C.1: Gasoline fuel cost (Yuan/mile)

Year	**Gasoline Fuel Cost (Yuan/mile)**			
	Average LDV	**Short wheel LDV**	**Long wheel LDV**	**New LDV Car**
2007	0.75	0.70	0.94	0.51
2008	0.86	0.79	1.08	0.59
2009	0.92	0.85	1.16	0.61
2010	1.07	0.99	1.34	0.68
2011	1.19	1.09	1.49	0.71
2012	1.22	1.12	1.53	0.74
2013	1.19	1.09	1.49	0.71
2014	1.18	1.09	1.47	0.69

A similar analysis was conducted for the use of methanol in vehicles. Table C.2 displays the methanol fuel cost when methanol is used in existing internal combustion engines using true methanol prices [47]. For this preliminary analysis, the use of methanol in existing vehicles is assumed to be associated with no efficiency improvement, to be on the conservative side. In this case, the methanol fuel cost is on a decreasing trend due to the overall decrease in Chinese methanol prices for the time period [47]. The lower methanol fuel cost on a Yuan/mile base for a new LDV car compared to gasoline suggests that conducting an analysis on methanol vehicle penetration is useful. Since the EPPA model is a general equilibrium model that assumes consumer rationality, that individuals choose options that provide the most utility for the least cost, in the absence of constraints, the model will not predict options that do not have economical advantages.

Table C.2: Methanol fuel cost (Yuan/mile) - Existing engine with no efficiency improvement with the addition of methanol

Year	Methanol Fuel Cost - Existing Engines (Yuan/mile)			
	Average LDV	**Short wheel LDV**	**Long wheel LDV**	**New LDV Car**
2007	0.81	0.75	1.01	0.55
2008	0.75	0.69	0.95	0.52
2009	0.41	0.37	0.51	0.27
2010	0.54	0.49	0.67	0.34
2011	0.68	0.62	0.85	0.44
2012	0.67	0.62	0.84	0.41
2013	0.70	0.65	0.88	0.42
2014	0.69	0.64	0.87	0.41

Lastly, the analysis was repeated for the case of methanol being used in a dedicated alcohol engine adapted for the use of methanol. This engine is assumed to be associated with an efficiency increase of 5%. The results of the analysis are shown in Table C.3. Again, the cheaper cost of methanol is why the EPPA model will allow for the penetration of methanol vehicles in the Chinese market. Therefore, implementing this structure in EPPA is valuable as it can provide insight into the magnitude of the methanol vehicle penetration in the Chinese light duty vehicle sector.

Table C.3: Methanol fuel cost (Yuan/mile) - Alcohol engine with an assumed efficiency improvement of 5% over conventional engines

Year	**Methanol Fuel Cost - Existing Engines (Yuan/mile)**			
	Average LDV	**Short wheel LDV**	**Long wheel LDV**	**New LDV Car**
2007	0.77	0.71	0.96	0.52
2008	0.71	0.66	0.90	0.49
2009	0.39	0.36	0.48	0.25
2010	0.51	0.47	0.64	0.32
2011	0.64	0.59	0.81	0.42
2012	0.64	0.59	0.80	0.39
2013	0.67	0.61	0.84	0.40
2014	0.66	0.61	0.82	0.39

Appendix D

Distribution Cost Analysis

This appendix describes the distribution costs needed to obtain the adequate vehicle markups to account for the fact that additional methanol stations are required to be set up to satisfy the required demand for methanol vehicles. The fuel cost and distribution cost analyses allow us to determine the difference in cost of a methanol run vehicle relative to a conventional vehicle. The development of the required fueling infrastructure for methanol vehicles will be almost identical to existing refueling infrastructure, leading to minimal changes on the consumer end. Tables D.1 and D.2 display the material and labor costs associated with two options for obtaining methanol supply at stations. The first option, shown in Table D.1, is increasing the storage capacity at existing stations. The second option, shown in Table D.2, is displacing existing gasoline storage capacity with methanol. As expected, the addition of new tanks is more expensive than refurbishing existing tanks, about twice as expensive.

Table D.1: Infrastructure costs associated with increasing storage capacity at existing stations, at a capacity of 10,000 gallons (Data obtained for 1999 and converted to 2014 values for use in the model)[73]

Costs	**Add new 10,000 gal underground tank**	**Add new 10,000 gal above-ground tank**
Materials	$49,568	$63,835
Labor	$39,050	$15,620
Total	**$88,618**	**$79,455**

Table D.2: Infrastructure costs associated with displacing existing gasoline storage capacity with methanol, at a capacity of 10,000 gallons (Data obtained for 1999 and converted to 2014 values for use in the model)[73]

Costs	**Clean existing 10,000 gal underground tank**	**Install fiberglass liner in an existing 10,000 gal tank**
Materials	$22,151	$22,200
Labor	$5,077	$21,409
Total	**$27,227**	**$43,610**

As the table above indicates, an existing gasoline or diesel tank can be cleaned and the rest of the system can be provided with methanol compatible components for less than $28,000. Note that the cost estimates for the tank cleaning processes assumes that the work can be through existing manholes. In terms of the time requirements, tank cleaning takes less than a day, the installation of new piping and dispenser requires a week, and placing a fiberglass liner in an existing tank also requires a week [73].

Appendix E

Model Sensitivity

This appendix outlines the sensitivity of the EPPA model results to different geographical regions. It also presents a comparison of the EPPA crude oil price output to projections by the Annual Energy Outlook to give the reader a better sense of how EPPA projections of crude oil prices compare to other sources.

E.1 Geographical Variations

This section displays the geographical variations in electric vehicle penetration across v regions[1]. Figure E-1 displays EPPA-predicted electric vehicle market shares in different regions up to 2050. For electric vehicles, the input share for services (percentage spent on services relative to the overall expenditures) is higher not because the service expenditure is higher, but because the electricity cost is smaller compared to refined oil. Therefore, for electric vehicles, the increase in service input share is offset by the decrease in fuel input share. In this case, the reason for the higher penetration observed in the Middle East and China is due to the markups used for labor and maintenance, which are multiplied by the service input share in determining the overall price, being lower compared to the markups for labor and maintenance used

[1]Methanol vehicle penetration trends outside of China are omitted from this thesis due the inconsistency of trends for Russia and the Middle East. This is because the transportation data for the two regions require calibration for the case of the implementation of methanol vehicles to better reflect the variation in expenditure trends in these two regions. This is outside the scope of this thesis.

in other regions.

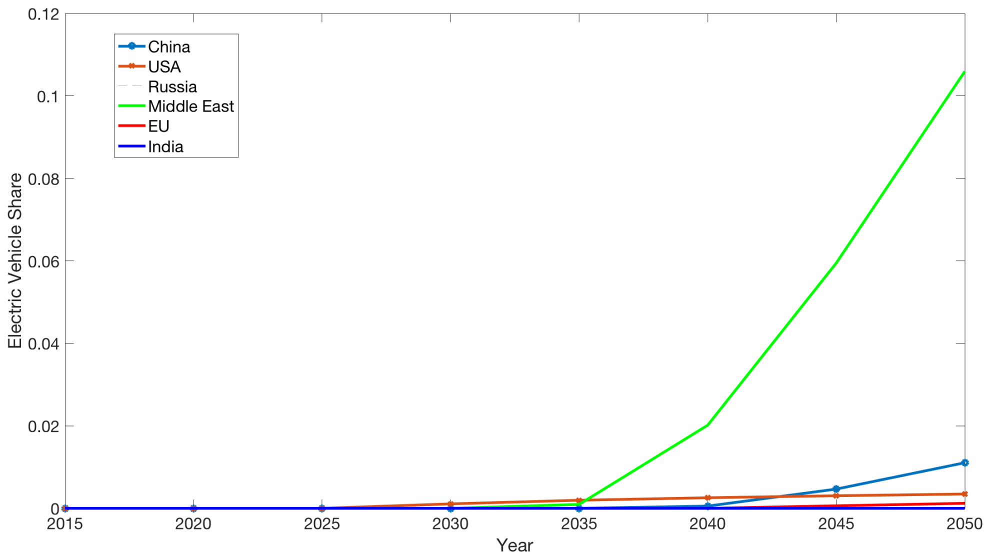


Figure E-1: Variation of electric vehicle market shares across EPPA regions

E.2 Crude Oil Prices

This section displays the crude oil prices projected by the EPPA model compared to the projections of the Annual Energy Outlook (AEO). As can be seen from Figure E-2, after 2020, EPPA's projections of crude oil prices closely match the reference oil price projections of the AEO.

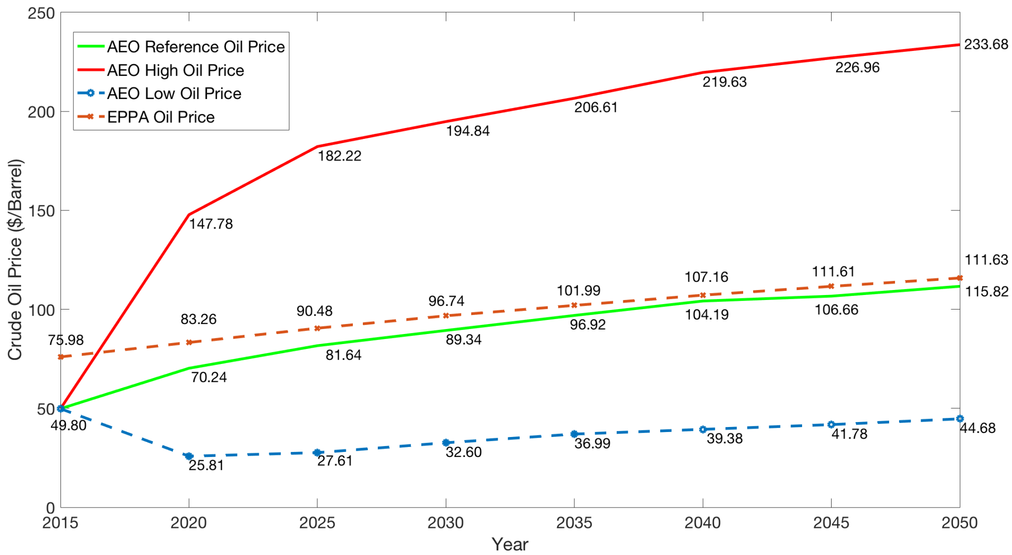


Figure E-2: Comparison between EPPA's projections of crude oil prices and the Annual Energy Outlook's crude oil price projections until 2050 [64]

Appendix F

Chinese Transportation Incentives

This appendix goes into further detail on existing transportation incentives in China. Table F.1 outlines policies in some of the Chinese cities regarding electric vehicles. As can be seen from the table, Beijing and Shanghai, which are the two major cities in terms of vehicle number, do not adopt the national catalog used by the Chinese Ministry of Industry and Information Technology (MIIT) for subsidy qualification. Additionally, some cities in China, specifically Shanghai, Hangzhou, and Nanjing have large inconsistencies between national and local subsidies. This leads to various negative impacts. First, it creates ambiguity among consumers about which models are included under existing subsidies. Moreover, because Beijing and Shanghai currently do not adopt the national MIIT catalog for local subsidy qualification, they are creating an advantage for their local models over foreign and other domestic vehicles. This creates inconsistencies in the eye of a consumer and also stands in the way of creating a local competitive market for electric vehicles in China.

Given that achieving a shift to electric vehicles requires deeper understanding of consumer preferences and behavior, existing subsidy structures must be designed to accelerate consumer adoption and industry innovation in the field rather than standing in its way. The existing subsidy structure for electric vehicles in China is creating an artificial market segmentation in which buying a Shenzhen manufactured car in Shanghai excludes a consumer from obtaining the subsidies that would have otherwise encouraged them to follow the path of buying an electric vehicle. Since the reason for this regional subsidy is the local industrial protection instead of reducing emissions, a market failure exists since a market that is small to begin with is now further hindered from progress by artificially segmenting it. The Ministry of Science and Technology, for the benefit of the electric vehicles market in China, should revise the existing standards to reflect a national subsidy value regardless of the city in which the vehicle is manufactured or sold, thereby encouraging electric vehicle adoption and also protecting interstate trade.

Table F.1: Policies in China surrounding electric vehicles [48][14]

City	Adopts National Catalog?	Local subsidy difference
Beijing	No	PHEV exclusive
		Total subsidy <60% of retail price
Shanghai	No	40,000 RMB for BEV
		30,000 RMB for PHEV
Shenzhen	Yes	N/A
Chongqing	Yes	Total subsidy <60% of the retail price
Guangzhou	Yes	Total subsidy <60% of the retail price
Hangzhou	Yes	30,000 RMB for BEV
		20,000 RMB for PHEV
Hefei	Yes	BEV with range >150 km
		Other EV: 20% of national subsidy
Nanjing	Yes	35,000 RMB for BEV
		20,000 RMB for PHEV
Tianjin	Yes	N/A
Wuhan	Yes	Total subsidy <60% of the retail price

Additionally, Figure F-1 displays the Chinese provinces strongly incentivizing electric vehicles and provinces with methanol blending programs (M15 or higher). As can be seen from the figure, there are stark variations amongst the provinces based on local priorities, illustrating the challenges associated with arriving at a policy solution that satisfies all parties. One could compare this situation to a tragedy of the commons situation in which individual provinces are neglecting the well-being of the country as a whole in the pursuit of individual provincial gains.

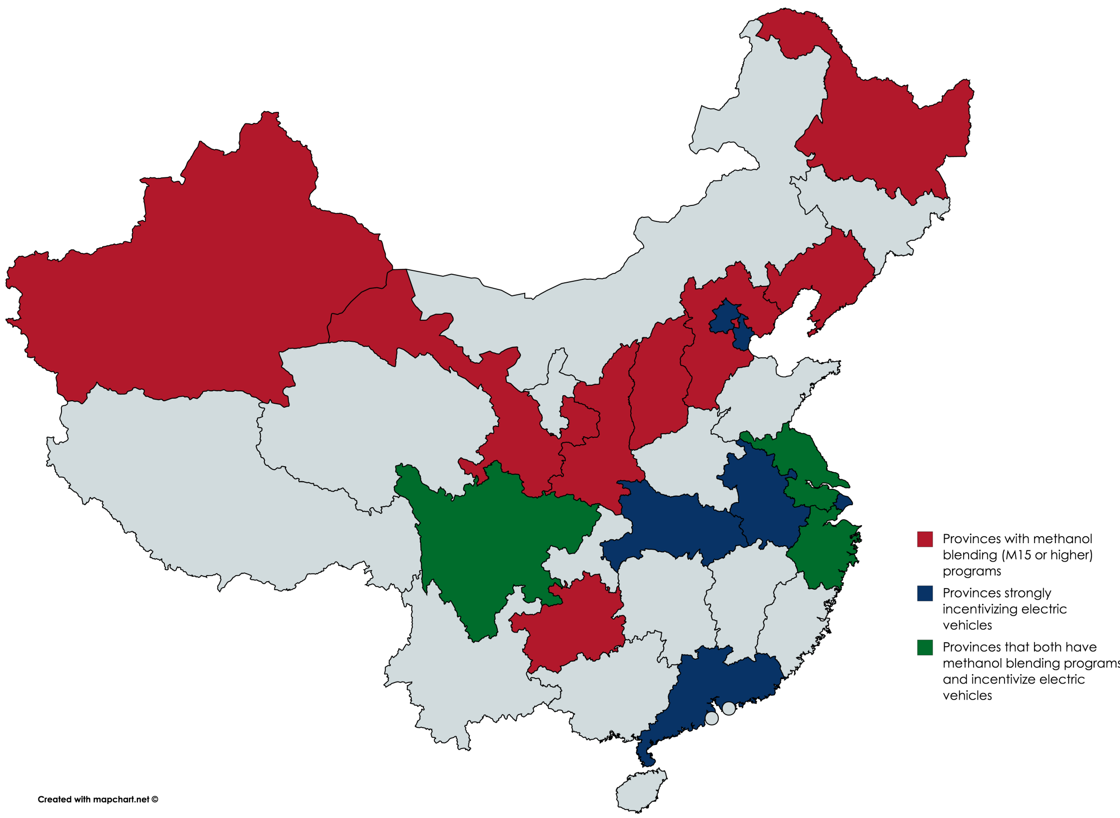


Figure F-1: Variation in incentives amongst different Chinese provinces

Bibliography

[1] An Interdisciplinary MIT Study. *The Future of Natural Gas*, 2011.

[2] U.S. Energy Information Administration. *How much gasoline does the United States consume?* https://www.eia.gov/tools/faqs/faq.cfm?id=23&t=10.

[3] U.S. Energy Information Administration. *U.S. Gasoline and Diesel Retail Prices*, April 2017.

[4] Stratas Advisors. China Expected to Expand Use of Automotive Methanol Blends. September 2015. https://stratasadvisors.com/Insights/China-Methanol-Blends.

[5] International Energy Agency. Global EV Outlook OECD/IEA. 2015. http://www.iea.org/evi/Global-EV-Outlook-2015-Update_1page.pdf.

[6] United States Environmental Protection Agency. The Social Cost of Carbon. https://www.epa.gov/climatechange/social-cost-carbon.

[7] D. Cohn at the MIT Energy Initiative. Personal communication, (December 25, 2016).

[8] The World Bank. Cost of Pollution in China, Economic Estimates of Physical Damages. 2007. http://siteresources.worldbank.org/INTEAPREGTOPENVIRONMENT/Resources/China_Cost_of_Pollution.pdf.

[9] The World Bank. World Bank Commodity Price Data (The Pink Sheet). 2016.

[10] R. L. Bechtold. Alternative Fuels Guidebook - Properties, Storage, Dispensing, and Vehicle Facility Modifications. *Society of Automotive Engineers, Inc.*, 1997.

[11] British Petroleum (BP). Statistical Review of World Energy. June 2011. http://www.bp.com/bodycopyarticle.do?categoryId=1&contentId=7052055S.

[12] L. Bromberg and W.K. Cheng. Methanol as an Alternative Transportation Fuel in the US:Options for Sustainable and/or Energy-Secure Transportation. *Sloan Automotive Laboratory - Massachusetts Institute of Technology*, page 78, July 2010.

[13] M.J. Brusstar and C.L. Gray Jr. High Efficiency with Future Alcohol Fuels in a Stoichiometric Medium Duty Spark Ignition Engine. *Society of Automotive Engineers, SAE paper*, page 3993, October 2007.

[14] M. Carboy. China's Green Move, Vehicle Electrification Ahead. August 2012. https://www.db.com/cr/en/docs/China_GreenCars_080712.pdf.

[15] P. E. Cassady. *The Use of Methanol as a Motor Vehicle Fuel*. PhD thesis, Argonne National Laboratory. https://web.anl.gov/PCS/acsfuel/preprint%20archive/Files/20_2_PHILADELPHIA_04-75_0059.pdf.

[16] US Alternative Fuels Data Center. Fuel Properties Comparison. October 2014. http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf.

[17] McKinsey Company. Supercharging the Development of Electric Vehicles in China. April 2015. http://www.mckinseychina.com/wp-content/uploads/2015/04/McKinsey-China_Electric-Vehicle-Report_April-2015-EN.pdf?5c8e08.

[18] China Daily. Tougher Rules for Electric Vehicle Subsidies. 2017. http://www.chinadaily.com.cn/business/motoring/2017-01/03/content_27842725.htm.

[19] The Economist. The East is Grey. 2013. http://www.economist.com/news/briefing/21583245-chinaworlds-worst-polluter-largest-investor-green\-energy-its-rise-will-have.

[20] China Radio International English. *China Considers Raising Fuel Consumption Tax*, 2016. http://english.cri.cn/12394/2016/01/26/4081s914596.htm.

[21] B. Wu et al. Comparison of Lean Burn Characteristics of an SI Engine Fueled with Methanol and Gasoline Under Idle Condition. *Applied Thermal Engineering*, 95:264–270, 2016.

[22] H. Hao et al. Natural Gas as Vehicle Fuel in China: A Review. *Renewable and Sustainable Energy Reviews*, 62:521–533, 2016.

[23] H. Huo et al. Vehicle-Use Intensity in China: Current Status and Future Trend. *Energy Policy*, pages 6–16, 2012.

[24] N. Laing et. al. Comparison of PM emissions from a Gasoline Direct Injected (GDI) Vehicle and a Port Fuel Injected (PFI) Vehicle Measured by Electrical Low Pressure Impactor (ELPI) with Two Fuels: Gasoline and M15 Methanol Gasoline. *Beijing Institute of Technology, Journal of Aerosol Science*, 57:22–31, 2013.

[25] P. Chen et al. Processes Simulation Study of Coal to Methanol Based on Gasification Technology . *International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering*, 4:351359, October 2010.

[26] Paltsev et al. Disaggregating Household Transport in the MIT-EPPA Model. July 2004. http://web.mit.edu/globalchange/www/MITJPSPGC_TechNote5.pdf.

[27] W. Ke et al. Well-To-Wheels Energy Consumption and Emissions of Electric Vehicles: Mid-term Implications from Real-World Features and Air Pollution Control Progress. *Applied Energy*, 188:267–377, 2017.

[28] W. Shen et al. Well-to-Wheels Life-Cycle Analysis of Alternative Fuels and Vehicle Technologies in China. *Energy Policy*, 49:296–307, 2012.

[29] X. Zhang et al. Carbon Emissions in China: How Far Can New Efforts Bend the Curve? *Energy Economics*, 54:388–395, 2016.

[30] Y. Hang et al. Emission Characteristics of Vehicles Fueled with Different Proportion Mixtures of Methanol-Gasoline Fuel. *Research of Environmental Sciences*, 24, 2011.

[31] Institute for the Analysis of Global Security. Methanol Blending in China, Trip Report. http://www.iags.org/Shanxi_trip_report.pdf.

[32] Methanol Fuels. *Demonstration Projects Using Methanol as a Vehicle Fuel from Around the World.* http://www.methanolfuels.org/on-the-road/demonstration-projects/.

[33] N. Hosoe, K. Gasawa, and H. Hashimoto. *Textbook of Computable General Equilibrium Modelling: Programming and Simulations*, volume 1, chapter 2, pages 13–22. 2006.

[34] A. Greszler. DME from Natural Gas or Biomass: A Better Fuel Alternative. *SAE International*, 2013.

[35] H. He and J. Tu. The New Passenger Car Fleet in China, 2010. *The International Council on Clean Transportation*, page 70, 2012.

[36] A. Hu and Q. Dong. On Natural Gas Pricing Reform in China. *Natural Gas Industry B*, 2:374382, October 2015.

[37] T. Wang, Visiting Student in the Green Group at MIT. Personal communication, (April 27, 2017).

[38] Methanol Institute. *Methanol Facts, China: The Leader in Methanol Transportation*, 2016. http://www.methanol.org/wp-content/uploads/2016/06/China-Methanol-Fact-Sheet-1.pdf.

[39] International Energy Agency Advanced Motor Fuels. Methanol. http://www.iea-amf.org/content/fuel_information/methanol.

[40] V. Karplus. *Prospects for Plug-in Hybrid Electric Vehicles in the United States: A General Equilibrium Analysis*. Master's thesis, Massachusetts Institute of Technology, June 2008.

[41] P. Kooy and C.M. Kirk. *The Production of Methanol and Gasoline*. http://nzic.org.nz/ChemProcesses/energy/7D.pdf.

[42] O.C. Kragha. *Economic Implications of Natural Gas Vehicle Technology in U.S. Private Automobile Transportation*. Master's thesis, Massachusetts Institute of Technology, June 2010. https://globalchange.mit.edu/sites/default/files/Kragha_MS_2010_0.pdf.

[43] National Energy Technology Laboratory. *Baseline Analysis of Crude Methanol Production from Coal and Natural Gas*. PhD thesis, U.S. Department of Energy, Office of Fossil Energy, October 2014. https://www.netl.doe.gov/energy-analyses/temp/BaselineAnalysisofCrudeMethanolProductionfromCoalandNaturalGas_101514.pdf.

[44] A. Koening, W. Lee and W. Bernhardt. Technical and Economical Aspects of Methanol as an Automotive Fuel. *SAE 760545, Volkswagenwerk AG (Germany)*, 1976.

[45] Kable Intelligence Limited. *George Olah CO2 to Renewable Methanol Plant, Reykjanes, Iceland*, April 2012. http://www.chemicals-technology.com/projects/george-olah-renewable-methanol-plant-iceland/.

[46] C.Y. Lin and J. Zeng. The Optimal Gasoline Tax for China. *Theoretical Economics Letters*, 4:270–278, 2014.

[47] Bloomberg Markets. Energy Commodities. 2016. https://www.bloomberg.com/markets/commodities.

[48] McKinsey&Company. Supercharging the Development of Electric Vehicles in China. April 2015. http://www.mckinseychina.com/wp-content/uploads/2015/04/McKinsey-China_Electric-Vehicle-Report_April-2015-EN.pdf?5c8e08.

[49] Argus Media. Developments in China's Methanol Market and Implications for Global Supply. May 2015. https://www.argusmedia.com/mkting/petchems/~/media/371d2fc2c53c4f43afff1e8c53e8b27e.ashx.

[50] E. Miller. An Assessment of CES and Cobb-Douglas Production Functions. *Congressional Budget Office*, June 2008.

[51] MMSA. Methanol Notes. December 2012. http://www.methanolmsa.com/wp-content/uploads/2013/10/MMSA-Methanol-Notes-1212111.pdf.

[52] Y.H. Chen, S. Paltsev, J.Reilly, J. Morris. The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption. October 10, 2014. https://www.gtap.agecon.purdue.edu/resources/download/7221.pdf (visited: 2017-02-13).

[53] B. Motor. Shanxi: Methanol Fuel Application Development Model. 2013. http://www.bestonmotor.com/en/new.asp?id=21.

[54] Geely News. *First Geely Auto Methanol Vehicles Arrive in Iceland*, February 2016. http://global.geely.com/news_info.php?84.

[55] R.J. Nichols. The Methanol Story: A Sustainable Fuel for the Future. *Journal of Scientific and Industrial Research*, 62:97–105, February 2003.

[56] OECD. *IEA CO2 Emissions from Fuel Combustion Statistics*, 2015.

[57] United States Department of Energy. *Evaluation of Ultra Clean Fuels from Natural Gas*, 2006. https://www.ntis.gov/assets/pdf/st-on-cd/DE2006893603.pdf.

[58] Trading Economics, National Bureau of Statistics of China. China Gasoline Prices. http://www.tradingeconomics.com/china/gasoline-prices.

[59] National Bureau of Statistics of the People's Republic of China. *China Statistical Yearbook*, 2007-2014. http://www.stats.gov.cn/tjsj/ndsj/.

[60] State Administration of Taxation of The People's Republic of China. Perspectives on New Consumption Tax Policy Due to Oil Price Dropping. 2014. http://www.chinatax.gov.cn/2013/n2925/n2953/c1465648/content.html.

[61] Ministry of Transport of China. Amount of Passenger Cars in China from 2004 to 2014. *National Bureau of Statistics of China*, September 2015.

[62] Bureau of Transportation Statistics, Average Fuel Efficiency of US Light Duty Vehicles. Average Fuel Efficiency of U.S. Light Duty Vehicles. https://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_23.html.

[63] MIT Joint Program on the Science and Policy of Global Change. *The MIT Economic Projection and Policy Analysis (EPPA) Model: Version 5, Technical Note 16*, 2017. https://globalchange.mit.edu/sites/default/files/MITJPSPGC_TechNote16.pdf.

[64] Annual Energy Outlook. Petroleum and Other Liquid Prices. 2017. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=12-AEO2017&region=0-0&cases=ref2017~highprice~lowprice&start=2015&end=2050&f=Q&linechart=ref2017-d120816a.3-12-AEO2017~highprice-d120816a.3-12-AEO2017~lowprice-d120816a.3-12-AEO2017&sourcekey=0.

[65] I. Parry and K. Small. Does Britain or the United States Have the Right Gasoline Tax? *American Economic Review, 95*, pages 1276–1289, 2005. http://dx.doi.org/10.1257/0002828054825510.

[66] The Statistics Portal. *Car Sales (Passenger and Commercial Vehicles) in China from 2008 to 2016*. https://www.statista.com/statistics/233743/vehicle-sales-in-china/.

[67] G. A. Olah, A. Goeppert, G.K. Prakash. *Beyond Oil and Gas: The Methanol Economy*. John Wiley and Sons, Los Angeles, California, USA, second edition, 24 August 2011.

[68] J.F. Morris, J. Reilly, and Y.H. Henry Chen. *Advanced Technologies in Energy-Economy Models for Climate Change Assessment*. PhD thesis, Massachusetts Institute of Technology, December 2014.

[69] Reuters. China Retail Gasoline, Diesel Prices Since 2003. June 2012. http://www.reuters.com/article/china-fuel-prices-idUSL4E8H87D720120608.

[70] Reuters. China's Retail Gasoline, Diesel Prices Since 2015. May 2016. http://af.reuters.com/article/energyOilNews/idAFL3N1883KZ.

[71] J. Fletcher, V. P. Roan and D. Betts. An Investigation of the Feasibility of Coal-Based Methanol for Application in Transportation Fuel Cell Systems. *3rd International Energy Conversion Engineering Conference, San Francisco, California*, August 2005.

[72] R. Sandoval. *Quantitative Analysis of Alternative Transportation under Environmental Constraints*. Master's thesis, Massachusetts Institute of Technology, June 2006. https://globalchange.mit.edu/sites/default/files/Sandoval_MS_06_0.pdf.

[73] EA Engineering , Science, and Technology , Inc. *Methanol Refueling Station Costs*, February 1999. http://www.afdc.energy.gov/pdfs/methfr.pdf.

[74] T.H. Fleisch, A. Basu, R.A. Sills. *Introduction and advancement of a new clean global fuel: The status of DME developments in China and beyond.*

[75] S. Srinivasan. *Fuel Cells: From Fundamentals to Applications*, volume 1, chapter 8.4, pages 414–417. Springer, New York, NY, 2006.

[76] OECD 2015 Taxing Energy Use. *Gasoline and Diesel Fuel Taxes by Country*, 2016. http://www.afdc.energy.gov/data/10327.

[77] H. Weijia, Global Times. Chinas consumption tax on oil may be high, but environmental issue also matters. February 2016. http://www.globaltimes.cn/content/969098.shtml.

[78] Office of Technology Assessment U.S. Congress. Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles. *OTA-E-364*, September 1990.

[79] S. Verhelst. Methanol as an Engine Fuel. *European Methanol Policy Forum, Department of Flow, Heat and Combustion Mechanics, Universiteit Gent*, October 2015.

[80] C.J. Yang and R.B. Jackson. China's Growing Methanol Economy and Its Implications for Energy and the Environment. *Energy Policy*, 41:878–884, December 2012.

[81] A.H.C. Yip. *Modelling the Global Prospects and Impacts of Heavy Duty Liquefied Natural Gas Vehicles in Computable General Equilibrium.* Master's thesis, Massachusetts Institute of Technology, June 2014. http://hdl.handle.net/1721.1/95587.