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Alternative Energy Vehicles: A comprehensive comparative analysis and prediction under the international carbon emission scene

MASTER IN
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ENVIRONMENT
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MASTER IN
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The research entitled “Alternative Energy Vehicles: A comprehensive comparative analysis and prediction under the international carbon emission scene” has been made at the University of Oviedo under my supervision by Song Meng, graduated in Biotechnology at University of Shandong.

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Abstract

Nowadays, as the main contributor to many environmental issues, the transportation sector receives much attention for developing cleaner fuels. Due to the extensive adoption of alternative energy vehicles worldwide, this work intends to assess their performances in environmental impacts mitigation through a comprehensive well-to-wheels (WTW) comparative analysis.

This WTW fuel cycle analysis referred to TLCAM model and PLCA method, with focus on three indicators: Primary Energy Consumption (PEC), Green House Gas (GHG) and Air Pollutant (AP) emissions. Firstly the WTW fuel cycle of various alternative vehicles in China case was analyzed and compared with conventional gasoline vehicles (GICEV). Then Electric Vehicles (EV) cases in different countries were compared. Finally a prediction for the CO_2 emission reduction of Electric Vehicles in China case in 2050 was made.

The analysis results showed that on PEC, the highest one is Coal to Liquid Vehicle (CTLV) while the lowest one is EV. On GHG emissions, CTLV also is the highest and the lowest is Compressed Natural Gas Vehicle (CNGV). Related to AP emissions, although conventional GICEV emits the highest VOCs and CO due to China's electricity mix generation, EV has the highest emissions of NOx, SOx and Particulates, while Liquefied Petroleum Gas Vehicle (LPGV) and Compressed Natural Gas Vehicle (CNGV) both emit relatively low APs.

Besides, PEC, GHG and AP emissions of EVs in China case are the highest among all the compared countries, while the lowest are in European countries.

Finally in 2050 under an electricity generation mix dominated by renewable energies in China, there will be a CO_2 emission reduction of 500 million $tCO_{2,eq}$ from EVs by replacing conventional GICEVs.

From this work it can be concluded that environmental impacts of various AFVs mainly depend on the upstream stages and fuel economy. Only in non fossil energy dominated regions like Norway and France, EVs can have low impacts. CNGV and LPGV can be currently promoted in China, while EVs can be adopted until comes a greener power generation mix.

Resumen

Hoy en día el sector del transporte persigue desarrollar combustibles más limpios para dejar de ser el principal contribuyente de diversos problemas ambientales. Este trabajo tiene la intención de evaluar el desempeño en la mitigación de los impactos ambientales de vehículos con energías alternativas a través de un análisis comparativo del tipo del pozo a las ruedas (*well-to-wheels,* WTW).

Este análisis WTW sigue el modelo TLCAM y el método PLCA, enfocándose en tres indicadores: Consumo primario de energía (PEC), emisiones de gases de efecto invernadero (GHG) y emisiones de contaminantes atmosféricos (AP). En primer lugar se analiza el ciclo WTW en China para vehículos con diferentes tipos de combustibles, a continuación se estudia el desempeño de los vehículos eléctricos (EV) en diferentes países y se finaliza con una predicción de la reducción de emisiones de CO_2 mediante la implantación de vehículos eléctricos en China en el año 2050.

Los resultados del análisis mostraron que el mayor consumo primario de energía es el de los vehículos movidos con combustible licuado procedente de carbón (CTLV) mientras que el consumo más bajo es el de los vehículos eléctricos. En lo relativo a emisiones de gases de efecto invernadero, los vehículos CTLV también son los más desfavorables, mientras que los vehículos movidos por gas natural comprimido (CNGV) presentan las menores emisiones de GHG. Por último, los vehículos de combustión interna convencionales (GICEV) arrojan las mayores emisiones de compuestos orgánicos volátiles (VOCs) y monóxido de carbono (CO), mientras, el mix eléctrico chino basado en carbón hace que los vehículos eléctricos en este país sean lo que arrojan mayores emisiones de óxidos de nitrógeno, azufre y partículas por kilómetro recorrido. Los vehículos con menor contaminación atmosférica son los que utilizan gas licuado de petróleo (LPGV) y gas natural comprimido.

Adicionalmente, se observó que el vehículo eléctrico en China tiene asociado un consumo energético primario y unas emisiones de GHG y de contaminantes mayores que el resto de países comparados, siendo las menores las de los países europeos.

Finalmente, se calculó que en 2050 al reemplazar los vehículos de combustión por vehículos eléctricos y cambiar el mix de generación eléctrica en China por uno basado en energías renovables, se podría alcanzar una reducción de emisiones de GHG de 500 millones de tCO_2 en este país.

De este trabajo se puede concluir que los impactos ambientales de los diferentes usos de combustibles alternativos, dependen principalmente de la fuente de producción de energía. Solo en regiones no dominadas por la energía fósil como Noruega y Francia, los vehículos eléctricos pueden tener un impacto bajo. Por su parte, el gas natural y el gas licuado de petróleo podrían ser promovidos en China, mientras que los vehículos eléctricos podían ir introduciéndose en espera de un mix de generación de energía más limpia.

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Abbreviation Table

Acronyms and abbreviations used in this work	
AFV	Alternative Fuels Vehicle
AP	Air Pollutants
BEV	Battery Electric Vehicle
CH_4	Methane
CNGV	Compressed Natural Gas Vehicle
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CTLV	Coal to Liquid Vehicle
EV	Electric Vehicle
GHG	Greenhouse Gas
GICEV	Gasoline Internal Combustion Engine Vehicle
GWP	Global Warming Potential
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
LLR	Line Loss Rate
LPGV	Liquefied Petroleum Gas Vehicle
N_2O	Nitrous Oxide
NOx	Nitrogen Oxide
PEC	Primary Energy Consumption
PFEC	Primary Fossil Energy Consumption
PHEV	Plug-in Hybrid Electric Vehicle
$PM_{2.5}$	Fine Particulate Matter (equivalent diameter ≤2.5)
PM_{10}	Fine Particulate Matter (2.5≤ equivalent diameter ≤10)
SOx	Sulphur Oxides
VOCs	Volatile Organic Compounds
WTW	Well-to-Wheels

1. Introduction

1.1. Current environmental, health and energy consumption issues

Since 1850, each of the last three decades has been successively warmer at the Earth's surface than any preceding decade; the globally averaged combined land and ocean surface temperature data show a warming of 0.85°C over the period 1880 to 2012 [1]. Warming of the climate system is undoubted. In recent decades, climate changes have caused increasingly severe impacts on natural environment and all the terrestrial and aquatic creatures, including human health. Precipitation change or melting snow and ice are modifying hydrological systems in many regions, along with affecting water resources in terms of quality and quantity. Many terrestrial, freshwater and marine species have shifted their geographical distribution, seasonal activities and species interactions in response to changes of the climate system.

Meanwhile, the effects of air pollution are alarming, as is known to cause acid rain and eutrophication, also to create severe respiratory and heart problems for human health. Previous report indicated that about 90% of the population in low and middle income countries is in dangerous exposure to the local air pollution [2]. Premature human mortality is highly associated with concentrations of ground-level ozone (O_3) and fine particulate matter (PM) [3-5]. Further, recently Silva et al. have predicted that increases in air pollution will trigger an additional 60,000 premature deaths each year around the globe by 2030, and as many as 260,000 more premature deaths annually by 2100 [6].

Furthermore, the increasing growth rate of primary energy consumption (PEC) has also become one of the hot issues that urgently need to be solved in human society [7]. Among it, the transportation sector accounts for nearly one-third of global PEC and was increased by 1.0% annually according to IEO 2017 [8]. The IEA also investigated that there are two sectors almost produced two-thirds of global CO_2 emissions from fuel combustion in 2015: electricity and heat generation sector accounting for 41%, and transportation accounting for 24%; since 1990s, transport related emissions have grown rapidly, increasing by 68% in less than 2 decades; among them, road sector accounts for nearly 75% [9].

However, the dominant causes of these issues lie in human activities. Since the pre-industrial era, largely driven by the population and economy growth, atmospheric concentrations of GHG (i.e. CO_2, N_2O and CH_4) being unprecedented over the years [10].

1.2. Adopted alternative energy for vehicles in transportation sector

Nowadays, these environmental, health and energy consumption issues along with rising petroleum prices and stringent environmental regulations attract more and more attention on the solutions to reduce vehicle tailpipe emissions and fuel consumption [11-13]. Since the internal combustion engine (ICE) emits harmful air pollutants such as CO, NOx, particulates, etc, many governments and vehicle manufactures around the world start to show an intense interest in exploring cleaner alternative non-petroleum fuels and advanced power systems for vehicles [14].

Table 1. Alternative Fuels Vehicles classification

Single fuel source	Multiple fuel source
Engine air compressor	Flexible fuels (multifuel engine)
Battery electric	
Dimethyl ether fuel	
Ammonia fuel	
Bioalcohol and ethanol	Hybrid electric
Biodiesel	
Biogas	
Charcoal	
Compressed Natural Gas (CNG)	Plug-in hybrid electric (PHE)
Formic acid	
Hydrogen	
Liquid Nitrogen (LN2)	
Liquefied Natural Gas (LNG)	Pedal-assisted electric hybrid vehicle
Liquefied Petroleum Gas (LPG)	
Steam	
Wood gas	

Alternative Energy Vehicles refer to vehicles that use non-traditional petroleum fuels (i.e. non gasoline or diesel); and also refer to any technology of powering an engine which does not contain exclusively petroleum. They include low-carbon fuels, electricity, and hybrid technologies combing ICE with electromotor [15], as classified in Table 1. For instance, today in U.S. governments and private-sector vehicle fleets are the primary users, but individual consumers are increasingly interested in them [16].

Alternative energy vehicles majorly depend on their distinct advantages of fuel usage. For instance, the electricity based vehicles provide an easily chargeable and noiseless urban transportation, mainly coming in three types as battery electric vehicles (BEVs), fuel cell vehicles (FCVs) and plug-in hybrid electric vehicles (PHEVs); LPG vehicles use natural gas and by-products of crude oil refining process emitting less air pollutant than petroleum; CNG vehicles burns cleaner than petrol-based fuels due to its cleaner fuel compositions.

1.3. Global development of alternative energy vehicles

Over the years the AFVs market has witnessed healthy growth owing to increases in the demand for fuel-efficient vehicles, stringent government laws and regulations toward vehicle emission as well as in public charging infrastructures.

North American region is the most appealing market for AFVs, largely attributable to various regulations by US government to control the emissions and import of fuels (*Energy Independence and Security Act of 2007, Energy Policy Act*, etc.). The Alternative Fuels Data Center of U.S. Energy Department show six alternative fuel types in the current U.S. AFV market; they respectively are biodiesel, electricity, ethanol, hydrogen, natural gas and liquefied petroleum gas (LPG, also known as propane autogas). Thousands of electric vehicle charging stations, hundreds of biodiesel and hydrogen fueling stations are deployed throughout the country in key areas for public charging [16]. In the meantime, Government of Canada has also continuously launched new policies to grow AFV infrastructures for helping Canadians make green choice. Biofuels, electricity and natural gas are three main alternative fuels for current Canadian AFV market [17].

After the 1970's oil crisis, increased commodity trade and a growing middle-class with the increasing demands for social mobility contributed to increased transportation energy demand in South America. Today under the government interventions, over two million light vehicles in Argentina can use CNG, which is the largest CNG fleet in South America, and among the top 5 in the world; besides Argentina became the fourth largest producer of biodiesel in the world since 2013 [18]. As the world's largest sugarcane ethanol producer and a pioneer in using ethanol as a motor fuel, in 2015/16, Brazilian ethanol production reached 30.23 billion liters, mostly absorbed by the domestic market as either pure ethanol fuel or blended with gasoline [19]. Now more than 90% of new cars sold in Brazil use flex fuel which means gasohol, ethanol, or any combination of the two fuels, making up about 60% of the country's entire light vehicle fleet. Besides Brazil has also promoted the production of biodiesel as a substitute for petroleum-derived diesel fuels; but NGVs, HEVs, PHEVs and BEVs remain limited in this country [20].

As for European Union, electricity, hydrogen, biofuels, NG and LPG are currently the principal alternative fuels used for transportation sector based on a series of policies, such as *Europe 2020 Strategy* and *2011 White Paper on Transport*, issued by EU for the objective of reducing CO_2 emissions of 80-95% by the year 2050. The European Automobile Manufacturers' Association reported that overall in 2017 registrations of AFVs went up 39.7% higher than in 2016, reaching 852,933 units. The strongest rise was in hybrid electric cars and electrically chargeable vehicles. In spite of the still low 5.7% EU market share, the trend is clearly upwards. From the national perspective, Netherlands, France and Germany are the top 3 countries with the number of electric passenger cars; among them, Netherlands has the largest number of PHEVs while France has the largest number of BEVs. Moreover, Italy has the largest number of CNG vehicles which account for 75% of the EU market, and also the largest number of CNG stations [21].

Africa, with 16% of the world's population, in which some countries have large NG reserves, some have rivers and waterfalls suitable for hydro-electric energy. However, as low developing region, countries here explore AFV market rarely in spite of beneficial NG and oil energy access, due to several weighty factors like political commitment, marketing support and the availability of domestic and external investment capital. South Africa is the current AFV market leader in Africa, whereas the number of infrastructures was limited; today various companies and public sector entities have been working on renewable energy strategies and infrastructures supporting alternative fuel use [22].

Asia Pacific led the global AFVs market by holding nearly half of the shares in recent years according to *ESTICAST Market Research Report* in 2017; and it is expected to continue the dominance throughout the forecast period by 2024. As an Asia-pacific member, China has the largest auto market in the world, causing a tendency of the major shift to the electrification of personal transportation. The *"Thirteenth Five-Year Plan"* for the emerging industries development calls for a significant increase of AFV market; by 2020, the output value should reach more than 10 trillion Yuan. Chinese government also offers overly generous incentives for the purchase of AFVs. Automotive News China revealed that in 2017 sales of domestically-produced electrified passenger vehicles totaled 579,000 units, consisting of 468,000 BEVs and 111,000 PHEVs [23]. In addition, the AFVs market in Japan is small with main alternative fuel types of Methanol, CNG, EVs and FCVs, but still continuously improved to reduce the GHG emissions based on *Japan's new Strategy Energy Plan* [24]. South Korea's *Renewable Fuel Standard* policy also mandates for the transportation fuel business; it is expected that in the near future, bioethanol will be used for gasoline vehicles accounting for approximately 47.1% of total vehicles in South Korea, also that LPGVs will account for 10.6% and NGVs for 0.2% [25]. Table 2 shows the main alternative fuel types in various regions mentioned above.

Table 2. The current AFV types in different regions

Regions		Current AF types for Vehicles	Sources
North America	the United states	Biodiesel, Electricity, Ethanol (E10/E15/E85), Hydrogen, NG, LPG	Alternative Fuel Data Center (AFDC) [16]
	Canada	Biofuel, Electricity, NG	Canadian Petroleum Product Institute (CPPI) [17]
South America	Argentina	CNG, Biodiesel	World Energy Council [18]
	Brazil	Flex fuels, Biodiesel, NG, Electricity	The International Council on Clean Transportation (ICCT), SugarCane.org [19][20]
European Union		Electricity, Hydrogen, Biofuels, NG, LPG	European Commission [21]

Africa	South Africa	Few number of AFVs	Transport World Africa (TWA) [22]
Asia Pacific	China	LNG, CNG, LPG, Bioethanol, CTL, Methanol, Electricity	State Information Center [26]
	Japan	Methanol, CNG, Electricity	International Energy Agency (IEA) [24][25]
	South Korea	Bioethanol, LPG, NG	

1.4. Objectives of this work

Nowadays, gradually severe environmental issues such as global warming, air pollutions and energy shortage, etc make green transportation the necessity. Many governments have published relevant policies to promote the development of alternative energy vehicle markets, especially EVs markets. The purpose of this work is to assess the performances of various alternative fuel vehicles in environmental impacts mitigation, by conducting a comprehensive well-to-wheels comparative analysis for them, especially electric vehicles.

For achieving this purpose, firstly China as a specific case was selected to conduct the WTW environmental impact comparative analysis of conventional and alternative vehicles (i.e. gasoline, BE, PHE, LPG, CNG and CTL vehicles) based on three indicators (i.e. primary energy consumption; GHG and air pollutant emissions); then BEV and PHEV of China case were compared with EVs cases in other five countries; these countries are the U.S., Norway, France, Germany and Japan, all of which have the recent world top EVs registrations and also representative electricity generation mixes; finally a prediction for the CO_2 emission reduction of EVs of China case in 2050 was made under an assumed scenario, which is based on government support policies.

2. Methodology

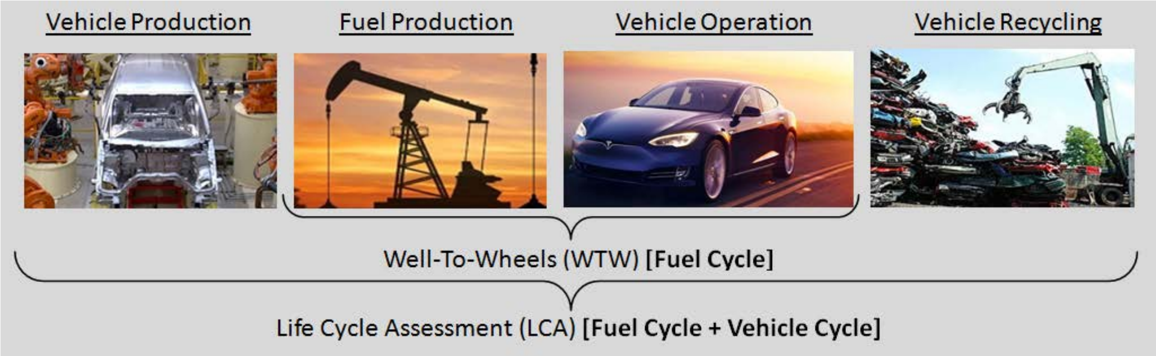
2.1. Reviews of the state of related literatures in the transportation field

Life Cycle Assessment (LCA) has been widely used to analyze the impact of energy use processes on the environment, such as biofuels production [27][28], building carbon emissions [29][30], and alternative vehicle energy [31][32], etc. The application of LCA in the transportation field began in the 1990s. Delucchi conducted a full LCA of various fuels from 1991 to 1993, followed by the creation of the LEM model (Life Cycle Emission Model) in 2003 [33] [34]. During this time, scholars and companies in different countries began to make LCA for the road transportation system and the brand cars, of which results all showed great assessment effects [35-40]. The Argonne National Laboratory (ANL) conducted a large number of researches on the automotive LCA and created the Greenhouse gas, Regulated Emissions and Energy use in Transportation (GREET) model for North America, Europe and other regions [41][42]. The conclusions drawn from these analyses indicated strong regional differences, which suggested that the basic model cannot simply be applied to other regions of the world [43-48]. In the GREET 1.0 version model, it was proposed a method from "oil well" to "vehicle Wheels" [49]. Since then, the WTW method has been widely used in the transportation field.

2.1.1. The basic concepts of WTW analysis

Well-to-wheel (WTW) assessment is namely a specific LCA without consideration of vehicle production and disposal process [49], as shown in Figure 1. It is usually based on two stages: the well-to-tank (WTT) stage for mainly analyzing fuel production, and the tank-to-wheel (TTW) stage for the vehicle operation process. WTW analysis can be adopted to evaluate and compare the environmental impacts and economic costs of different alternative and conventional vehicles. Various WTW analyses have been proposed in the literatures to capture different aspects of the transportation fuel life-cycle in different regions of the world.

Figure 1. Difference between LCA and WTW framework in the automobile industry



2.1.2. Reviews of WTW analysis studies for different regions

WTW analyses for EVs in the United States have been studied since 2005, the WTT stage generally was analyzed by GREET model, while the TTW stage was analyzed by several methods such as ADVISOR and Powertrain Analysis Tool (PSAT) which are vehicle simulators, as well as stochastic model to generate realistic driving cycles which represent the vehicle usage; they all were used to calculate TTW stage efficiencies; among them, the key factor in assessing the environmental impacts of PHEVs is the primary energy sources for producing electricity to vehicle batteries [50-53]. Moreover, a comparative analysis study of conventional and alternative light-duty vehicles by Christopher W. el al. created a spatially, temporally and chemically accurate LCA model; the results showed that the coal-based or grid electricity and corn ethanol powered vehicles increase the environmental health impacts by 80% or more in comparison with gasoline vehicles; besides EVs powered by low-emitting electricity produced from renewable energies will conversely reduce the environmental health impacts by 50% or more [54].

EUCAR, CONCAWE and European Commission Joint Research Center (ECJRC) also studied extensively on the energy consumptions of European transportation systems by using AVL Cruise, a commercially available simulator like ADVISOR, for performing vehicle simulation and powertrain analysis [55]. Campanari S et al. investigated the potential energy saving strategies of electric and fuel cell vehicles by using WTW methodology in the Economic Commission for Europe-Extra Urban Driving Cycle (ECE-EUDC) [56]. Mashael et al. performed a comparative analysis of WTW primary energy demand and GHG emissions for the operation of multiple AFVs in Switzerland by considering various energy carrier production pathways; they found that the WTW performance of EVs strongly depends on the electricity source, and ICE drivetrains using alternative fuels especially biogas and CNG yield remarkable WTW energy and emission reductions as well [57].

China's LCA researches in the transportation field adopted the internationally common WTW methodology as well. Relevant researches started in 1998, scholars of Tsinghua University used WTW method to analyze coal-based methanol fuel vehicles and coal-fired electricity powered BEVs [58]. Xunmin Ou and Xiliang Zhang in Tsinghua University Automotive Energy Center (CAERC) developed the Tsinghua-CA3EM model, which aimed at implementing WTW analysis of various AFVs particularly based on China's energy situation [59-61]. Zhiyuan Hu et al. have been conducting LCA of biodiesel and other diesel alternative fuels since 2002 [62] [63]. Rui Wu and Yuxi Ren have carried out life cycle energy consumption of NG-based alternative vehicles [64]. Huang Ying et al. calculated the fuel cycle GHG emissions of BE passenger cars and gasoline cars based on EIO LCA model in 2012 [65]. J Shugang et al. also compared and analyzed the life cycle CO_2, $PM_{2.5}$, NO_X, and HC emissions of EVs and conventional gasoline vehicles from 34 cities in China [66]. In addition, several Chinese alternative fuel LCA studies based on GREET model also appeared [67-69]. Recently scholars in CAERC have developed the Tsinghua University Life Cycle Analysis Model (TLCAM), which is based on the GREET and the Tsinghua-CA3EM model. This model employs a variety of localized data and updates frequently to provide accurate LCA analysis of vehicle fuel pathways in Chinese actual situation [70].

2.1.3. Reviews of standardization of LCA system

In term of the standardization of LCA Research System, since the 1990s, it has got gradually improved. In 1993, Society of Environmental Toxicology and Chemistry (SETAC) published the report *"Life Cycle Assessment Outline: A Practical Guide"* providing a basic technical research framework for the LCA methodology as a guide principle in the field of LCA research [71]. In the same year, ISO also officially drafted the ISO14000 series of environmental management standards. In 1997, ISO promulgated the international standard *"Environmental Management - Life Cycle Assessment Principles and Framework"*, namely the ISO14040 standard followed by the corresponding ISO14041-ISO14043 standards in successive years. In order to better define and standardize the LCA methodology, ISO revised the ISO14040-ISO14043 series of standards in 2006 and released new ISO14040 [72] and ISO14044 [73] standards. These two standards are also the current international standards for the application of LCA methods.

2.1.4. Limitations of current WTW analysis studies

It can be seen from literature reviews that WTW studies of AFVs in China adopting GREET model for analysis could lead to inaccurate analytical results due to the regional difference. Besides many AFV's studies mainly concentrated on their energy consumption and GHG emissions without consideration of air pollutant emissions, while previous studies indicated that air pollutant damage externalities generally exceed those from global warming [74][75]. Furthermore, comparative analysis of AFV between different countries appears rarely. This work intends to make a relatively comprehensive comparative analysis by avoiding these issues.

2.2. A Well-to-Wheels model for comparative environmental impacts analysis

2.2.1. Model definition and scope boundary

The WTW analysis mainly contains four stages, which respectively are feedstock exploitation, feedstock transportation, road fuel production, road fuel transmission and distribution to the vehicle, and vehicle operation. In accordance with the standard ISO 14040 and the LCA technical framework from SETAC, the objective and scope of WTW model are defined below.

Figure 2. Basic system framework of WTW model in this work

Gasoline, LPG, CNG and CTL, BE, PHE vehicles are the main analyzed vehicle types in China case, while the analysis indicators are: 1) Input PEC (coal, crude oil, NG and other energy); 2) Output GHG emissions (CO_2, CH_4 and N_2O) [1]; 3) Output conventional air pollutant emissions (VOC, CO, NOx, PM_{10}, $PM_{2.5}$ and SOx) [76]. Light-duty vehicle is selected as the studied vehicle type due to its largest portion of almost 72% in the world passenger transportation energy consumption [8], likewise in China with a 54.38% portion of total amount of motor vehicles in use by 2017 [77]. WTW stages of multi-fuel pathways in this work are described in Table 3.

Table 3. Well-to-Wheels (WTW) stages of different fuel pathways

Well-to-Tank (upstream stages)					**Tank-to-Wheels**
Fuel Types	**Feedstock Production**	**Feedstock Transportation**	**Fuel Production**	**Fuel Transmission and Distribution**	**Vehicle Operation**
Gasoline	Crude oil exploitation	Crude oil transportation	Refining gasoline	Gasoline transportation and distribution	Fuel combustion in the ICE
LPG			Refining LPG	LPG transportation and distribution	
CTL	Coal mining, processing and washing	Coal transportation	Coal liquefaction	CTL transportation and distribution	
BEV	Crude oil, NG, coal, etc exploitation and processing	Primary energy transportation	Electricity generation	Electricity transmission, distribution and battery charging	Driving electric motor
PHEV			Electricity generation;	Electricity transmission, distribution and battery charging;	Driving electric motor (CD mode);
			Refining gasoline	Gasoline transmission and distribution	Gasoline usage in the ICE (CS mode)
CNG	Natural gas exploitation, purification	Extracted and purified NG transportation	NG compression	CNG transmission and distribution	Fuel combustion in the ICE

Table 4 shows the involved energy types of alternative fuel pathways during the WTT stages; these process and end-use energy types account for more than 90% of total process energy sources [59]. The functional units are: 1) PEC (MJ/km); 2) GHG emissions ($gCO_{2,eq}$/km); 3) air pollutant emissions (g/km).

Table 4. Primary and second energy types in the WTT stages

	Primary energy (*i*)	**Process and end-use energy (*j,z,x*)**	**WTT stages (*m*)**
1	Coal	Crude coal	Feedstock exploitation
2	Oil	Crude oil	Feedstock transportation
3	NG	Crude NG	Fuel production
4	Non-fossil	Gasoline	Fuel transportation
5		Fuel oil	
6		Diesel	
7		Electricity	

2.2.2. Calculation of PEC for different fuel pathways in WTT stages

According to the PLCA method [78] and TLCAM model [79], PEC intensity of a specific fuel pathway is defined as the sum of all the PEC during entire WTW stages for 1 unit end-use fuel obtained. The WTW analysis model can be divided into two parts for calculation: WTT stages and TTW stage. As Table 4 shows, four types of primary energy (PE, as *i* represents, *i* = 1,2,3,4) and seven types of second energy (as *j* represents, *j* = 1,2,…,7) will be iteratively calculated due to their mutual involvement in each WTT stage (*m* = 1, 2, 3, 4).

Therefore, in WTT stages, PEC intensity (MJ/MJ) means the total PEC for 1MJ second energy obtained; GHG emission intensity ($gCO_{2,eq}$/MJ) means the total CO_2 equivalent emissions for 1MJ second energy obtained; Air pollutant emission intensity (g/MJ) means the total emissions of air pollutant types for 1MJ second energy obtained. Similarly, in TTW stage, the energy consumption (MJ/km), GHG emission ($gCO_{2,eq}$/km) and air pollutant emission (g/km) are respectively the total fuel energy consumption, GHG and air pollutant emissions for vehicle driving 1km distance.

In WTT stages, for a type *j* end-use energy pathway, its PEC intensity $\boldsymbol{E_{WTT,j}}$ (MJ/MJ) is calculated as the sum of all the $\boldsymbol{E_{WTT,j,i}}$ (PE *i* intensity of end-use energy *j* per unit). And $\boldsymbol{E_{WTT,j,i}}$ is calculated by using $\boldsymbol{EI_{m,j}}$ (MJ/MJ) (the total primary energy input for 1MJ of end-use energy *j* obtained during stage *m*) and $\boldsymbol{SH_{m,j,z}}$ (the share of process energy *z* in total energy use during stage *m* for 1MJ of end-use energy *j* obtained). $\boldsymbol{E_{WTT,z,i}}$ represents PE *i* intensity of process energy *z* per unit.

$$E_{WTT,j} = \sum_{i=1}^{4} E_{WTT,j,i} \qquad (j = 1,2,\ldots,7) \tag{1}$$

$$E_{WTT,j} = \sum_{i=1}^{4}\sum_{m=1}^{4}\left(EI_{m,j}\sum_{z=1}^{7}\left(SH_{m,j,z}E_{WTT,z,i}\right)\right) + \gamma_{i,j} \tag{2}$$

$$\gamma_{i,j} = \begin{cases} 0 & \text{for j} = 7 \\ 1 & \text{otherwise} \end{cases}$$

For non-electricity end-use energy (j=1-6), energy input ***EI*** can be derived from $\boldsymbol{\varphi_{m,j}}$

(energy transformation efficiency factor during stage *m* while 1MJ of end-use energy *j* obtained) and the conversion factor of fuel to feedstock during the fuel production stage for end-use energy *j* ($\boldsymbol{\partial_j}$, MJ/MJ):

$$EI_{m,j} = \left(1/\varphi_{m,j} - 1\right)/\partial_j \qquad (j = 1,2,\dots,6; m = 1,2,\dots,4) \tag{3}$$

For the electricity pathways (*j* = 7), power lost on the electricity transmission lines should be considered. The calculation processes for the feedstock exploitation and transportation stages (i.e. *m*= 1,2) are the same as those for non-electricity pathways, while the electricity production and transmission stages (i.e. *m*= 3, 4) are mainly calculated below.

$$EI_{3,7} = \sum_{i=1}^{4} \varphi_{3,7,i}/\beta_{7,i} \tag{4}$$

Where $\boldsymbol{\varphi_{3,7,i}}$ is the ratio of PE *i* in the electricity generation mix, namely $\boldsymbol{\varphi_{3,7,1}}$, $\boldsymbol{\varphi_{3,7,2}}$, $\boldsymbol{\varphi_{3,7,3}}$ and $\boldsymbol{\varphi_{3,7,4}}$ represent coal-based, oil-based, NG-based and non-fossil energy based power generation structures, respectively. And $\boldsymbol{\beta_{7,i}}$ is the power generation efficiency of each PE *i* based power structure. In addition, $\boldsymbol{EI_{4,7}}$ is related to the line loss rate $\boldsymbol{\varepsilon}$ during the electricity transmission stage (*m*=4).

2.2.3. Calculation of PEC for different fuel pathways in WTW stage

Assuming the fuel efficiency of vehicle type *b* is $\boldsymbol{EE_b}$ (MJ/km), the total PEC per unit driving distance for the entire WTW stages $\boldsymbol{E_{WTW}}$ (MJ/km) can be calculated as:

$$E_{WTW} = E_{WTT} * \ EE_b \tag{5}$$

Here unlike the single-fuel driving vehicle (GICEV and BEV), PHEV adopts a drive system combining electric motor with ICE. It firstly runs in the charge-depleting (CD) mode, which is same as a BEV until its battery state-of-charge reaches a minimum threshold when the running distance exceeds the CD range; then it operates in the charge-sustaining (CS) mode, which allows the ICE operate in an optimal condition for maximum efficiency [80]. Therefore, the primary energy consumption of PHEV can be calculated as:

$$E_{WTW,PHEV} = E_{WTT,electricity}EE_eSH_e + E_{WTT,gasoline}EE_g(1 - SH_e) \tag{6}$$

EE_e (MJ/km) is the fuel efficiency of PHEV per *km* driven in CD mode, while ***EE_g*** (MJ/km) is the fuel efficiency of PHEV per *km* driven in CS mode. ***SH_e*** is the share of distance travelled in CD mode in the total distance travelled.

2.2.4. Calculation of GHG emissions for different fuel pathways in WTW stages

The species of GHG mainly include CO_2, CH_4 and N_2O, all of which are accordingly converted to CO_2 equivalents based on the Global Warming Potential (GWP). The *Fifth Assessment Report* (AR5) of IPCC indicated that GWP of CH_4 and N_2O respectively are 34 and 298 [81]. Then the total GHG emissions ($gCO_{2,eq}$/km) of end-use energy *j* can be identified as the following. ***$CO_{2,WTW,j}$, $CH_{4,WTW,j}$ and $N_2O_{WTW,j}$*** represent CO_2, CH_4 and N_2O emissions per unit driving distance for the entire WTW stages, respectively.

$$GHG_{WTW,j} = CO_{2,WTW,j} + 34CH_{4,WTW,j} + 298N_2O_{WTW,j} \tag{7}$$

For CO_2 emission, it consists of two parts: the upstream part ***$CO_{2,up,j}$*** (i.e. WTT stages) and the combustion part ***$CO_{2,direct}$*** (i.e. TTW stage).

$$CO_{2,WTW,j} = CO_{2,up,j} + CO_{2,direct} \tag{8}$$

$$CO_{2,direct,j} = \frac{44}{12} CC_j OF_j \tag{9}$$

$CO_{2,up,j}$ represents the WTT CO_2 emission intensity of end-use energy *j* ($gCO_{2,eq}$/MJ), and ***$CO_{2,direct,j}$*** represents the direct combustion CO_2 emission intensity of energy *j* ($gCO_{2,eq}$/MJ). ***CC_j*** is the carbon content factor of energy *j*; ***OF_j*** is the fuel oxidation rate of energy *j*, and 44/12 is the mass conversion rate from C to CO_2. The upstream CO_2 emission intensity also results from the direct CO_2 emission intensity of process energy *x* (**$CO_{2,direct,x}$**, $gCO_{2,eq}$), **$CO_{2,direct,x}$** can be calculated by the equation (9).

$$CO_{2,up,j} = \sum_{m=1}^{4} \sum_{x=1}^{7} \left(EI_{m,j} SH_{m,j,x} \left(CO_{2,direct,x} + CO_{2,up,x} \right) \right) \tag{10}$$

Similarly, CH_4 and N_2O emission intensities can be identified as:

$$CH_{4,WTW,j} = \sum_{m=1}^{4}\sum_{x=1}^{7}\left(EI_{m,j}SH_{m,j,x}\left(CH_{4,direct,m,x} + CH_{4,up,x}\right)\right) + CH_{4,j,noncomb} + CH_{4,direct} \tag{11}$$

$$N_2O_{WTW,j} = \sum_{m=1}^{4}\sum_{x=1}^{7}\left(EI_{m,j}SH_{m,j,x}\left(N_2O_{direct,m,x} + N_2O_{up,x}\right)\right) + N_2O_{direct} \tag{12}$$

$\boldsymbol{CH_{4,direct,m,x}}$ (g/MJ) is the direct CH_4 emission intensity for process energy *x* during stage *m* while $\boldsymbol{CH_{4,j,noncomb}}$ (g/MJ) is the indirect one for end-use energy *j* from non-combustion sources, like spills and losses during the feedstock exploitation stage. Besides $\boldsymbol{N_2O_{direct,m,x}}$ (g/MJ) indicates direct N_2O emissions for energy *x* during stage *m*.

Similarly, during TTW stage, the GHG emissions of PHEV are zero in CD mode while the PHEV CS mode generates GHG emissions like GICEV. And the GHG emissions of BEV are from the WTT stages.

2.2.5. Calculation of Air Pollutants emissions for different fuel pathways in WTW stages

There are six major conventional air pollutant species for the analysis, i.e. VOC_S, CO, NO_X, SO_X, $PM_{2.5}$ and PM_{10}. In this work, air pollutant emissions from the upstream part of lost electricity during transmission stage are also considered. Similarly, the air pollutant species are represented by *s* (*s*=1,2,…,5). According to previous equations, air pollutant emission intensities (g/MJ) of end-use energy *j* during WTT stages can be calculated as:

$$P_{s,WTT} = \sum_{j}^{7}\sum_{m}^{4} P_{s,WTT,m,j} \tag{13}$$

$$P_{s,WTT,m,j} = EI_{m,j}PF_{s,j} \tag{14}$$

$\boldsymbol{PF_{s,j}}$ (g/MJ) represents the pollutant emission factors of species *s* for the end-use energy *j*. For the TTW stage, similarly, during the driving process of ICEV and PHEV CS mode, the air pollutants emission can be identified as:

$$P_{s,TTW,j} = E_{TTW,j} PF_{s,j} \tag{15}$$

Where $E_{TTW,j}$ (MJ/km) is the energy consumption of energy *j* in the TTW stage; and by concerning the vehicle efficiency EE_b (MJ/km) of light-duty vehicles, the total emissions of air pollutant *s* for energy *j* can be identified as:

$$P_{s,WTW,j} = EE_b P_{s,WTT,j} + P_{s,TTW,j} \tag{16}$$

2.2.6. WTW environmental impacts comparison of EVs in different countries

According to section 1.2 and global EV outlook 2017 [81], considering the rapid increase in sales of global EVs market and great efforts of governments to vigorously promote EVs, a horizontal WTW comparative analysis of EVs between different countries is conducted, in order to assess the feasibility of extensive EVs usage under various domestic energy circumstances. These countries are selected based on the annual EVs registrations [81] and typical domestic power structures, which have critical influences to analysis results.

In term of the WTW comparative PEC of EVs in different countries, the upstream PEC of electricity and vehicle fuel economies are key parameters. And for the WTW comparative GHG and air pollutant emissions of EVs in each country, the emission factors of different regions are key parameters.

2.3. Data and parameters for the WTW fuel cycle analysis of China case

2.3.1. Data for WTT analysis of different fuel pathways

According to the equations above, $\varphi_{m,j}$, ∂_j and $SH_{m,j,z}$ are the required data for PEC intensity $E_{WTT,j,i}$ (*j*=1,2,…,6) of non-electricity fuel pathways while $\varphi_{3,7,i}$, $\beta_{7,i}$ *and* ε are required for the $E_{WTT,7,i}$ of electricity pathway. By referring to the official annual reports and previous scholar literature, the basic data are listed below.

Table 5. Basic data of coal-based fuel pathways

Coal exploitation and processing efficiency	Each EC[a] in coal exploitation and processing (MJ/kg)	Coal transportation mode and average distance
621.4MJ/kg (crude coal)	Crude coal (465.98), Diesel (30.44), NG (5.59), Electricity (116.18), Fuel oil (0.12) and Gasoline (1.86)	Railway: 70%, 646km; waterway: 19%, 1255km; long-distance road: 10%, 310km; short-distance road: 100%, 50km
[83]		[78]

[a] EC: Energy Consumption

Table 6. Basic data of oil-based fuel pathways

Oil exploitation and processing (MJ/kg crude oil)	Crude oil transportation and average distance	The EC mix in oil products processing (MJ/kg crude oil)	Oil products transportation mode and average distance
Petroleum import proportion: 65% (2016); Exploitation efficiency: 4.97MJ/kg; Raw coal (0.17), Crude oil (1.20), Diesel (0.15), NG (2.54), Electricity (0.85), Gasoline (0.03), Fuel oil (0.02)	Railway: 45%, 950km; waterway: 10%, 250km; Sea tanker: 59%, 11,000km; Pipeline: 80%, 500km	Refining efficiency: 1.90MJ/kg; Raw coal (0.37), Crude oil (1.02), Diesel (0.0038), NG (0.057) and Electricity (0.13), Fuel oil (0.03), Refinery dry gas (0.30)	Sea tanker: 25%, 7000km; waterway: 15%, 1200km; Railway: 50%, 900km; Pipeline: 11%, 160km; Short-distance road: 100%, 50km
[83][84]	[78][85]	[83][84]	[78]

Oil products refer to the refined oil after crude oil production, such as gasoline, diesel and fuel oil, etc. Refinery dry gas is not within the energy metering range in this work, thus it is considered as a by-product in the refining process without additional PEC. The NG import volume has been increasing in recent years. In 2016, the import volume of NG was 72.1 billion cubic meters and the import proportion reached to 34%.

Table 7. Basic data of NG-based fuel pathways

NG exploitation efficiency	The EC mix in NG exploitation and processing (kJ/L)	NG transportation mode and average distance
Exploitation efficiency: 0.42kJ/L;	Raw coal (0.02), Diesel (0.016), NG (0.28) and Electricity (0.09), Gasoline (0.003), Fuel oil (0.002)	Sea tanker: 15%, 8000km; Central Asian Pipeline: 15.6%, 2500km; China-Burma pipeline: 1.7%, 771km; Domestic pipeline: 100%, 625km
[84]	[83][84]	[78][86]

In 2016, China's total electricity generation was 6.1 trillion kWh [87], among it, coal-fired power is the main part, accounting for 65.2% of the total power generation; other generation mix contains NG power (3.1%), nuclear power (3.6%), hydropower (19.7%), wind power (4.0%), solar power (1.1%) and other renewable energy (3.3%). Meanwhile, the line loss rate of the national power grid has reached to 6.47%, higher than last year. The power generation efficiency is listed in Table 8 .

Table 8. The efficiency of each power generation structure in China

Coal power	NG power	Nuclear power	Hydropower	Wind power	Solar power	Other renewable power
35%	45%	35%	80%	35%	30%	-

Table 9. Data of various energy consumption of different transportation mode

[79]	SD[a] road	LD[b] road	Waterway	Sea tanker	NG pipeline	CO[c] pipeline
Diesel	68%	68%				
Electricity					1%	50%
Fuel oil			100%	100%		50%
Gasoline	32%	32%				
NG					99%	
EC intensity (MJ/ton*km)	1.4	1.2	0.15	0.02	0.4	0.3

[a]SD: short distance [b]LD: long distance [c]CO: crude oil

The earliest GHG emission factors originated from the 1996 *IPCC Guidelines for National Greenhouse Gas Inventories* based on the "*United Nations Framework Convention on Climate Change*", the latest version is of 2006 [88]. China issued the "*Guidelines for the compilation of provincial greenhouse gas inventories*" in 2011 [89], which announced the GHG emission factors of some industrial process. The basic data of GHG emissions factors in China case are mainly from the IPCC Guidelines, the "*Guidelines for the compilation of provincial greenhouse gas inventories*" and National Bureau of Statistics. GHG emissions factors of each process and end-use energy source are shown in Table 10.

Table 10. CO_2, CH_4 and N_2O emission factors of different process and end-use energy sources

	Crude coal	Crude oil	NG	Gasoline	Fuel oil	Diesel
$CH_{4,direct}$ (gCH_4/MJ)[88]	0.001	0.003	0.001	0.025	0.003	0.004
$CH_{4,indirect}$ (gCH_4/MJ)[79]	0.408	0.009	0.071	0.009	0.009	0.009

N_2O (gN_2O/MJ)[88]	0.0015	0.0006	0.0010	0.0078	0.0006	0.0037
CO_2 (gCO_2/MJ)[89]	88.4	71.4	54.4	68.0	74.8	71.4

Unlike the U.S. and EU [90][91], China has not established unified database of conventional pollutant emission factors. This work mainly determines these emission factors according to the series of technical guidelines for the preparation of air pollutant emissions list released by the Ecology and Environment Ministry since 2014 [92]. The air pollutant emission factors from various transportation sources during energy exploitation, production and transportation stages are showed in following Tables.

Table 11. Air pollutants emission factors of various transportation sources

	VOC_S[92]	**CO[92]**	**NO_X[92]**	**$PM_{2.5}$[92]**	**PM_{10}[92]**	**SO_x[92]**
Light Duty Vehicle-Gasoline (g/km)	0.17	0.68	0.03	0.003	0.003	0.01
Heavy Duty Vehicle-Gasoline (g/km)	0.20	4.50	0.91	0.044	0.049	0.30
Heavy Duty Vehicle-Diesel (g/km)	0.06	2.20	5.55	0.138	0.153	1.00
Railway (g/kg of Diesel)	6.14	8.29	55.73	1.970	2.070	10.00
Sea tanker (g/kg of Fuel Oil)	6.20	7.40	79.30	5.600	6.200	30.00
Sea tanker (g/kg of Diesel)	6.20	23.80	47.60	3.650	3.810	30.00

Table 12. Air pollutants emission factors of industrial fixed sources

	Crude coal (g/kg)	**Crude oil** (g/kg)	**NG** (g/m^3)	**Gasoline** (g/kg)	**Fuel oil** (g/kg)	**Diesel** (g/kg)
VOC_S[92]	0.40	0.37	0.10	0.10	0.35	18.30
CO[92]	15.20	0.90	0.37	0.05	0.80	10.70
NO_X[92]	4.00	5.10	1.76	16.70	5.85	32.80
$PM_{2.5}$[92]	0.74	0.70	0.03	0.13	0.67	0.50
PM_{10}[92]	1.60	0.85	0.03	0.25	0.85	0.50
SOx[92]	10.00	2.78	0.20	1.65	2.25	1.00

Table 13. Air pollutants emission factors of thermal power plant

	VOC_S[92]	**CO[92]**	**NO_X[92]**	**$PM_{2.5}$[92]**	**PM_{10}[92]**	**SOx[92]**
Coal (g/kg)	0.15	2.48	6.58	0.62	0.87	8.46
Oil (g/kg)	0.13	0.6	5.09	0.62	0.85	2.75
NG (g/m^3)	0.045	1.3	1.76	0.03	0.03	0.18

According to data from previous related studies [70][78], PEC, GHG and air pollutants emissions of several fuel pathways in WTT stages are showed in following tables. Since the air pollutant emissions studies of Chinese alternative vehicles appears rarely, the WTT air pollutant emissions data of LPGV and CNGV are referred from *National IV Standard* for Chinese automobile emissions and GREET model to make comparisons with GICEV and EVs. Air pollutant emissions of CTLV are not analyzed due to non-available data source.

Table 14. The WTT primary energy consumption intensities of different fuel pathways

	PFEC intensity (MJ/MJ)				
	Coal	**Oil**	**NG**	**[a]NonF**	**Total PFEC**
LPG	0.049	1.161	0.047	-	**1.257**
CTL	2.172	0.004	0.034	-	**2.210**
CNG	0.071	0.006	1.120	-	**1.197**
Gasoline	0.148	1.069	0.070	0.021	**1.287**

[a]NonF: Non Fossil Energy

Table 15. The WTW GHG emissions factors ($gCO_{2,eq}/MJ$) of LPG, CNG and CTL pathways

	LPG	**CNG**	**CTL**	Sources
GHG emissions	82.2	72.3	202.1	[70]

Table 16. The WTW air pollutants emissions factors (g/MJ) of LPG and CNG pathways

	VOC_S	**CO**	**NO_X**	**$PM_{2.5}$**	**PM_{10}**	**SO_x**
LPG[42]	0.05157	0.26576	0.06706	0.00199	0.00232	0.02014
CNG[42]	0.04903	0.26295	0.08171	0.00151	0.00191	0.01680

2.3.2. Data for TTW analysis of different fuel pathways

As for the TTW stage, according to average data in the domestic light-duty vehicle market [93], this work assumes that in 2016 the fuel economies of GICEV and BEV are 8L/100km and 15kWh/100km, respectively. At present, Chinese BEVs (such as BYD, Beiqi, etc.) are usually powered by lithium iron phosphate batteries. Besides generally 60% of the trips driven in PHEV are in CD mode and 40% are in CS mode [94][95].

According to the previous study [70], the fuel economies of LPGV, CNGV and CTLV are respectively 1.05, 1.05 and 0.85 times that of conventional GICEV, thus the fuel consumptions of each alternative vehicle is calculated below. The vehicle energy consumption EE_b (MJ/km) can be calculated by using constant values (i.e. gasoline density 0.74g/ml, calorific value of gasoline 44kJ/g), as shown in Table 17.

Table 17. Fuel consumption intensities (MJ/km) of different alternative vehicles

	LPGV	CNGV	CTLV	GICEV	BEV	PHEV (CS)	PHEV (CD)
EE_b (MJ/km)	2.7	2.7	2.2	2.6	1.4	1.04	0.84

From Table 17, it is clear that during vehicle operation stage LPGV and CNGV consumes 2.7MJ fuel per 1km of driving distance which is the highest among all the studied alternative vehicles, while BEV has the lowest fuel consumption intensity about 1.4MJ/km.

2.3.3. Data for WTW analysis of BEV and PHEV in different countries

Given the incredible growth of electric vehicle sales in the global transport sector, this work selects six countries in which the domestic EV markets are developing rapidly. As shown in Table 18, the total EVs new registrations of these six countries in 2016 account for 83% of the global registrations. Moreover, since the results of WTW comparative analysis are highly related to the electricity generation mix, each selected country has representative electricity generation structure. China owns a coal-dominated (65%) electricity generation structure; Norway focuses on hydropower with 95.8% of the total generation mix; France is dominated by nuclear power whose share is about 72.3% while Japan has the highest oil power share than others, accounting for 9% of total generation mix. Germany mainly focuses on coal, nuclear and other renewable energy sources, accounting for 42.5%, 14.5% and 29.7%, respectively. Besides the United States has a relatively balanced electricity generation mix.

Table 18. Electricity generation mix and EVs new registrations of different countries

Country	Coal (%)	NG (%)	Oil (%)	Nuclear (%)	Hydro (%)	Others (%)	LLR (%)	EVs new registrations (thousands)[81]
China[87]	65.2	3.1	0.1	3.6	19.7	8.3	6.47	336.00
U.S.[8]	30.4	33.8	0.6	19.8	6.6	8.8	6.50	159.62
Norway[96]	0.1	1.8	0.02	0	95.8	2.28	6.8	50.18
France[97]	1.4	6.6	0.6	72.3	12.0	7.1	7.1	29.51

Japan[98]	34.0	39.2	9.0	0.9	8.4	8.5	4.1	24.85
Germany[99]	42.5	8.5	1.0	14.5	3.8	29.7	4.3	24.61

According to GREET model, JRC TTW report and JC-08 driving cycle data, fuel consumptions of BEV and PHEV in different countries are calculated in the Table 19.

Table 19. Fuel consumption intensities (MJ/km) of BEV and PHEV in different regions

	China	**U.S.**	**EU**	**Japan**
BEV	1.4	0.9	0.5	0.6
PHEV (CD)	0.84	0.45	0.15	0.42
PHEV (CS)	1.04	1.39	1.01	0.64
Sources	This work	[42]	[100]	[101]

The gasoline pathway is from GREET model as reference to offer corresponding data for comparative WTW analysis of PHEV in other countries except China, as shown in Table 20.

Table 20. The WTW analysis data of gasoline pathway in GREET

PEC (MJ/MJ)		**GHG emissions** ($gCO_{2,eq}$/MJ)				**Air pollutant emissions** (g/MJ)					
		CO_2	**CH_4**	**N_2O**	**GHG_{total}**	**VOCs**	**CO**	**NOx**	**PM_{10}**	**$PM_{2.5}$**	**SO_X**
GREET[42]	1.287	90.05	5.78	1.31	97.14	0.08009	0.73	0.08396	0.00469	0.00344	0.02341

3. Results and discussions

3.1. WTW comparative analysis of various alternative vehicles in China case

According to the equations above, the PEC, GHG and air pollutant emissions of GICEV, BEV, PHEV, LPGV, CNGV and CTLV of China case during the WTW stages are calculated as below.

3.1.1. WTT analysis of PEC of gasoline and electricity pathways

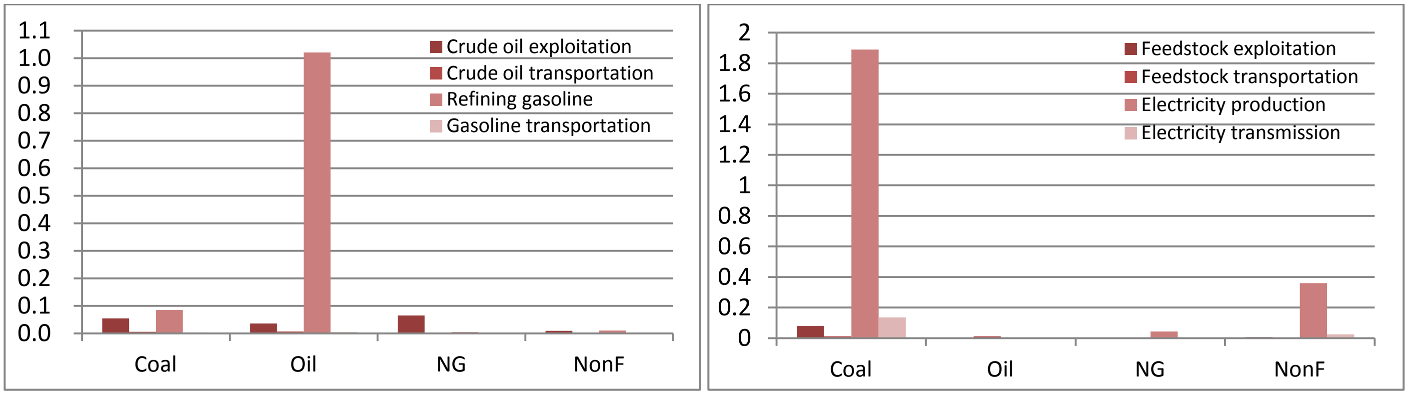
As Table 14 and Table 21 shows, the total PEC intensity for 1MJ gasoline and electricity obtained are respectively 1.31MJ and 2.58MJ, while the energy transformation efficiency reaches to 76.4% and 38.8%, respectively.

Table 21. The WTT primary energy consumption intensity (MJ/MJ) of electricity

Coal	Oil	NG	[a]NonF	Total PFEC	Total PEC
2.1160	0.0183	0.0507	0.3922	**2.1850**	**2.5772**

[a]NonF: Non Fossil energy

Figure 3. The WTT primary energy consumption (MJ/MJ) structure of gasoline and electricity



As shown in Figure 3, the PEC in gasoline refining stage is the highest for the whole WTT stage; also oil consumption is the highest. Primary coal energy is mainly consumed in the gasoline refining stage, followed by the exploitation stage. NG is mainly consumed in the crude oil exploitation stage, followed by the gasoline refining stage. Non-fossil energy is mainly consumed in gasoline refining and crude oil exploitation stages. Besides, the total PFEC of gasoline in WTT stages is about 1.29MJ/MJ, accounting for 98.4% of total PEC.

Besides, PEC for the electricity generation stage is the highest, accounting for 89.0%; under the current electricity mix, the highest consumed primary energy is coal with a share of 82.1% of the total PEC. Coal, NG and non-fossil energy are mainly consumed in electricity production stage, respectively accounting for 89.3%, 87.8% and 91.6% of their total consumption. Oil is mainly used for the feedstock exploitation and transportation, accounting for 23.5% and 70.0% of the total oil consumption.

From the results above, in the WTT stages, energy conversion efficiency of electricity is far lower than that of gasoline, which means, to obtain 1MJ electricity the required primary energy is 1.97 times that to obtain 1MJ gasoline. Besides, the PFEC of electricity pathway mainly originates from coal energy whereas the main PFEC of gasoline is from oil energy.

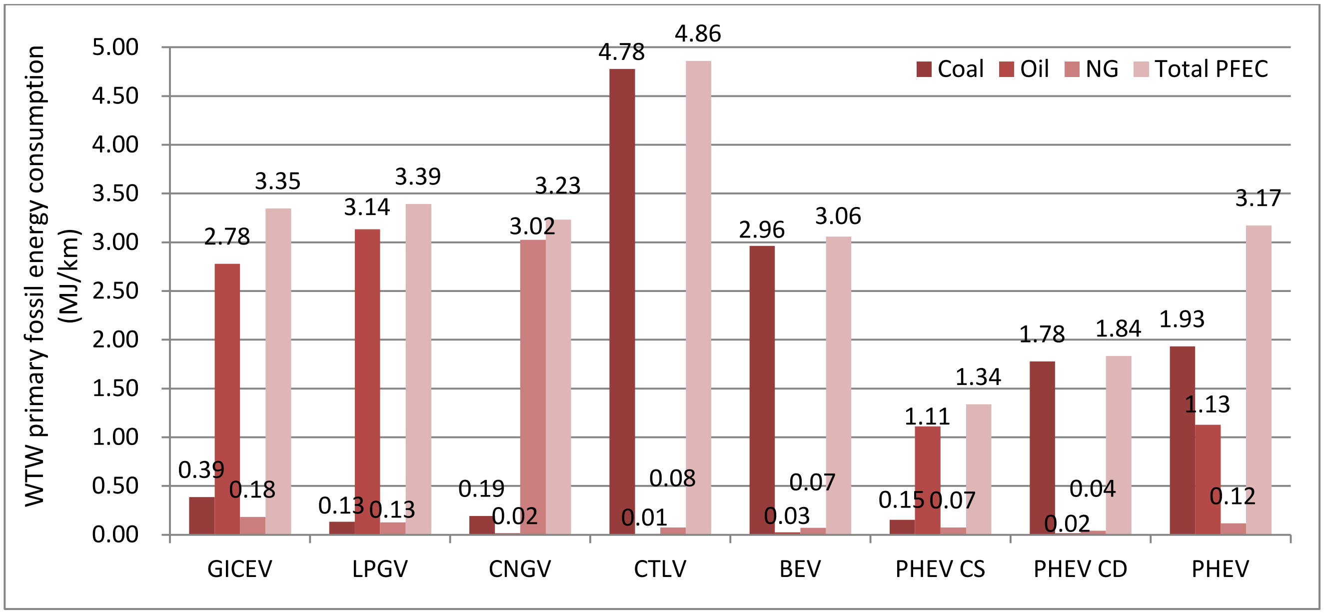
3.1.2. WTW comparison of PFEC of alternative fuel vehicles

The energy consumption results of GICEV, BEV, PHEV, LPGV, CNGV and CTLV in TTW stage were listed in Table 17. Therefore, on the basis of the equation (5), the total PFECs of each alternative vehicle during WTW fuel cycle are listed in Table 22.

Table 22. The WTW primary fossil energy consumption (MJ/km) of alternative fuel vehicles

	LPGV	**CNGV**	**CTLV**	**GICEV**	**BEV**	**PHEV(CS)**	**PHEV(CD)**	**PHEV(Total)**
Coal	0.132	0.192	4.778	0.386	2.962	0.154	1.777	1.932
Oil	3.135	0.016	0.009	2.779	0.026	1.112	0.015	1.127
NG	0.127	3.024	0.075	0.183	0.071	0.073	0.043	0.116
Total PFEC	**3.394**	**3.232**	**4.862**	**3.348**	**3.059**	**1.339**	**1.835**	**3.174**

Figure 4. The primary fossil energy consumption of different alternative vehicles for fuel cycle



As shown in, BEV has the lowest PFEC of 3.06MJ/km while CTLV has the highest PFEC of 4.86MJ/km, which is about 1.6 times that of BEV; it is because CTLV consumes large amount of coal energy for the upstream stages, accounting for 98.3% of its total PFEC. Besides currently the energy conversion efficiency of CTL plant in China is still low due to the high requirement of direct liquefaction technology for coal quality with low heat value and high hydrogen content. Coal consumption dominates the WTW stages of BEV with a

96.7% share of total PFEC due to the current coal-governed power generation mix in China. Except for CTL pathway, PFECs of LPGV, CNGV are almost similar with that of GICEV; among them, CNGV has a relatively low PFEC of 3.23MJ/km, which is mainly due to its high transportation efficiency through pipelines.

Unlike other fuel pathways, the coal and oil consumption respectively account for 61% and 35% of total PFEC in PHEV WTW fuel cycle owing to its two driving systems. However, since the charging facility amounts for the EVs in China still need to improve, and the charging time is long, some PHEV users may use more gasoline than electricity to drive, it will further increase the oil consumption.

In addition, the oil consumptions of BEV and CNGV are only 1% and 0.7% that of GICEV, which means BEV and CNGV are good substitutes of oil-based fuel vehicles. The large-scale use of BEV and CNGV can have a good effect on the reduction of increasing dependence of oil imports. However, as the current electricity generation mix in China is still dominated by coal, the large-scale use of BEV will further increase the demand for coal, which has a serious influence to global warming and air quality.

3.1.3. WTT analysis of GHG emissions of gasoline and electricity pathways

Table 23 and Table 24 respectively show the GHG emission intensities of the gasoline and electricity in the WTT stages. The total WTT GHG emissions for 1MJ gasoline obtained are 23.7g$CO_{2,eq}$, while for 1MJ electricity are 221.3g$CO_{2,eq}$. CO_2 is the main GHG emission species, followed by CH_4 and N_2O.

Table 23. The WTT GHG emission intensities (g$CO_{2,eq}$/MJ) of gasoline

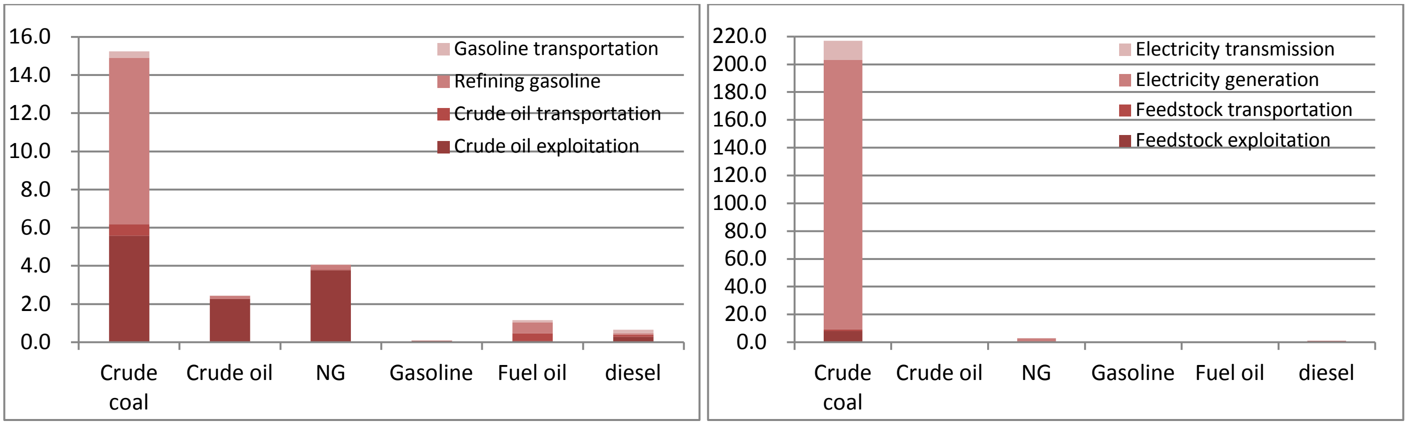
	Crude coal	Crude oil	NG	Gasoline	Fuel oil	Diesel	Total
CH_4	2.043	0.014	0.173	0.001	0.002	0.001	**2.234**
N_2O	0.066	0.006	0.021	0.003	0.003	0.010	**0.109**
CO_2	13.124	2.431	3.876	0.094	1.163	0.636	**21.318**
$^{a}CO_{2,eq}$	15.232	2.451	4.080	0.098	1.166	0.646	**23.664**

$^{a}CO_{2,eq}$: carbon dioxide equivalent

Table 24. The WTT GHG emission intensities ($gCO_{2,eq}/MJ$) of electricity

	Crude coal	Crude oil	NG	Gasoline	Fuel oil	Diesel	Total
CH_4	29.138	0.001	0.125	0.001	0.001	0.002	**29.24**
N_2O	0.942	0.000	0.015	0.003	0.001	0.014	**0.976**
CO_2	187.000	0.117	2.805	0.077	0.312	0.864	**191.08**
$^{a}CO_{2,eq}$	216.920	0.118	2.944	0.080	0.313	0.881	**221.34**

Figure 5. The WTT GHG emissions ($gCO_{2,eq}/MJ$) structure of gasoline and electricity



As shown in Figure 5, the main emission energy source is crude coal, which is mainly attributed to the direct coal combustion during the crude oil exploitation and gasoline refining stages as well as the indirect coal consumption of required electricity as process energy in upstream stages. NG and crude oil also have high GHG emissions, mainly due to the fuel combustion in feedstock exploitation stage. Moreover, GHG emissions of gasoline in crude oil exploitation stage are the highest, crude coal and NG become the main emission sources in this stage; then gasoline refining stage is the second highest mainly from the crude coal combustion. GHG emissions in both feedstock and fuel transportation stages are relatively low, which are mainly from the consumptions of crude coal, fuel oil and diesel during the railway, pipeline and sea tanker transportation processes.

As for each WTT stage, 88.8% of electricity GHG emissions are concentrated in the electricity generation stage, mainly from the crude coal combustion due to the current Chinese electricity generation mix. The GHG emissions during the electricity transmission stage account for 6.4% due to the electricity loss. Besides, GHG emissions from feedstock extraction and transportation stages account for only 3.5% and 0.9%, respectively. In addition, WTT GHG emissions of electricity mainly come from crude coal, accounting for 98%, due to the coal-dominated power structure and the currently low power generation efficiency in China.

From the above it can be seen that the total WTT GHG emissions of electricity are about 9.3 times that of gasoline, and the GHG emissions of gasoline production is much lower than that of electricity generation. It is because the energy conversion efficiency of gasoline is much higher than electricity, about 1.97 times; besides, the majority of primary energy will be used in the TTW stage.

3.1.4. WTW comparison of GHG emissions of alternative fuel vehicles

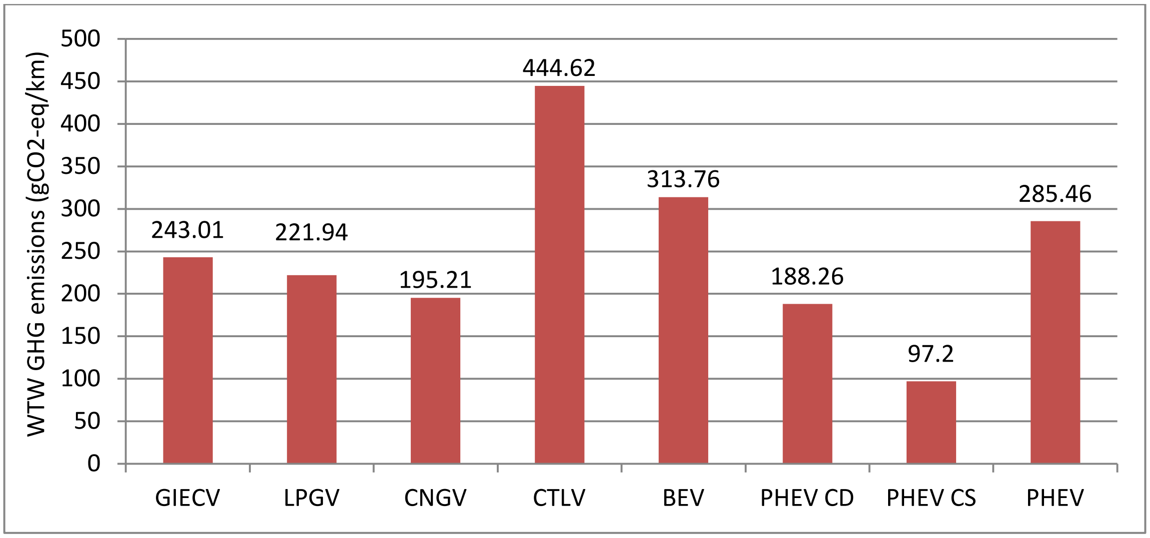
During the vehicle driving stage, electricity-powered vehicle emits no GHG while other fuel-powered ICEVs generate massive GHG emissions. By calculation, the TTW gasoline GHG emissions are 182.4g$CO_{2,eq}$/km, including CO_2 emissions of 174.2g$CO_{2,eq}$/km, CH_4 emissions of 2.2g$CO_{2,eq}$/km and N_2O emissions of 6.0g$CO_{2,eq}$/km, respectively. Table 25 lists the calculated results of GHG emissions of GICEV, LPGV, CNGV, CTLV, BEV and PHEV during the entire WTW fuel cycle.

Table 25. The WTW GHG emissions (g$CO_{2,eq}$/km) of different alternative fuel vehicles

	GIECV	**LPGV**	**CNGV**	**CTLV**	**BEV**	**PHEV(CD)**	**PHEV(CS)**	**PHEV(Total)**
Total GHG	243.01	221.94	195.21	444.62	313.76	188.26	97.20	285.46

Among all the AFVs, CTLV has the highest GHG emissions of 444.62g$CO_{2,eq}$/km, about 2.27 times that of CNGV, which has the lowest GHG emissions of 195.21g$CO_{2,eq}$/km, as shown in Figure 6; they are mainly from feedstock exploitation, fuel production and fuel combustion stages with high emission factors.

Figure 6. The GHG emissions of different alternative vehicles for fuel cycle



Then BEV emits the second highest GHG quantity with 313.76g$CO_{2,eq}$/km mainly from the electricity generation stage, due to the current coal-dominated electricity generation mix and its low power generation efficiency. Since PHEV drives in 60% of CD mode and 40% of CS mode, it leads to relatively high GHG emissions of 285gCO_2/km in WTW fuel cycle than GICEV. LPGV and CNGV both have relatively lower emissions than other AFVs, which respectively are 221.94g$CO_{2,eq}$/km and 195.21g$CO_{2,eq}$/km, mainly from the TTW vehicle driving stage.

In terms of the comparative results of GHG emissions, under the current electricity generation mix in China, despite the lowest PFEC of BEV than other AFVs, BEV is still not an optimal choice to replace conventional gasoline vehicle. CNGV and LPGV can be the recommended AFVs until the electricity generation mix doesn't depend on coal power.

3.1.5. WTT analysis of Air Pollutants emissions of gasoline and electricity pathways

The WTT conventional air pollutants emissions of gasoline in WTT stages in Table 26 showed that the highest emission intensity is VOCs with 0.170g/MJ, followed by SO_X with 0.147g/MJ; then NOx, CO, PM_{10} and $PM_{2.5}$, whose emission intensities are 0.072g/MJ, 0.044g/MJ, 0.015g/MJ and 0.011g/MJ, respectively. As shown in Table 27, the highest air pollutant emissions intensity of electricity in WTT stages is SO_X with 0.860g/MJ, followed by NOx with 0.666g/MJ; then the emission intensities of CO, PM_{10}, $PM_{2.5}$ and VOCs are 0.285g/MJ, 0.090g/MJ, 0.063g/MJ and 0.032g/MJ, respectively.

Table 26. The WTT air pollutants emission intensities (g/MJ) of gasoline

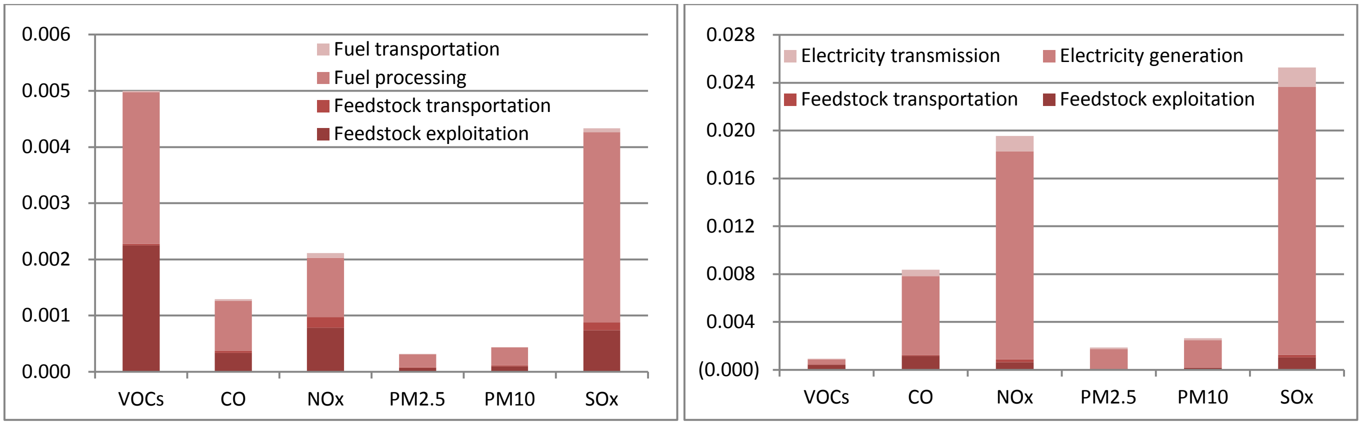
	Crude coal	Crude oil	NG	Gasoline	Fuel oil	diesel	Total
VOCs	1.66E-03	1.63E-01	2.13E-03	2.66E-06	4.73E-04	2.19E-03	**0.1697**
CO	4.05E-02	6.70E-04	6.94E-04	2.20E-05	6.43E-04	1.47E-03	**0.0439**
NOx	4.18E-02	1.51E-02	3.16E-03	3.38E-04	6.32E-03	5.00E-03	**0.0717**
$PM_{2.5}$	4.59E-03	5.58E-03	5.37E-05	2.70E-06	5.03E-04	1.00E-04	**0.0108**
PM_{10}	7.48E-03	6.70E-03	5.37E-05	5.24E-06	5.81E-04	1.03E-04	**0.0149**
SOx	6.26E-02	8.16E-02	3.23E-04	3.34E-05	2.40E-03	3.47E-04	**0.1472**

Table 27. The WTT air pollutants emission intensities (g/MJ) of electricity

	Crude coal	Crude oil	NG	Gasoline	Fuel oil	diesel	**Total**
VOCs	2.65E-02	1.48E-03	1.71E-03	5.27E-07	2.48E-04	1.69E-03	**0.0316**
CO	2.82E-01	2.61E-05	1.64E-03	5.95E-07	3.03E-04	1.13E-03	**0.2849**
NOx	6.56E-01	3.74E-04	2.28E-03	9.83E-05	3.20E-03	4.35E-03	**0.6664**
$PM_{2.5}$	6.26E-02	1.05E-04	3.88E-05	7.38E-07	2.31E-04	9.96E-05	**0.0632**
PM_{10}	8.94E-02	1.30E-04	3.88E-05	1.47E-06	2.57E-04	1.03E-04	**0.0901**
SOx	8.57E-01	1.38E-03	2.33E-04	9.42E-06	1.21E-03	3.77E-04	**0.8602**

Various WTT air pollutant emissions of gasoline mainly originate from fuel processing and feedstock exploitation stages. From the perspective of energy sources, in WTT stages, crude oil consumption emits the highest air pollutant emissions, followed by crude coal consumption.

Figure 7. The WTT air pollutants emissions (g/MJ) structure of gasoline and electricity



The simplification of PFEC structure in WTT stages of electricity determines that most of its air pollutants are emitted from crude coal. As shown in Table 27, the 84.0% of VOCs emission, 98.8% of CO emission, 98.5% of NOx emission, 98.9% of $PM_{2.5}$ emission, 99.2% of PM_{10} emission and 99.6% of SO_X emission are all derived from crude coal consumption. In addition, WTT air pollutants emissions mainly originate from electricity generation stage, including 43% of VOCs emission, 78.7% of CO emission, 88.7% of NOx emission, 88.2% of $PM_{2.5}$ emission, 86.8% of PM_{10} emission and 88.5% of SO_X emission.

It is obvious that except for VOCs, other air pollutant emissions of electricity in WTT stages are much higher than that of gasoline. Especially during the electricity generation stage, a large amount of raw coal consumption leads to high emission intensities of CO, NOx, $PM_{2.5}$, PM_{10} and SO_X. However, the VOCs emissions of gasoline in WTT stages are higher than electricity, mainly due to the high VOCs emissions from the gasoline processing and crude oil exploitation stages. In terms of the WTT stages, electricity production has a much worse impact on the environment than gasoline.

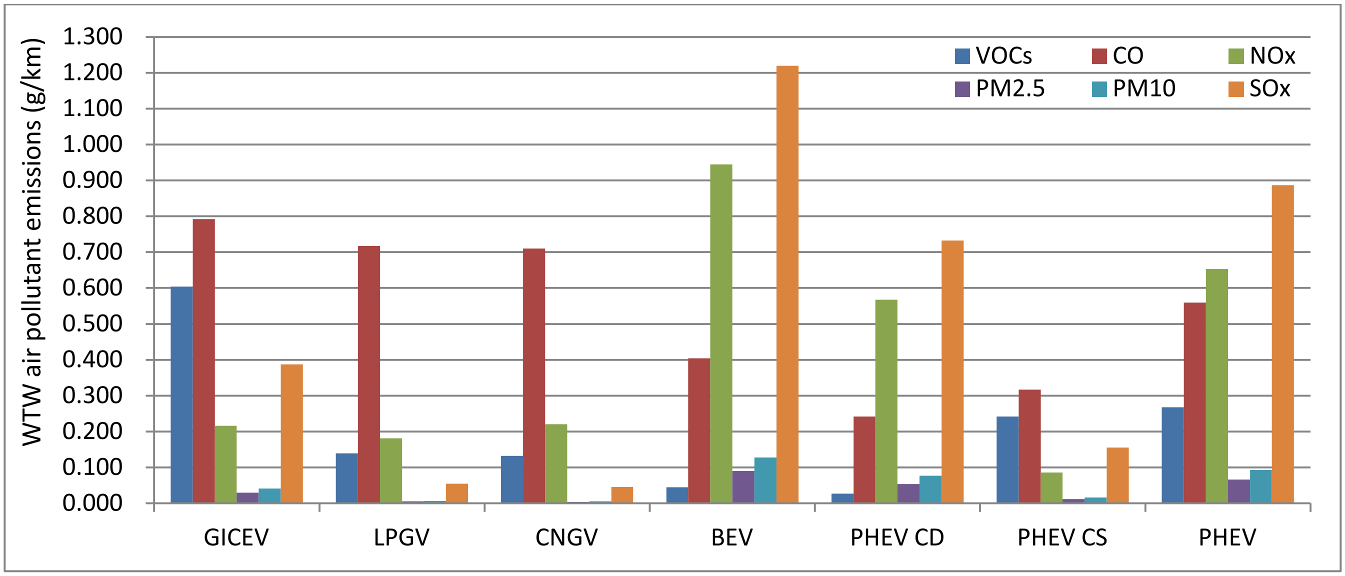
3.1.6. WTW comparison of Air Pollutants emissions of alternative fuel vehicles

As a clean secondary energy, electricity emits no air pollutants during vehicle driving process while the combustion of other alternative fuels in ICE produces high air pollutant emissions. In the TTW stage, according to Table 11, the highest emission intensity is CO with 0.680g/km, followed by VOCs with 0.169g/km. Then emission intensities of NOx, SO_X, PM_{10} and $PM_{2.5}$ respectively are 0.075g/km, 0.032g/km, 0.001g/km, 0.003g/km and 0.003g/km, respectively.

Table 28. The WTW air pollutants emissions (g/km) of different alternative vehicles

	GICEV	LPGV	CNGV	BEV	PHEV		
					CD	CS	Total
VOCs	0.604	0.139	0.132	0.045	0.027	0.242	0.268
CO	0.792	0.718	0.710	0.404	0.242	0.317	0.559
NOx	0.216	0.181	0.221	0.945	0.567	0.086	0.653
$PM_{2.5}$	0.030	0.005	0.004	0.090	0.054	0.012	0.066
PM_{10}	0.041	0.006	0.005	0.128	0.077	0.016	0.093
SOx	0.387	0.054	0.045	1.219	0.732	0.155	0.887

Figure 8. The air pollutants emissions of different alternative vehicles for fuel cycle



During the whole WTW fuel cycle (Figure 8), emissions of VOCs and CO in GICEV are higher than other AFVs due to the gasoline combustion; PHEV also have a relatively high VOCs emission due to the CS driving mode powered by gasoline. GICEV, LPGV and CNGV have relatively close CO emissions, which are about 1.96, 1.78 and 1.76 times that of BEV, respectively; it is owing to high CO emission factors of ICEs during vehicle operation stage. However, emissions of NOx and SO_X from BEV are much higher than other AFVs; among them, SOx emission of BEV is almost 3.1, 22.6 and 27.1 times that of GICEV, LPGV and CNGV, which is mainly from coal consumption during the electricity generation stage.

Besides crude coal has much higher sulfur and nitrogen contents comparing to crude oil and NG. This also leads to a high SOx emission of PHEV of which the CD driving mode powered by electric motor has a 60% share of average traveled distance. Moreover, although PM_{10} and $PM_{2.5}$ emissions of all the AFVs are much lower than other air pollutant emissions, in contrast with other AFVs, BEV has much more PM_{10} and $PM_{2.5}$. Because currently under the *National IV standard* PM_{10} and $PM_{2.5}$ emissions from gasoline combustion is relatively low but thermal power plants inevitably generate large amounts of particulate matters.

It can be seen from the above comparison that at present large-scale use of BEV will lead to higher NOx and SOx emissions in the atmosphere causing the formation of acid rain. Whereas extensive use of ICE based vehicles will emit higher CO and VOCs which have serious influences to human health. Therefore, it is very necessary to speed up the transformation of Chinese domestic electricity generation mix for the sustainable development of alternative transportation sector.

3.2. WTW comparative analysis of BEV and PHEV in different countries

3.2.1. WTT analysis of PEC of grid electricity in different countries

From calculated results it can be seen that PEC in electricity generation and transmission stages accounts for 95.4% of total upstream PEC. Thus differences in electricity generation mix (Table 18) will cause different WTT PECs of electricity pathways, as shown in Table 29.

Table 29. The WTT primary energy consumption intensities of grid electricity in different countries

	Coal	**NG**	**Oil**	**Nuclear**	**Hydro**	**Others**	**Total PEC** (MJ/MJ)	Sources
China	2.12	0.05	0.02	0.04	0.24	0.11	**2.58**	This work
U.S.	0.97	0.85	0.04	0.23	0.07	0.09	**2.25**	GREET[42]
Norway	0.003	0.04	0.001	0	1.04	0.017	**1.10**	GREET[42]
France	0.02	0.09	0.01	2.30	0.13	0.06	**2.63**	JEC Report[100]
Japan	0.99	0.94	0.30	0.01	0.08	0.27	**2.60**	GREET[42]
Germany	0.75	0.10	0.02	0.45	0.04	0.33	**1.69**	JEC Report[100]

As for the WTT stages of grid electricity pathways, France has the highest PEC than other countries, which is about 2.63MJ/MJ, due to its nuclear-dominated power generation mix and low energy transformation efficiency of nuclear power plants. Then Japan and China have similar PECs, i.e. 2.60MJ/MJ and 2.58MJ/MJ, respectively; because according to the GREET database, PEC in the thermal power plants is higher than in other power plants; this also causes the total PFEC of grid electricity in Japan is similar to China, both accounting for 85% of total PEC, although their electricity generation structures are different. And the WTT PEC of electricity in U.S. is 2.25MJ/MJ, neither high nor low in comparison with other countries due to its balanced power generation structure.

In addition, there are also some countries consuming small amount of primary energy for electricity pathway in WTT stages. Owing to the high energy transformation efficiency of thermal power plants on EU average level, Germany has a relatively less PEC of grid electricity than the above four countries with 2.25MJ/MJ. Norway has the lowest electricity PEC of 1.10MJ/MJ due to its absolutely hydropower-dominated generation mix, which accounts for 95.8% of total energy generation structures.

3.2.2. WTW comparative PEC of BEV and PHEV in different countries

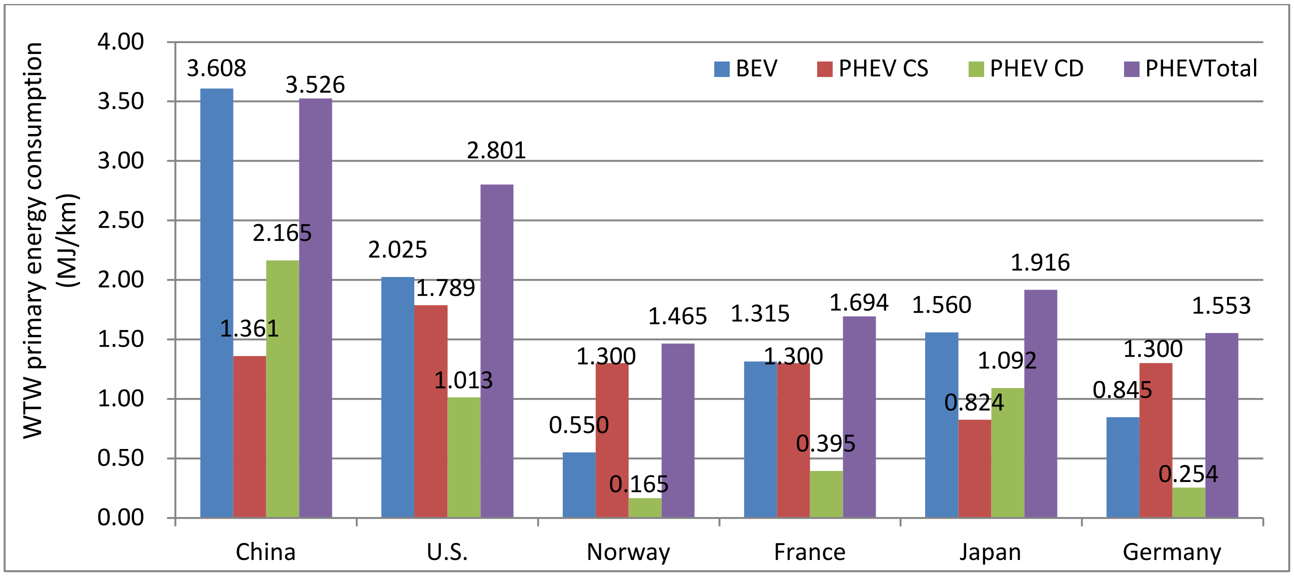
According to the basic data of TTW fuel consumption in Table 19, the PECs during WTW fuel cycle of BEV and PHEV in different countries are calculated in Table 30. In terms of the entire WTW fuel cycle, among all the BEVs in different countries, BEV in China has the highest PEC with 3.61MJ/km, which is about 6.5 times that in Norway, where the PEC of BEV is the lowest. Besides BEVs in European countries all have relatively low PECs, although the WTT PEC of grid electricity in France is the highest among all the countries. The reason is that fuel economy of BEVs in European countries is very low, which is about 0.35, 0.55 and 0.83 times that of China, the U.S. and Japan.

Table 30. The WTW primary energy consumption (MJ/MJ) of BEV and PHEV in different countries

	China	U.S.	Norway	France	Japan	Germany
BEV	3.608	2.025	0.550	1.315	1.560	0.845
PHEV CS	1.361	1.789	1.300	1.300	0.824	1.300
PHEV CD	2.165	1.013	0.165	0.395	1.092	0.254
$PHEV_{Total}$	3.526	2.801	1.465	1.694	1.916	1.553

PHEV of China case also consumes the most primary energies, while Norway still has the lowest PEC of PHEV for the entire fuel cycle, as shown in Figure 9.

Figure 9. The primary energy consumption of BEV and PHEV for fuel cycle in different countries



Besides except for China, PHEV in each country consumes less primary energies than BEV, because in these developed countries, PEC of gasoline powered vehicle is higher than electricity powered vehicle. On the contrary, electricity powered vehicle of China case has higher PEC than gasoline vehicles, due to the large amount of PFEC in the thermal plants during upstream electricity generation stage. In addition, unlike the European and American countries, PHEV CS modes of China and Japan case consume more primary energies than CD modes, due to the relatively high share of electric driving range during the vehicle operation stage.

3.2.3. WTT analysis of GHG emissions of grid electricity in different countries

Table 31. The WTT GHG emission intensities ($gCO_{2,eq}/MJ$) of grid electricity in different countries

	China	**U.S.**	**Norway**	**France**	**Japan**	**Germany**
CO_2	191.08	140	2.58	16.91	162.52	125.43
CH_4	29.24	9.52	0.25	2.47	11.03	18.70
N_2O	0.99	0.67	0.02	0.18	0.92	1.41
GHG_{Total}	**221.31**	**150.19**	**2.85**	**19.56**	**174.47**	**145.54**
Sources	This work	GREET[42]	GREET[42]	JEC Report[100]	GREET[42]	JEC Report[100]

It is obvious from the above that GHG emissions per MJ grid electricity obtained in China are the highest among all the countries which are about 1.3 times and 1.5 times those in the U.S. and Japan, respectively. Because China is still dominated by coal power, which as fossil energy with oil and NG mostly contribute to the GHG emissions. Besides, China has relatively higher GHG emissions factors during electricity generation stage than other developed countries due to the low power generation efficiency. Similarly, the U.S. and Japan also have higher WTT GHG emissions intensities than other European countries since they both have relatively fossil energy dominated electricity generation mixes.

However, for the European countries, Norway has the lowest WTT GHG emissions intensity which is 0.013 times that in China, while in France it is 0.088 times that in China, mainly due to the large proportion of non-fossil energy in their electricity generation mixes, i.e. the 95.8% of hydropower structure in Norway and the 72.3% of nuclear power structure in France. The emission intensity in Germany is in the medium range, because there is an equally dominated electricity generation mix by fossil and non-fossil energy.

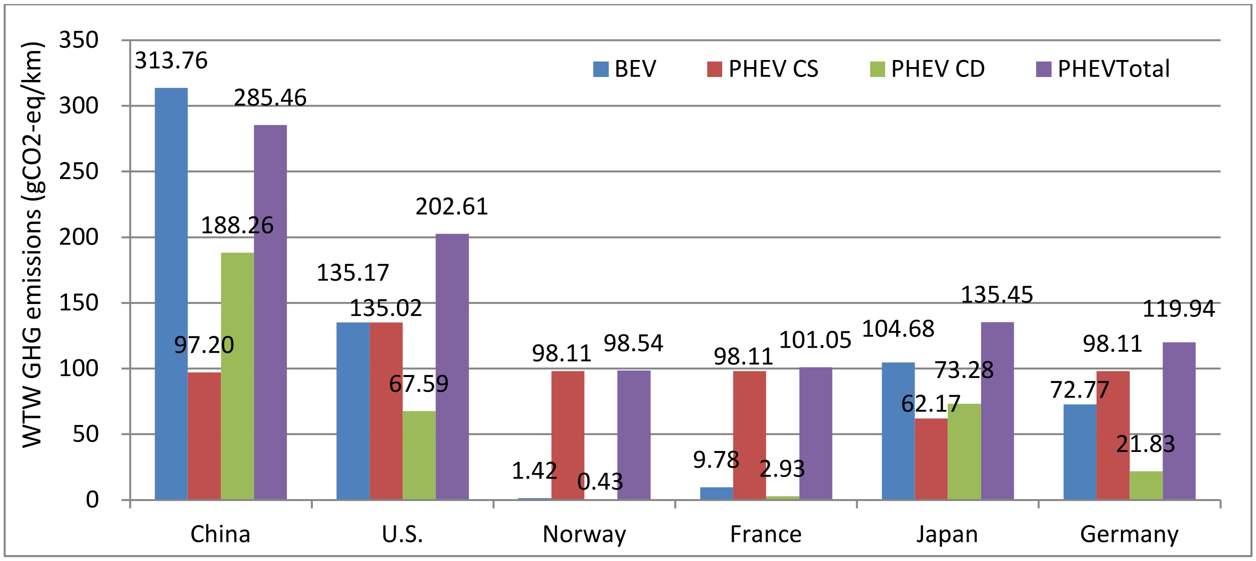
3.2.4. WTW comparative GHG emissions of BEV and PHEV in different countries

The calculated GHG emissions of BEV and PHEV for WTW fuel cycle in different countries are showed in Table 32 and Figure 10. It can be seen that GHG emissions of BEV and PHEV are quite different among this studied countries which have typical electricity generation mixes. BEV and PHEV of China case show really worst performances on GHG emissions than BEVs in other countries, especially European countries; their GHG emissions during WTW fuel cycle come to 313.76g$CO_{2,eq}$/km and 285.46g$CO_{2,eq}$/km, which are 219.4 and 2.9 times that of Norway, whose GHG emissions of BEV and PHEV are the lowest among all the studied countries. The great difference between China with Norway and France mainly lies in their distinct electricity generation mixes; in Norway the fossil energy based electricity generation only accounts for 1.92%.

Table 32. The WTW GHG emissions (g$CO_{2,eq}$/km) of BEV and PHEV in different countries

	China	**U.S.**	**Norway**	**France**	**Japan**	**Germany**
BEV	313.76	135.17	1.43	9.78	104.68	72.77
PHEV CS	97.20	135.02	98.11	98.11	62.17	98.11
PHEV CD	188.26	67.59	0.43	2.93	73.28	21.83
$PHEV_{Total}$	285.46	202.61	98.54	101.05	135.45	119.94

Figure 10. The GHG emissions of BEV and PHEV for fuel cycle in different countries



Moreover, BEV and PHEV of U.S. case also have relatively high GHG emissions, mainly due to 65% of its electricity generation mix dominated by fossil energy. In spite of similar share of fossil energy in electricity mix with China and the U.S., Japan has lower GHG emissions of BEV and PHEV due to its highly efficient fuel economy of ICEV and EV. BEV and PHEV of Germany case has averaged GHG emissions due to its balanced electricity structures.

Therefore, it can be discussed that in the developing countries with a fossil energy dominated electricity generation mix, the high GHG emissions of EV during its fuel cycle can be reduced by some external technologies applying to the power plants, because that can be easier to achieve than making emissions reduction in vehicle driving phase. This technology can be Carbon Capture and Storage (CCS) technology, which can capture up to 90% of the CO_2 emissions produced from fossil energies in electricity generation and industrial processes, preventing CO_2 entering the atmosphere [102].

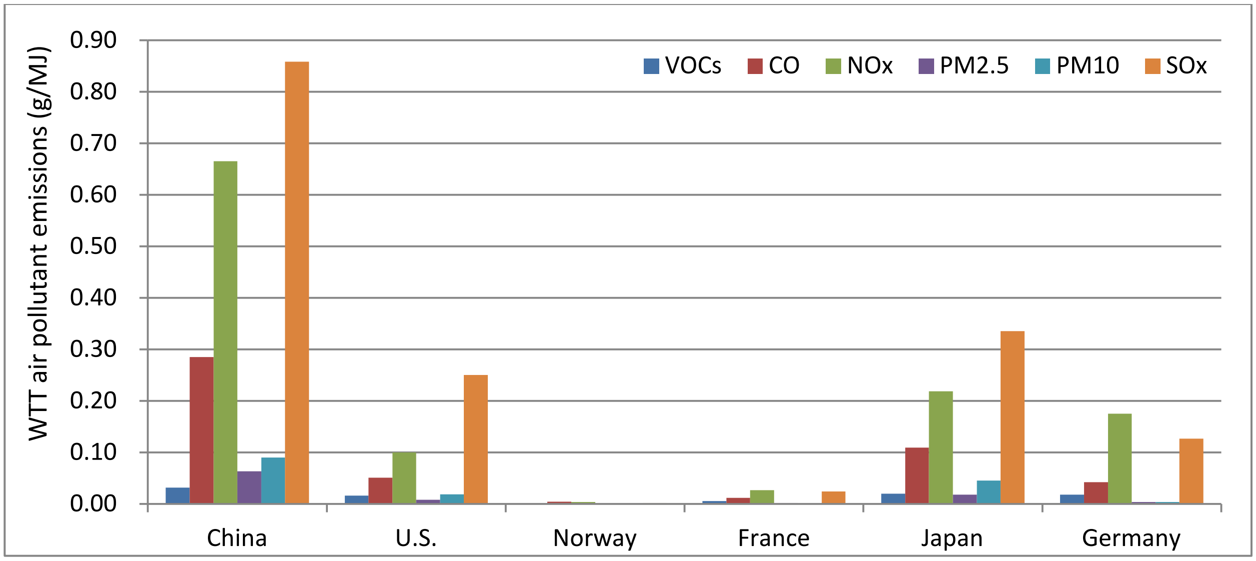
3.2.5. WTT analysis of Air Pollutants emissions of BEV and PHEV in different countries

The WTT comparative results of conventional air pollutants emissions in selected countries are indicated in Table 33 and Figure 11. As for WTT stages, it can be seen that China, the U.S. and Japan have relatively high SO_X, NOx and CO emissions of grid electricity due to their similar electricity generation mixes dominated by fossil energy, which is the main source of SO_2, NOx and CO emissions. Among them, China has the highest emissions mainly due to the large proportion of coal consumption during upstream stages, about 97% of whole PFEC; besides the SO_2, NOx and CO emission factors of coal are higher than oil and NG. Germany also has higher emissions of SO_2 and NOx than other air pollutants due to its coal-dominated PFEC structure.

Table 33. The WTT air pollutants emission intensities (g/MJ) of grid electricity in different countries

	China	**U.S.**	**Norway**	**France**	**Japan**	**Germany**
VOCs	0.03155	0.01603	0.00050	0.00521	0.01983	0.01767
CO	0.28493	0.05066	0.00440	0.01197	0.10923	0.04220
NOx	0.66544	0.10000	0.00328	0.02681	0.21878	0.17507
$PM_{2.5}$	0.06312	0.00793	0.00043	0.00182	0.01787	0.00386
PM_{10}	0.09000	0.01830	0.00127	0.00091	0.04549	0.00387
SO_X	0.85880	0.25000	0.00193	0.02388	0.33510	0.12676
Sources	This work	GREET[42]	GREET[42]	[103]	GREET[42]	[103]

Figure 11. The WTT air pollutants emission intensities of grid electricity in different countries



The WTT PM emissions mainly originate from the coal and oil consumptions, thus China, the U.S. and Japan have relevant PM emissions. VOCs emissions are mainly derived from oil consumption in feedstock exploitation and electricity production stages, so each country has corresponding emissions. Furthermore, Norway and France both have very low air pollutant emissions during WTT stages of electricity since their electricity generation mixes are dominated by clean energy structures.

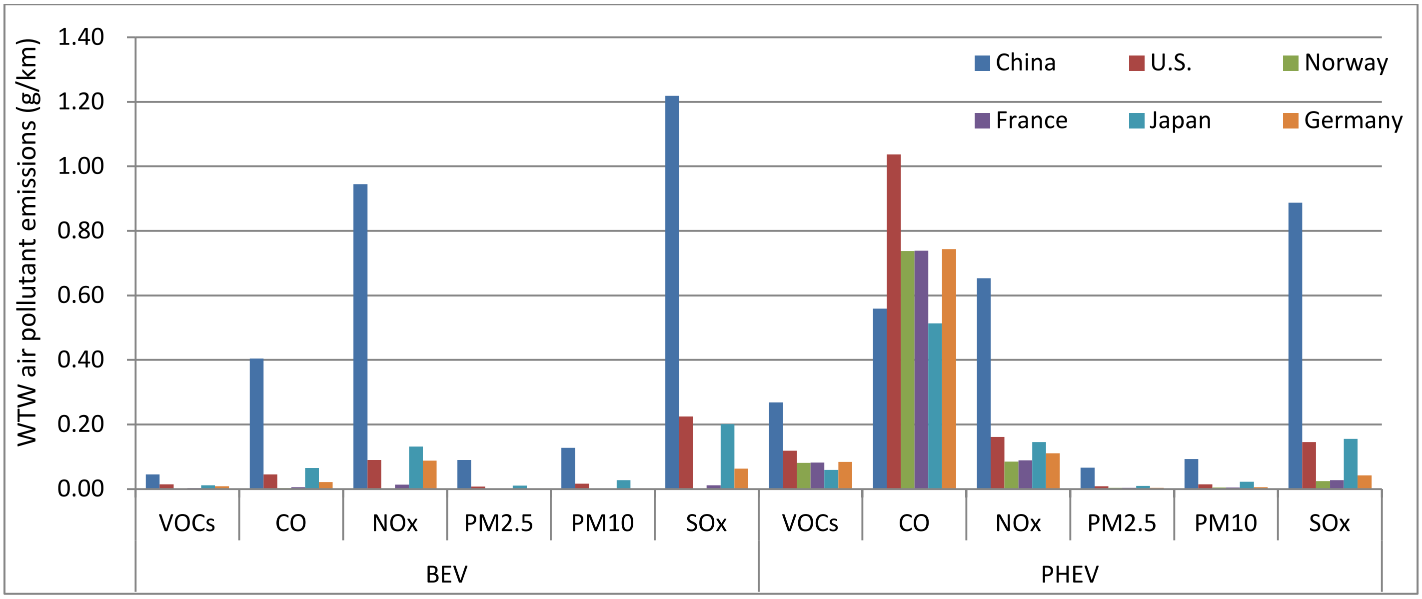
3.2.6. WTW comparative Air pollutants emissions of BEV and PHEV in different countries

Air pollutant emissions of BEV and PHEV during the WTW fuel cycle in different countries are calculated in Table 34.

Table 34. The WTW air pollutants emissions (g/km) of BEV and PHEV in different countries

		China	U.S.	Norway	France	Japan	Germany
BEV	VOCs	0.0450	0.0144	0.0003	0.0026	0.0119	0.0088
	CO	0.4040	0.0456	0.0022	0.0060	0.0655	0.0211
	NOx	0.9450	0.0900	0.0016	0.0134	0.1313	0.0875
	$PM_{2.5}$	0.0900	0.0071	0.0002	0.0009	0.0107	0.0019
	PM_{10}	0.1280	0.0165	0.0006	0.0005	0.0273	0.0019
	SO_X	1.2190	0.2250	0.0010	0.0119	0.2011	0.0634
PHEV	VOCs	0.2680	0.1185	0.0810	0.0817	0.0596	0.0835
	CO	0.5590	1.0375	0.7380	0.7391	0.5131	0.7436
	NOx	0.6530	0.1617	0.0853	0.0888	0.1456	0.1111
	$PM_{2.5}$	0.0660	0.0084	0.0035	0.0037	0.0097	0.0041
	PM_{10}	0.0930	0.0148	0.0049	0.0049	0.0221	0.0053
	SO_X	0.8870	0.1450	0.0239	0.0272	0.1557	0.0427

Figure 12. The Air pollutants emissions of BEV and PHEV for fuel cycle in different countries



As for the air pollutant emissions of BEVs during WTW fuel cycle, comparing to other developed countries, currently BEV of China case has the highest air pollutant emissions. Among them, SOx emission with 1.22g/km is about 5.3 and 6.0 times that of the U.S. and Japan cases; then NOx emission with 0.94g/km is about 7.2, 10.5 and 10.8 times that of Japan, the U.S. and Germany cases; CO emission as the third highest level with 0.404g/km is about 6.2 and 8.8 times of Japan and the U.S. cases. These high emissions are mainly from fossil energy consumption in the upstream stages of grid electricity.

Moreover, except for the high SOx and NOx emissions of PHEV in China case mainly due to the coal consumption, CO emissions of PHEV in each country are relatively higher than other air pollutants, because CO is mainly emitted in vehicle driving process. Since CO emission factor of gasoline vehicle of China case is lower than that of other countries (see Table 12 and Table 20), meanwhile CS mode of PHEV in China case has a relatively low share (40%), CO emission of PHEV in China is lower than other countries, about 0.54 and 0.75 times that of the U.S. and European countries. It can be seen that countries with fossil energy dominated electricity generation mix have higher conventional air pollutant emissions, especially CO, NOx and SOx emissions; and countries like European countries with non fossil energy dominated electricity generation mix have much lower air pollutant emissions.

Same as the previous section, technologies for air pollutants emissions reduction in power plants are also recommended to be developed, in the countries with high air pollutants emissions during EVs fuel cycle due to its fossil energy dominated electricity generation mix. For instance, in the thermal power plants, some technical processes [104] (eg. denitrification for NOx emission reduction, desulfurization for SOx emission reduction) and some precision filter devices for PM emission reduction can be applied in order to reduce the air pollutants emissions as much as possible in WTT upstream stages.

3.3. Prediction for CO_2 emissions of EVs in 2050 in China

According to the current auto market surveys[105][106], the development plan for AFVs from Chinese government[107] and previous prediction study for vehicle holdings[108], this work assumes a scenario for the development of light-duty vehicles in China. It assumes that the electric vehicle technologies will keep advancing with increasing expectations from consumers, and in 2050 the market share of EVs will reach to 50%, as shown in Table 35.

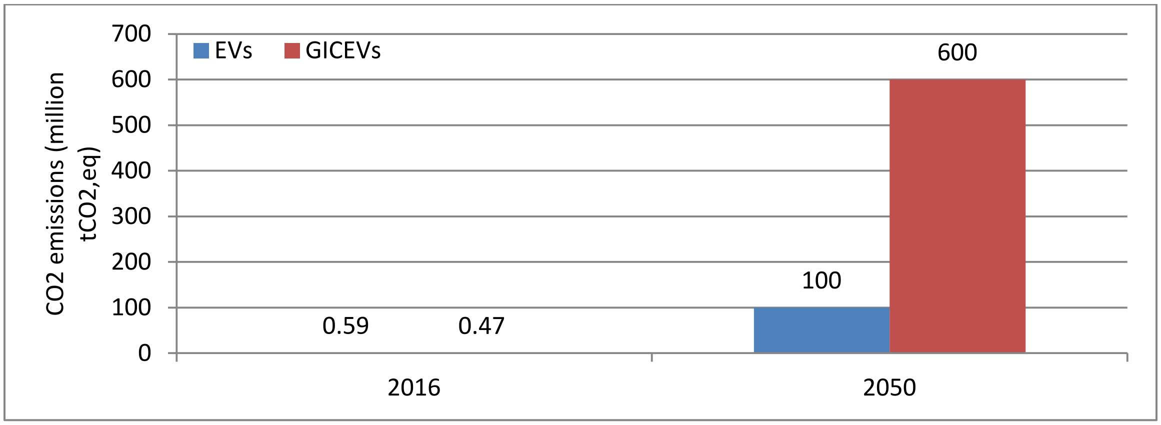
Besides, fuel economies of GICEV and BEV in 2050 are assumed to be 6L/100km and 9kWh/100km while the CD mode share of PHEV remains unchanged. Under the scenario, in 2050 the electricity generation mix in China is assumed to be 7% of coal power, 3% of NG power, 4% of nuclear power and 86% of renewable energy power; the electricity demands of BEV and PHEV reach 403.1 billion kWh and 15.4 billion kWh. The average annual driving distance of private cars set to be 15,000 km. The prediction for CO2 emissions of EVs in 2050 are based on the data of assumed scenario.

Table 35. Prediction of electric vehicle ownerships (million) based on the assumed scenario

	Total PPC[a]	**BEV**	Ratio	**PHEV**	Ratio	**Total EVs**	Ratio
2016	146	0.74	0.5%	0.34	0.2%	1.08	0.7%
2050	511	240.3	47%	15.3	3%	255.6	50%

PPC[a]: private passenger car

Figure 13. Comparison of CO_2 emissions (million $tCO_{2,eq}$) based on assumed scenario



In 2016, CO_2 emissions of total EVs ownerships in China have reached about 0.59 million $tCO_{2,eq}$ while CO_2 emissions of the same amount of GICEV reach 0.47 million $tCO_{2,eq}$. Since currently the electricity generation mix is dominated by coal power, the GHG emissions intensity of BEV is higher than that of GICEV.

However, under the assumed electricity generation scenario, in 2050, the large proportion of non-fossil energy in the electricity generation mix has led to the CO_2 emission intensity of BEV for the WTW fuel cycle dropped significantly. Thus in 2050 the CO_2 emission of total EVs ownerships in China reaches 100 million $tCO_{2,eq}$, which is only about 0.17 times that of same amount of GICEV, although the amount of EVs in 2050 already account for 50% of total passenger car ownerships with the strong support of government. It means that in 2050, 255.6 million EVs will have a CO_2 emission reduction of 500 million $tCO_{2,eq}$ by replacing conventional gasoline vehicles, under the assumed scenario with an electricity generation absolutely dominated by renewable energy sources.

4. Conclusions

In recent years the transportation sector has developed various alternative fuel vehicles (AFVs) for mitigating the environmental impacts. This work constructs an analytical well-to-wheels model for the fuel cycles of alternative fuel light-duty vehicles, Thus several conclusions are drawn as described below.

Regarding to the fuel cycle of those AFVs cases in China, conclusions mainly focus on three aspects:

1. Battery electric vehicles (BEV) has the lowest primary fossil energy consumption (PFEC) while coal to liquid vehicles (CTLV) has the highest about 1.6 times that of BEV; Liquefied petroleum gas vehicles (LPGV), compressed natural gas vehicles (CNGV) and conventional gasoline vehicles (GICEV) have similar relatively low PFECs at the middle level.

2. CNGV has the lowest greenhouses gases (GHG) emissions while CTLV has the highest about 2.27 times that of CNGV; BEV and Plug-in Hybrid Electric Vehicle (PHEV) have relatively higher GHG emissions than GICEV and LPGV.

3. VOCs and CO emissions of GICEV are the highest, while emissions of NOx, SOx and PM of BEV are the highest due to the coal based China’s electricity mix generation. Except for the CO emission, LPGV and CNGV both have relatively low emissions of various air pollutants species. Beside, among these pollutant species, PM emissions are much lower than other air pollutants.

Regarding to the fuel cycle of those EVs cases in different countries, conclusions can also be summarized in three aspects:

1. BEV in Norway has the lowest PEC while BEV in China has the highest, about 6.5 times that in Norway. BEV in the U.S. has the second highest PEC while Japan and France both show relatively low PECs of EVs cases. PEC of EVs in Germany is only a little higher than that in Norway. Moreover, except for China, PHEV in each country consumes less primary energies than BEV.

2. BEV and PHEV in China show extremely high GHG emissions, about 219.4 and 2.9 times that in Norway, which shows the lowest EVs GHG emissions. BEV and PHEV in the U.S. also have the second highest GHG emissions while those in Japan and other European countries all shows relatively low GHG emissions.

3. Comparing with other countries, except for CO emission, BEV and PHEV in China case both have too much higher emissions of other air pollutants than other countries. CO emissions of PHEVs in other countries are higher than in China due to their higher emission factors in vehicle driving phase; Besides CO emission of PHEV in each country is also higher than emissions of other air pollutants.

Furthermore, the prediction for CO_2 emission of EVs in China reveals that in 2050, under the assumed scenario, the CO_2 emission of total EVs ownerships reaches to 120 million $tCO_{2,eq,}$ which can lead to a CO_2 emission reduction of 500 million $tCO_{2,eq}$ by replacing the same amount of conventional gasoline vehicles.

Regarding to my personal point of view, there are also several conclusions:

1. The PEC, GHG and air pollutants emissions of EVs fuel cycle are affected by the combined effects of upstream power structures, vehicle fuel economy, coal power generation efficiency and other factors.
2. EVs cases in European countries show that low carbon electricity generation mix and highly efficient fuel economy lead to perfect performances in the mitigation of environmental impacts. Therefore, for European countries, EVs are an excellent choice for the vigorously promotion due to the optimal primary energy mix for electricity generation and the very advantageous vehicle fuel economy.

3. At present for China, CNGV and LPGV can be recommended alternative vehicles for next years due to their relatively lower carbon emissions and air pollutants emissions during fuel cycle than conventional gasoline vehicle. EVs could not be recommended to widely use in China until the domestic electricity generation mix is highly dominated by renewable energies and charging infrastructures for EVs was deployed.

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