Assessment of electrical vehicles as a successful driver for reducing CO_2 emissions in China

Jana Hofmann[1,2], Dabo Guan[1,2,*], Konstantinos Chalvatzis[2,3] Hong Huo[4*]

[1] School of International Development, University of East Anglia, Norwich, NR4 7TJ, UK
[2] Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, NR4 7TJ, UK
[3] Norwich Business School, University of East Anglia, Norwich, NR4 7TJ, UK
[4] Institute of Energy, Environment and Economy, Tsinghua University, Beijing 100084, China

*Correspondence email: Dabo.Guan@uea.ac.uk and hhuo@mail.tsinghua.edu.cn

Highlights:

- Evaluation of vehicle replacement programme with EVs, powered by 80% and 50% coal
- The introduction of EVs alone does not help reduce China's national GHG emissions
- Carbon intensity of electricity sector should be improved, before EVs are scaled up

Abstract

This paper analyses the impacts of the gasoline vehicle replacement programme with EVs at different penetration rates on petroleum and electricity sectors and their CO_2 emissions. The study utilises a top-down-type Environmental Input-Output (EI-O) model. Our results show that the replacement of gasoline cars with EVs causes greater impacts on total gasoline production than on total electricity generation. For example, at 5%, 20%, 50%, 70% and 100% gasoline vehicle replacement with EVs, the total gasoline production decreases by 1.66%, 6.65%, 16.62%, 23.27% and 33.24% in policy scenario 1, while the total electricity production only increases by 0.71%, 2.82%, 7.05%, 9.87% and 14.10%. Our study confirms that the gasoline vehicle replacement with EVs, powered by 80% coal, has no effect on overall emissions. The CO_2 emissions reduction in the petroleum sector is offset by the increase in CO_2 emissions in the electricity sector, leaving the

national CO_2 emissions unchanged. By decarbonising the electricity sector, i.e. using 30% less coal in electricity generation mix, the total CO_2 emissions will be reduced by 28% (from 10,953 to 7,870 Mt CO_2) on the national level. The gasoline vehicle replacement programme with EVs, powered by 50% coal-based electricity, helps reduce CO_2 emissions in petroleum sector and contributes zero or a very small proportion of additional CO_2 emissions to the electricity sector (policy scenario 2 and 3). We argue that EVs can contribute to a reduction of petroleum dependence, air quality improvement and CO_2 emission reduction only when their introduction is accompanied by aggressive electricity sector decarbonisation.

1. Introduction

China has experienced a rapid economic and energy sector growth over the past two decades. Its energy sector development is a balancing act to achieve targets for affordability, energy security and emissions control [1] while at the same time serving an enormous urbanisation movement. Due to improved living standards, road transportation has become a pressing issue [2]. It is predicted that the total Chinese motor vehicle stock will increase from 250 million to over 400 million by 2030 [3, 4, 5, 6]. To cater for such rapid growth, China is expected to increase its oil consumption to 702 million tons in 2030 [7]. According to Ou et al. [4], China's oil demand will account for 13-14% of the world total in 2030 and 55% of that oil will be used by the transportation sector [8].

Being the largest greenhouse gas (GHG) emitter, China's CO_2 emissions could reach 15.5 Gt by 2030 if no mitigation activities take place [9,10]. The CO_2 emissions of China's road transportation sector alone could reach 1,890 Mt in 2030, which accounts to 12% of the national total [11]. Without action to control the long-term growing trends of vehicle fleet, oil consumption and GHG emissions, China's transportation sector can have an impact on the global oil supply and demand, national energy security, air quality and CO_2 emissions [12, 13, 2].

Shifting part of the vehicle fleet from fuel to electricity (with EVs) is one of the current strategies to control the transportation sector's impacts. Currently, there are three different types of EVs on the market: conventional Hybrid Electric

Vehicles (HEVs), Plug-in Hybrid Electric Vehicle (PHEVs) and pure Battery Electric Vehicles (BEVs) [2]. EVs can help to decrease the dependence on petroleum either by increasing transportation efficiency or substituting with electricity generated using other energy sources, such as coal, hydro, nuclear and other renewables. EVs produce zero tailpipe GHG emissions or other harmful gas emissions, control urban air pollution and reduce noise [13, 14, 15, 16]. Although EVs do not generate direct emissions, they are responsible for indirect emissions caused by electricity generation [17]. Therefore, their environmental performance is directly related to that of the electricity sector they use for their charging.

China has been promoting EVs since 2009. The Chinese Government has set an ambitious plan to promote sales of 500,000 new-energy vehicles, including hybrids and EVs, by 2015 and 5 million by 2020 [18]. Until recently, the market share of EVs has remained very small in China with only 45,068 BEVs sold in 2014 nationwide, which accounts to 0.2% of total passenger vehicle sales [19]. The market uptake of EVs has faced a number of challenges, i.e. lack of charging stations, immature technology, high purchase prices and inadequate subsidy policies [13, 20, 21] all of which the Chinese Government is keen to address.

We analyse the impacts of the gasoline vehicle replacement programme with EVs at different penetration rates on petroleum and electricity sectors and their CO_2 emissions. Our research focuses on BEVs only. We consider light-duty passenger cars (or mini passenger vehicles) as per Huo & Wang's description [5].

The novelty of our study lies in its methodological approach. Most of the existing literature evaluates the environmental impacts of EVs using Life-Cycle Analysis (LCA). LCA is a well-established and extensively used systematic tool for comparing environmental impacts of transportation options over the entire life cycle of a product [22, 23, 24, 25]. It takes into account major stages and processes, and quantifies all environmental impacts over the life cycle of a product covering: raw materials extraction, manufacturing, product use, recycling and final disposal [26]. However, the LCA approach has been criticised by scholars because it cannot capture all GHG emissions associated with all passenger vehicle supply-chains and is based on subjective choices [27, 28, 29]. Due to LCA's limited features, there is insufficient evidence concerning the potential effects of large-scale adaptation of EVs [30] in a macro-economic context. This study uses a top-down type equilibrium EI-O model, which covers the entire economy and provides full accounting for all inputs in production from macro-economic analysis perspective [31]. In contrast to LCA, the I-O model is compiled on a regular basis as part of national statistics; hence well documented, transparent and freely available [28]. The EI-O model estimates results throughout the economy for each sector [22] and helps draw an informative conclusion about the impact of EVs replacement in China.

In this study, we incorporate parameters estimated by Huo et al. [32], who use LCA to predict vehicle consumption rates and the share of coal-based electricity in China for 2030, and employ a top-down EI-O model to estimate whether the substitution of conventional vehicles with EVs can be an effective policy for reducing CO_2 emissions in China. Our approach has multiple advantages:

1. It takes into account and assesses changes in exogenous final demand for petroleum and electricity sectors
2. It combines LCA data and evaluates any changes in relation to petroleum and electricity production sectors
3. It estimates environmental impacts of gasoline vehicle replacement with EVs at the national and sectoral level

This paper is organised as follows: section 2 presents a concise literature review on existing studies of vehicle replacement programmes; section 3 outlines the methodological framework; section 4 describes the data sources used to evaluate the impact of vehicle replacement and the CO_2 emissions caused at sectoral level; section 5 explains the hypothetical scenarios used in this study and section 6 presents and discusses the results; section 7 includes our concluding remarks.

2. Vehicle Replace Programmes – the international experience

One of the policies used for renewing the transport fleet is a large-scale replacement programme. The body of international research literature falls into two categories. The first category of research focuses on cost-benefit analysis of vehicle replacement programmes of old conventional with new fuel-efficient vehicles [33, 34, 35, 36, 37]. The secondary category of empirical research analyses the economic and environmental impacts of replacing Conventional Vehicles (CVs) with EVs [38, 39, 17, 40].

For example, Abrams & Parsons [34] conducted a cost and benefit analysis to evaluate the Car Allowance Rebate System (CARS) programme in the USA, commonly known as "Cash for Clunkers". Given that there were 700,000 vehicles in the programme, the authors estimated that the fuel consumption would decrease by 280 gallons per year per car, which according to Kagawa et al. [37] accounts to a reduction of 2.4 Mt of CO_2 a year. Knittel [33] re-examined the CARS programme and confirmed not only a positive impact on CO_2 emissions, but also a reduction of other criteria pollutants, such as NO_x, VOCs, PM_{10} and CO. For the same programme, Lenski [35] used the bottom-up type full LCA to capture all GHG emissions of old and new gasoline vehicles. The authors found positive impacts on CO_2 emissions estimating a total reduction of 4.4 million metric tons of life cycle GHG emissions or a saving of just under 0.4% of total annual US light-duty vehicle emissions. However, all scholars agree that the programme is an expensive way to reduce carbon dioxide as the US economy might result in a welfare loss.

Studies that focus on the replacement of conventional vehicles with EVs provide mixed results. For example, Wang [39] analysed the impacts of EVs penetration on California's economy. The author pointed out that EVs increase electricity expenditure, which cannot be offset by fuel savings. As incremental costs for electricity outweigh fuel savings, electric vehicles might have a slightly negative impact on California's economy. In contrast, Becker et al. [38] used a non-parametric conditional likelihood model to forecast the penetration of EVs in the US. The authors pointed out that adaptation of EVs would result in substantial improvement of US trade deficit and contribute between $94 and $266 billion of additional investment by 2030. Furthermore, EVs could have a positive impact on employment, creating between 130,000 and 350,000 jobs by 2030 mainly through development of domestic battery manufacturing industry and charging infrastructure network. If electricity is generated by renewable energy sources, electric vehicle deployment could lead to a 20-69% decline of greenhouse gas emissions between 2005 and 2030 [38].

Doucette & McCulloch [17] examined CO_2 emissions of EVs given different power generation mixes of several countries and compared them with CO_2 emissions reported by CVs. The authors found that EVs have the ability to reduce CO_2 emissions. However, countries, like China and India, with high carbon intensive power generation mixes will not benefit from EVs penetration. Unless their power generations are decarbonised, EVs may increase CO_2 emissions coming from automobile transportation sector.

With regards to evaluating environmental impact of EVs in China, the majority of studies use LCA to assess energy consumption and the CO_2 emission impacts of electric versus conventional gasoline vehicles [32, 41, 42, 43, 44, 16]. All studies agree that EVs are able to reduce CO_2 emissions and successfully displace petroleum-based fuels in the economy. But this potential could only be realised if China reduces the carbon intensity of electricity and implements a cleaner electricity generation mix. According to Huo et al. [32], EVs powered by coal-based electricity will increase CO_2 emissions by 7.3% compared to gasoline vehicles. More recently, Huo et al. [16] argued that EVs could double NO_x, increase SO_2 emissions by 4–5 times, triple PM_{10} emissions and quadruple $PM_{2.5}$ emissions in the high-coal-share regions of China. If EVs are powered by 80% renewable electricity or advanced coal-fired power plants, CO_2 emissions could be reduced by more than 85%, SO_2 and NO_x by more than 75% and PM emissions by more than 40%.

3. Methodology

3.1 Extended environmental Input-Output Framework

In this study we employ an extended EI-O model to quantify the environmental impacts of replacing passenger gasoline cars with EVs in China at the sector specific level. The EI-O model focuses on the interaction between sectoral production and consumption activities and captures energy consumption flows in physical units within the economy [45, 46, 47]. It takes into account direct and indirect effects of energy consumption required to produce one unit of economic output driven by changes in final demand [47, 48, 49]. We acknowledge that the Leontief-type production function is fixed and assumed to be linear. The basic input-output units are presented by fixed coefficients at a point in time and do not take into account any changes in prices throughout the economic cycle [48, 49].

Despite its simplicity and limitations mentioned above, the EI-O model is a widely used method for assessing environmental impacts, such as air quality, ecological footprints and tracking CO_2 emissions embodied in national and international trade [50, 51, 52, 53]. It can provide meaningful results as to how environmental coefficients respond to future structural changes i.e. changes in electricity and petroleum consumption as a consequence of the displacement programme. In our study, we assume that the replacement of gasoline cars with EVs only involves changes in exogenous final demand, while the production of all materials related to the substitution remains the same across all sectors. We briefly outline the EI-O model, however, details of the model are available in Miller & Blair [54]. The basic structure of I-O table is presented in Table 1.

z represents the intermediate relationship between the production and buying sectors. f is the total final consumption, which consists of urban and rural households, government, total capital formation, exports and imports. X is the row vector of total sectoral output ($\sum_{j=1}^{n} Z_{ij} + f_1$). v is the column vector of total value added needed to produce a given amount of input in a particular sector. X' is the column vector of total sector inputs ($\sum_{j=1}^{n} Z_{ij} + v_1$).

Table 1 Inter-industry flows of a standard I-O model (Leontief model) (expressed in Yuan)

		Buying sectors (intermediate demand)			Final Consumption	**Total Output**
		Industry 1	Industry 2 …..	Industry n		
Selling Sectors/ Producers	Industry 1	z_{11}	z_{12}	z_{1n}	f_1	X_1

	Industry 2 . Industry n	z_{21} z_{n1}	z_{21} z_{n2}	z_{2n} z_{nn}	f_2 f_n	X_2 X_n
Value Added (Labour, Domestic Payments)		v_1	v_2	v_n		
Total Input		X'_1	X'_2	X'_n		

Source: (amended based on Miller & Blair [52])

When dividing z_{ij}, each flow in a particular column of the producing sectors, by X_j, the total output (the row sum) of that sector, the technical coefficient or a direct requirement coefficient, a_{ij} can be obtained. It represents a fixed ratio of an input required to produce one monetary output unit in sector j [54]. There is a linear relationship between inputs and outputs and constant returns to scale are assumed in the Leontief model.

		Buying sectors (intermediate demand)		
		Industry 1	Industry 2 …………	Industry n
Selling Sectors/ Producers	Industry 1	$z_{11}/x_1 = a_{11}$	$z_{12}/x_2 = a_{12}$	$z_{1n}/x_n = a_{1n}$
	Industry 2	$z_{21}/x_1 = a_{21}$	$z_{22}/x_2 = a_{22}$	$z_2/x_{2n} = a_{2n}$
	⋮ Industry n	$z_{n1}/x_1 = a_{n1}$	$z_{nj}/x_2 = a_{n2}$	$z_{nn}/x_n = a_{nn}$

Adopting technical coefficients, the total output of an economy, X, can be expressed as follows:

$$X_1 = a_{11}x_1 + a_{12}x_2 + a_{1n}x_n + f_1 \quad (1)$$
$$X_2 = a_{21}x_1 + a_{22}x_2 + a_{2n}x_n + f_2$$
$$.$$
$$.$$
$$X_n = a_{n1}x_1 + a_{n2}x_2 + a_{nn}x_n + f_n$$

In matrix notation, **X** represents the vector of the total output of the economy and is the sum of intermediate sectoral consumption. ***A***, is the coefficient matrix of the $n \times n$ matrix. **x** and ***f*** are the corresponding vectors of the matrix.

$$\begin{pmatrix} X_1 \\ X_2 \\ \cdot \\ \cdot \\ X_n \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{1n} \\ A_{21} & A_{22} & A_{2n} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ A_{n1} & A_{n2} & A_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ x_n \end{pmatrix} + \begin{pmatrix} f_1 \\ f_2 \\ \cdot \\ \cdot \\ f_n \end{pmatrix} \qquad (2)$$

or

$$\boldsymbol{X = Ax + f} \qquad (3)$$

The equation can also be written as:

$$\boldsymbol{X = (I\text{-}A)^{-1} f} \qquad (4)$$

or

$$\boldsymbol{X = Lf \text{ and } \Delta X = L\Delta f} \qquad (5)$$

where $L=(I-A)^{-1}$

I is the identity matrix and $\boldsymbol{(I-A)^{-1}}$ is called the Leontief inverse. The inverse matrix measures how much sectoral output is required to produce to sufficiently satisfy the final demand, ***f***, and the intermediate consumption of each economic sectors, $\boldsymbol{(I-A)^{-1}}$. The Leontief inverse captures direct and indirect requirements of the sectoral output. The direct requirement is the revenue received from consumers, government and exports for final goods and services produced by sectors. The indirect requirement includes the expenditure to produce goods and services demanded by final demand. Any changes in exogenous final demand $\boldsymbol{\Delta f}$, will bring changes in the input-output relations of economic sectors, ***L***, and its total output, **ΔX**.

The economic I-O model can be combined with environmental impacts (e.g. CO_2 emissions) by multiplying the emission intensity vector calculated for the relevant sector $\mathbf{(G_j)}$ with Leontief inverse $\boldsymbol{(I-A)^{-1}}$ and any changes in exogenous final demand $\boldsymbol{(\Delta f_j)}$**.** The CO_2 emissions caused by an economic sector producing one unit (one million Yuan) of a specific commodity *j* can be estimated as follows:

$$\boldsymbol{CO_{2j} = G_j(I\text{-}A)^{-1}\Delta f_j} \qquad (6)$$

3.2 Total final consumption of electricity and petroleum sectors

Total electricity consumption by EVs and total petroleum consumption by gasoline cars is determined by vehicle-use intensity, i.e. annual vehicle kilometres travelled (VKT) and vehicle energy-use intensity, i.e. consumption rates measured in lt/100km [55, 56]. China's car VKT is predicted to gradually decrease in the future [57, 58]. This is due to China's substantial progress in developing low cost and high-efficient subways in urban areas and the world's largest high-speed rail network [57, 59]. The competitive public transit systems, such as highly-efficient inexpensive subway systems and regional intercity high-speed railways are likely to partly substitute private vehicle use in 2030. The VKT is therefore predicted to approach 12,000 km per year for EVs and gasoline cars in 2030 [32]. To determine the total energy consumption of an electric or gasoline vehicle *i*, we use the following equation:

$$\textit{Total Fuel Consumption}_i = \textit{VKT} \times \textit{Fuel Consumption rate}_i\ (\textit{FCR}_i) \quad (7)$$

The predicted consumption rates of electric and gasoline cars have been adopted from Huo et al. [32] (see Table A2). We define the size of petroleum and electricity total production sectors in physical units using the IEA [7] projections for 2030. We estimate the total consumption of EVs and gasoline cars based on different substitution rates e.g. 5%, 20%, 50%, 70%, 100%. Furthermore, we measure the impacts on total electricity and petroleum production in the economy in physical units. Consequently, we translate these values in percentages and adjust the final demand of the EI-O model, which is valued at constant producer prices.

4. Data sources

4.1 Data for Input and Output Table 2030

In our study, we forecast the I-O table, based on income elasticity growth rates [60], GDP growth, population growth and peoples' changing consumption pattern [61]. We balance RAS method in balancing input-output table. The RAS method is a widely used method to update an input-output table over a certain time period or to adjust a national table in order to derive a regional table. The mathematical details on the basic RAS technique are available in Miller & Blair [54]. The I-O matrix was updated using the structure of the latest available I-O table 2012 available at the Chinese National Bureau of Statistics (NBS) that consists of 42 sectors reported in current prices. The table covers different categories of final consumption, such as urban and rural households, government, total capital formation, exports and imports. Due to the overlap in classifications, the I-O table 2012 was aggregated into 18 uniform sectors (see Table A1). The double deflation method [62] was used to adjust the table for constant prices.

4.2 Data for energy and CO_2 emissions 2030

We base our study on the energy and CO_2 emission data forecasted for 2030 by the IEA [7]. As per Wu et al. [41], the future of electricity generation mix is uncertain. In our 1st policy scenario, we base the CO_2 emissions data on 80% share of coal-generated electricity. However, the Chinese Government plans to accelerate investment in renewable energy and to reduce the proportion of national coal consumption to less than 62% by 2020 [63] and furthermore by 2030. To reflect these changes, we adopt a 2nd policy scenario and update the CO_2 emissions data for 2030 based on 50% share of coal-generated electricity. The CO_2 emissions for China are projected using 2012 as the base year for the energy consumption pattern and volume. The energy data for 2012 was obtained from the China Energy Statistical Yearbook 2013 [64]. The data set includes 18 types of fuel, heat and electricity consumption in physical units (data is available at China's Emission Accounts and Dataset, http://www.ceads.net). The CO_2 emissions from industrial processes and fuel combustion were estimated using the IPCC methodological approach [65]. The energy data and emissions for 2030 consist of 37 production sectors and 2 household sectors (rural and urban sectors). To be able to perform the analysis between the I-O table 2030 and the CO_2 energy emission data 2030, we corrected for the overlap in classifications by aggregating the energy data into 18 uniform sectors.

5. Scenario Analysis

5.1 Scenario design

Due to uncertainties in China's policy development beyond 2020 we design three scenarios to assess how the vehicle replacement programme will impact on petroleum and electricity production sectors and their CO_2 emissions at an accelerated rate of EVs penetration. The first policy scenario assumes replacement of most fuel-efficient gasoline cars with EVs, provided that the power generation sector remains unchanged with electricity generated by 80% coal. In the second policy scenario, we replace high emission gasoline cars with EVs, charged by 50% zero emissions electricity from hydro, nuclear and other renewables (solar, wind). In the third scenario, we aim to replace new-fuel efficient gasoline cars with fuel efficient EVs. We assume in our scenarios that the number of EVs in the economy will replace the corresponding number of gasoline cars regardless of their fleet age.

In the policy scenario 1, we assume that there are no changes or upgrades of coal-fired power plants and that electricity continues to be generated by 80% coal in 2030. The average fuel efficiency of EVs will remain at 20KWh/100km as per Huo et al. [32]. However, there will be a drastic improvement in the gasoline fuel economy and we assume that China will phase in Euro 5 and 6 fuel emission standards nationwide by 2030. The average consumption rate of gasoline cars is at 5.5L/100km. The average lifetime of gasoline LDVs is 15 years [66]. We assume that EVs will replace new fuel-efficient gasoline cars.

In the policy scenario 2, we aim to analyse the effects of major improvements in the electricity generation mix. We assume that zero emissions electricity generation mix is utilised at 50%. The fuel economy of EVs will reach 12KWh/100km as per Huo et al. [32] - an improvement of 40% relative to the policy scenario 1. However, in this scenario the rollout of strict emission standards in China is delayed and gasoline cars with Euro 3 and 4 fuel emission standards remain in production. The average consumption rate of gasoline cars is at 8L/100km [32]. The aim in this scenario is to replace all high-emission gasoline cars with EVs, whose fuel economy is substantially improved.

In the policy scenario 3, we combine both policy scenarios 1 and 2 and analyse the vehicle replacement impact of latest fuel-efficient gasoline cars with EVs powered by 50% coal. The fuel economy of EVs is 12KWh/100km. Fuel emission standards for gasoline cars are Euro 5 and 6 and the average consumption rate of gasoline cars is 5.5L/100km. The purpose of this scenario is to analyse the replacement of new-fuel efficient gasoline cars with fuel efficient EVs.

It is important to note that our scenarios are subject to uncertainties in policy changes and reflect the potential difficulties in status quo upsetting known in centrally planned economies [67]. However, they are relevant for our study since they provide meaningful assessments of environmental impacts of two ambitious future plans (drastic progress in electricity sector emissions reduction and EV fuel efficiency). The major assumptions are summarised in Table 3 as follows:

Table 2 Major assumptions for 2030 scenarios [32]

	Policy scenario 1	**Policy scenario 2**	**Policy scenario 3**
Fuel Quality Standards	Euro 5,6	Euro 3,4	Euro 5,6
Gasoline Consumption rates (L/100km)	5.5	8	5.5
Vehicle kilometres travelled (VKT) (km)	12,000	12,000	12,000
EVs fuel economy (kWh/100km)	20	12	12

6. Results and Discussion

Our results show that the replacement of gasoline cars with EVs causes greater impacts on total gasoline production than on total electricity generation in both policy scenarios (see Table 3). For example, at 5%, 20%, 50%, 70% and 100% gasoline vehicle replacement with EVs, the total gasoline production decreases by 1.66%, 6.65%, 16.62%, 23.27% and 33.24% in policy scenario 1, while the total electricity production only increases by 0.71%, 2.82%, 7.05%, 9.87% and 14.10%. IEA [7] suggests that an average of 23% (3,4 mb/d) of petroleum will be produced internally in China in 2030, whereas the remaining amount of petroleum, 77%, (12 mb/d), will be imported. Our results show that at 100% vehicle replacement with EVs, China can either cease its internal petroleum production or partially reduce its reliance on petroleum imports.

Policy scenario 1 reveals that the replacement of latest fuel-efficient gasoline cars with EVs, powered by 80% coal, does not bring any changes. The CO_2 emissions reduction in the petroleum sector is offset by the increase in CO_2 emissions in the electricity sector, leaving the national CO_2 emissions unchanged (Table 3). By decarbonising the electricity sector, i.e. using 30% less coal in electricity generation mix, the total CO_2 emissions are reduced by 28% (from 10,953 to 7,870 Mt CO_2) at the national level. The carbon intensity and the CO_2 emissions of electricity sector are reduced by 38% (see Table 4).

In case of 100% gasoline cars substitution with EVs in the policy scenario 2, 3.24% of CO_2 emissions are saved in petroleum sector at the national level. At 5% replacement level, we find that EVs do not emit any additional CO_2 in the electricity sector. However, CO_2 emissions marginally increase in the electricity sector at a higher rate of substitution (Table 3).

The policy scenario 3 shows a combination of similar results between policy scenario 1 and 2. At 100% gasoline cars replacement with EVs, powered by 50% coal, an additional 2.47% of CO_2 emissions could be saved in petroleum sector at the national level. This is less than in the policy scenario 2. As per Huo et al. [32, 68], vehicle technology improvements and stronger emissions standards (e.g. Euro 5 and 6) would have already helped to reduce the CO_2 emissions of the latest fuel-efficient gasoline cars. At 5% and 10% EVs penetration, no additional CO_2 emissions are caused in electricity sector. It is evident that at a higher rate of substitution CO_2 emissions tend to slightly increase (Table 3). The policy scenario 3 shows that technological improvements and stronger emission standards are important factors to consider and will help reduce additional emissions in the petroleum and the electricity sector caused by gasoline cars and EVs.

The replacement of gasoline cars with EVs is directly linked to petroleum dependency reduction, improvement of urban air quality and reduction of the GHG emissions in China. Our study confirms that the vehicle replacement programme with EVs can achieve the former goals, but in itself it cannot deliver the latter. For example, 100% gasoline cars replacement with EVs in the policy scenario 2 contributes to a reduction of 48% in petroleum production. However, the introduction of EVs alone does not help reduce national GHG emissions.

The reduction of CO_2 emissions is mainly driven by structural changes in economic sectors e.g. reduction of carbon intensity in the electricity sector. Ou et al. [69, 70] and Schill & Gerbaulet [71] confirmed that including renewable and nuclear energy technologies in the electricity generation can significantly reduce GHG emissions of electricity sector. An improved integration of policies for transport and electricity could be beneficial in assessing the added social and environmental benefits of renewable energy expansion [72]. As a result, increasing the share of renewables in the electricity sector should remain the primary goal for China before any EVs can be phased in on a large scale. It is evident that as long as electricity generation remains based on coal, there will be no benefits in replacing gasoline cars with EVs.

It is important to note that our study has certain methodological limitations that should be taken into account when interpreting the results. The impact on petroleum and electricity sectors has been quantified by taking into account only exogenous final demand changes. A larger market penetration of EVs will significantly impact the manufacturing sector and cause subsequent changes in interdependent relationships across different economic sectors. Further research is needed to determine future production costs of EVs and how these inputs indirectly affect the sectoral economic activities (outputs) at the national level. By combining direct and indirect effects, one would have a better overview of macro-economic impacts and CO_2 emissions caused by EVs.

Furthermore, this study has been conducted at the national level, whereas Chinese policies aim to stimulate EVs penetration at regional and city levels [73; 18; 74]. It would be therefore our next step to narrow down our research and investigate potential impacts of EVs penetration at provincial and city levels. It is also meaningful to analyse EVs penetration based on regional carbon burden of electricity [41, 43, 44] as the introduction of EVs would be less useful in Chinese regions with high proportion of coal-fired electricity. Currently, all Chinese provinces have 70% - 85% of coal based electricity generation. In the future, the situation may change and it is within our plan to predict future economic and energy mix changes at regional and city levels. However, currently this is out of scope of this study.

7. Conclusion

The purpose of this paper is to examine direct impacts on total gasoline production and electricity generation and their CO_2 emissions as a result of gasoline vehicle replacement with EVs in China. We find that the introduction of EVs in China is only sensible if the power sector is decarbonised by using renewable energy sources. As long as power is generated by coal, the vehicle replacement programme has no effect (policy scenario 1). As soon as the electricity sector is decarbonised, EVs contribute zero or a very small amount of additional CO_2 emissions to the electricity sector (policy scenario 2 and 3).

Our study shows that EVs are able to reduce dependency on petroleum and to improve air quality, however, they are not the main driver for reducing the national CO_2 emissions in China. Policies on structural changes in primary economic sectors, i.e. improvement of carbon intensity in the electricity sector, are needed to achieve a substantial reduction of national CO_2 emissions before any new products, such as EVs, can be rolled out in the transportation sector in the future. Currently, renewable and low-carbon energy sources are still under-used and the electricity sector is largely powered by coal in China [75, 76]. It is therefore an ineffective and counterproductive activity for Chinese Government to promote EVs.

Within the framework of this study i.e. vehicle replacement and its causality in emissions reduction, one more key attribute of mass EV adoption should not be disregarded. That is the role of EVs in providing auxiliary services to the electricity grid, such as stability and demand response that could be facilitated by the EVs capacity for energy storage. These features of energy storage (inherent in EVs) and their value have been studied extensively both from the viewpoint of static large-scale systems [77, 78] and mobile disaggregated systems [79] and have shown to have potential benefits to emissions reduction [80]. By adopting regulations and speeding up transitions to zero emissions electricity energy sources, such as hydro, nuclear, solar, wind and biogas, China will not only be able to curb its national CO_2 emissions, but also shape the future development of its transportation sector. The introduction of EVs as an alternative solution to conventional cars becomes extremely important considering the current crisis in the motor industry (Volkswagen Emissions Scandal). EVs are the safe option for not only reducing CO_2 emissions, but also minimising other harmful pollutants, such as SO_2, NO_x, VOC and $PM_{2.5}$ emitted by conventional vehicles in the transportation sector [81, 40].

Acknowledgements

This study was supported by the Natural Science Foundation of China (41328008 and 41222036), the UK Economic and Social Research Council (ES/L016028/1) Natural Environment Research Council (NE/N00714X/1) and British Academy Grant (AF150310).

Table 3: Results of vehicle replacement programme with EVs at different substitution rates in policy scenarios 1, 2 and 3

Policy scenario 1 (80% coal-based electricity generation) *Total national CO_2 emissions (Mt): 10,953*									
Gasoline cars substitution with EVs	**Number of EVs (million)**	**Gasoline consumption by passenger cars (million/liters)**	**Reduction in petroleum sector total production**	**Petroleum sector CO_2 (Mt)**	**CO_2 emissions in petroleum sector**	**Electricity consumption by EVs (million/KWh)**	**Increase in electricity sector total production**	**Additional CO_2 emissions spending in electricity sector (Mt)**	**Additional CO_2 emissions spending in electricity sector**
5%	19	12,771	1.66%	327	0.10%	46,440	0.71%	4,815	0.09%
20%	77	51,084	6.65%	326	0.42%	185,760	2.82%	4,829	0.37%
50%	194	127,710	16.62%	324	-1.05%	464,400	7.05%	4,855	0.93%
70%	271	178,794	23.27%	323	-1.47%	650,160	9.87%	4,873	1.30%
100%	387	255,420	33.24%	321	-2.10%	928,800	14.10%	4,900	1.86%

(Source: estimated by the authors)

Policy scenario 2 (50% coal-based electricity generation) *Total national CO_2 emissions (Mt): 7,870*									
Gasoline cars substitutio n with EVs	**Number of EVs (million)**	**Gasoline consumption by passenger cars (million/liters)**	**Reduction in petroleum sector total production**	**Petroleum sector CO_2 (Mt)**	**CO_2 emissions in petroleum sector**	**Electricity consumption by EVs (million/KWh)**	**Increase in electricity sector total production**	**Additional CO_2 emissions spending in electricity sector (Mt)**	**Additional CO_2 emissions spending in electricity sector**
5%	19	18,576	2.42%	325	-0.13%	27,864	0.42%	1,864	0.10%
20%	77	74,304	9.67%	323	-0.66%	111,456	1.69%	1,867	0.25%
50%	194	185,760	24.18%	320	-1.63%	278,640	4.23%	1,872	0.54%
70%	271	260,064	33,85%	318	-2.28%	390,096	5.92%	1,876	0.73%
100%	387	371,520	48.35%	314	-3.24%	557,280	8.46%	1,881	1.03%

(Source: estimated by the authors)

Policy scenario 3 (50% coal-based electricity generation) *Total national CO_2 emissions (Mt): 7,870*									
Gasoline cars substitution with EVs	**Number of EVs (million)**	**Gasoline consumption by passenger cars (million/liters)**	**Reduction in petroleum sector total production**	**Petroleum sector CO_2 (Mt)**	**CO_2 emissions in petroleum sector**	**Electricity consumption by EVs (million/KWh)**	**Increase in electricity sector total production**	**Additional CO_2 emissions spending in electricity sector (Mt)**	**Additional CO_2 emissions spending in electricity sector**
5%	19	12,771	1.66%	324	-0.41%	27,864	0.42%	1,865	-0.19%
20%	77	51,084	6.65%	323	-0.73%	111,456	1.69%	1,861	-0.04%
50%	194	127,710	16.62%	321	-1.38%	278,640	4.23%	1,867	0.28%
70%	271	178,794	23.27%	319	-1.82%	390,096	5.92%	1,871	0.49%
100%	387	255,420	33.24%	317	-2.47%	557,280	8.46%	1,877	0.80%

(Source: estimated by the authors)

Table 4: CO_2 emissions by sector and the intensity emission coefficients

Sectors	Total CO_2 emissions (Mt) (80% coal-based electricity)	Carbon intensity coefficient	Total CO_2 emissions (Mt) (50% coal-based electricity)	Carbon intensity coefficient
Agriculture	139	0.051	139	0.051
Metal and other mining and processing	759	0.076	740	0.074
Electricity Industry	4811	3.016	1862	1.168
Coal mining and processing, coking	178	0.109	171	0.104
Petroleum and gas mining and processing	328	0.213	325	0.211
Chemistry	421	0.038	409	0.037
Machinery, electric and electronic products	1466	0.058	1414	0.056
Construction materials and non-metallic products	795	0.262	765	0.252
Wood processing and furniture manufacturing	16	0.008	15	0.007
Food processing	103	0.017	99	0.016
Textiles	78	0.019	77	0.018
Wearing apparel, leather, furs, down and related products	58	0.019	56	0.019
Paper production and cultural goods	73	0.020	70	0.019
Other manufacturing	35	0.027	34	0.026
Construction	40	0.009	40	0.009
Transport, post and Telecommunication	1473	0.219	1473	0.219
Wholesales, Restaurants and hotels	73	0.010	73	0.010
Passengers transport, finance, insurance, health, education and other social services	108	0.008	108	0.008
Total CO2 emissions (Mt)	**10,954**		**7,870**	

(Source: estimated by the author)

Appendix A

See Tables A1, A2 and A3

Table A1: Sector classification of Chinese economy

Input-Output sector names 2030	Sectoral Code	Input-Output sector names 2012
Agriculture	1	Agriculture
Metal and other mining and processing	2	Ferrous metals mining and dressing
		Nonferrous Metals Mining and Dressing
		Fabricated Metal Products
		Metal smelting and rolling processing industry
Electricity Industry	3	Electric Power, Steam, and Hot Water Production & Supply
		Gas Production & Supply
		Tap Water Production & Supply
Coal mining and processing, coking	4	Coal mining and dressing
Petroleum and gas mining and processing	5	Oil and gas industry
		Petroleum Processing and Coking
Chemistry	6	Chemical Industry
Machinery, electric and electronic products	7	Machinery, Electric Equipment, Electronic Manufacturing Communications equipment, computers and other electronic equipment
		General, special equipment manufacturing industry
		Instrumentation and office machinery manufacturing
Construction materials and non-metallic products	8	Non-metal Mineral Mining and Dressing
Wood processing and furniture manufacturing	9	Wood processing and furniture manufacturing
Food processing	10	Food, Beverage, and Tobacco Processing
Textiles	11	Textile Industry
Wearing apparel, leather, furs, down and related products	12	Leather, Furs, Down, and Related Products
Paper production and cultural goods	13	Papermaking and Paper Products
Other manufacturing	14	Other Manufacturing Industry
		Scrap waste
Construction	15	Building industry
Transport, post and Telecommunication	16	Transportation Equipment Manufacturing
		Postal Services
Wholesales, Restaurants and hotels	17	Wholesale and Retail Trade
		Accommodation and Catering Services
Passengers transport, finance, insurance, health, education and other social services	18	Transportation and warehousing
		Information transmission, computer services and software inc
		Finance and insurance
		Real Estate
		Leasing and Business Services
		Tourism industry
		Scientific career services

	Integrated Technical Services
	Other social services
	Education
	Health social security and social welfare
	Culture, Sports and Entertainment
	Public Management and Social Organisation

Table A2: Fuel mix parameters & consumption rates [32]

	2030
Share of coal based power generation	80%, 50%
Fuel economy of EVs, kWh/100km	20, 12
Fuel economy of ICEVs, liters/100km	8, 5.5
Vehicle kilometres travelled (VKT) (km)	12,000

Table A3: Projected vehicle stock levels (in millions) [5]

		2030
Private LDVs	Low Growth	335.2
	High Growth	390.3
Commercial LDVs		22.9
Trucks		25.2
Buses		3.6
Total		**387-442**

References

[1] Chalvatzis K.J., Rubel K., (2015), "*Electricity portfolio innovation for energy security: The case of carbon constrained China*", Technological Forecasting and Social Change, 100, pp. 267-276

[2] Zhao X., Doering O.C., Tyner W.E., (2015), *"The economic competitiveness and emissions of battery electric vehicles in China"*, Applied Energy, 156, pp. 666-675

[3] Wang, M., Huo, H., Johnson, L., He, D., (2006), *"Projection of Chinese Motor Vehicle Growth, Oil Demand, and CO_2 emissions through 2050*", Energy Systems Division, Argonne National Laboratory

[4] Ou, X., Zhang, X., Chang, S., (2010), *"Scenario analysis on alternative fuel/vehicle for China's future road transport: Life-cycle energy demand and GHG emissions"*, Energy Policy, 38 (8), pp. 3943–3956

[5] Huo, H., Wang, M., (2012), *"Modeling future vehicle sales and stock in China",* Energy Policy 43, pp. 17–29

[6] Zheng B., Zhang Q., Borken-Kleefeld J., Huo H., Guan D., Klimont Z., Peters G., P., He K., (2015) *"How will greenhouse gas emissions from motor vehicles be constrained in China around 2030?"*, Applied Energy, 156, pp. 230-240

[7] International Energy Agency, (2012), *"World Energy Outlook 2012"*, International Energy Agency, Paris, France, available at: http://www.iea.org/publications/freepublications/publication/WEO2012_free.pdf (accessed August 2015)

[8] Ou X., Zhang, X., (2010), *"The Status Quo and Development Trend of Low-carbon Vehicle Technologies in China"*, Advances in Climate Change Research, 1 (1), pp. 34-39

[9] Liu, Z., Guan, D., Moore, S., Lee H., Su, J., Zhang, Q., (2015), *"Steps to China's carbon peak"*, Nature, 522, pp.279-281

[10] Boyd R., Stern N., Ward B., (2015), "*What will global annual emissions of greenhouse gases be in 2030, and will they be consistent with avoiding global warming of more than 2°C?"*, Policy Paper, Centre for Climate Change Economics and Policy and Grantham Research Institute on Climate Change and the Environment, London, UK, available at: http://www.lse.ac.uk/GranthamInstitute/wpcontent/uploads/2015/05/Boyd_et_al_policy_paper_May_2015.pdf (accessed September 2015)

[11] Gambhir, A., Tse L. K.C., Tong D., Martinez-Botas R.,(2015), *"Reducing China's road transport sector CO2 emissions to 2050: Technologies, costs and decomposition analysis",* Applied Energy, 157, pp. 905-917

[12] Yan, X., Crookes, R.J., (2009), *"Reduction potentials of energy demand and GHG emissions in China's road transport sector*", Energy Policy 37 (2), pp. 658–668

[13] Zhang, X., Rao, R., Xie, J., Liang, Y., (2014), *"The Current Dilemma and Future Path of China's Electric Vehicles"*, Sustainability 6 (3), pp. 1567–1593

[14] Yao, M., Liu, H., Feng, X., (2011*), "The development of low-carbon vehicles in China"*, Energy Policy 39 (9), pp. 5457–5464

[15] Sun, L., (2012), *"Development and Policies of New Energy Vehicles in China"*, Asian Social Science 8 (2), pp. 86–94

[16] Huo, H., Cai, H., Zhang, Q., Liu, F., He, K., (2015*), "Life-cycle assessment of greenhouse gas and air emissions of electric vehicles: A comparison between China and the U.S."*, Atmospheric Environment, 108, pp. 107–116

[17] Doucette T. R., McCulloch M.D., (2011), *"Modeling the prospects of plug-in hybrid electric vehicles to reduce CO2 emissions"*, Applied Energy, 88 (7), pp. 2315-2323

[18] China's State Council, (2012), *"Development Plan of Energy-Efficient and New-Energy Vehicles 2012-2020"*, Beijing, China, available at: http://www.nea.gov.cn/2012-07/10/c_131705726.htm in Chinese (accessed August 2015)

[19] China Association of Automobile Manufacturers, (2015), *"Automotives Statistics"*, available at: http://www.caam.org.cn/newslist/a101-4.html (accessed on July 2015)

[20] Howell, S., Lee, H., Heal, A., (2014), *"Leapfrogging or Stalling Out? Electric Vehicles in China"*, HKS Faculty Research Working Paper Series, Harvard Kennedy School, Belfer Center for Science and International Affairs

[21] Wan, Z., Sperling, D., Wang, Y., (2015), *"China's electric car frustrations"*, Transportation Research Part D: Transport and Environment 34, pp. 116–121

[22] Lave, L.B., Cobas-Flores, E., Hendrickson, C.T., McMichael, F.C., (1995), *"Using Input-Output Analysis to Estimate Economy-wide Discharges"*, Environmental Science & Technology, 29 (9), pp. 420A–426A

[23] Hertwich, E.G., (2005), *"Life Cycle Approaches to Sustainable Consumption: A Critical Review"*, Environmental Science & Technology, 39 (13), pp. 4673–4684

[24] Hendrickson, C.T., Lave L.B., Matthews H.S. (2006), *"Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach"*, Resources for the Future, Washington, US

[25] Hawkins T.,R., Gausen O., M., Strømman A., H., (2012), *"Environmental impacts*

of hybrid and electric vehicles—a review", International Journal of Life Cycle Assessment, 17, pp. 997-1014

[26] Guinée J., Gorree M., Heijungs R., Kleijn R., de Koning A., van Oers L., Wegener Sleeswijk A., Suh S., Udo de Haes H., van Duin R., Huijbregts M., (2002*), "Handbook of Life Cycle Assessment, Operational Guide to the ISO Standards"*, Kluwer Academic Publishers, Dordrecht, The Netherlands

[27] Joshi S., (2000), *"Product Environmental Life-Cycle Assessment Using Input-Output Techniques",* Journal of Industrial Ecology, 3, 95-120

[28] Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G., (2004), *"System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches"*, Environmental Science & Technology, 38 (3), pp. 657–664

[29] Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., (2009), *"Recent developments in Life Cycle Assessment"*, Journal of Environmental Management, 91, pp. 1–21

[30] Bauer C., Hofer J., Althaus H.-J., Duce A.D., Simons A., (2015), *"The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework"*, Applied Energy, 157, pp. 871-883

[31] Rose A., (1995), *"Input-output economics and computable general equilibrium models"*, Structural Change and Economic Dynamics (6), pp. 295-304

[32] Huo, H., Zhang, Q., Wang, M.Q., Streets, D.G., He, K., (2010.), *"Environmental Implication of Electric Vehicles in China"*, Environmental Science & Technology, 44 (13), pp. 4856–4861

[33] Knittel, C.R., (2009), *"The Implied Cost of Carbon Dioxide under the Cash for Clunkers Program"*, Center for the Study of Energy Markets: UC Berkeley, Working Paper No. CSEM WP 189

[34] Abrams B. A., Parsons G.R., (2009), *"Is Cars a Clunker?",* The Economists' Voice, 6 (8), pp. 1-4

[35] Lenski, S.M., Keoleian, G.A., Bolon, K.M., (2010), *"The impact of 'Cash for Clunkers' on greenhouse gas emissions: a life cycle perspective"*, Environmental Research Letters, 5 (4), p. 044003

[36] Kagawa, S., Nansai, K., Kondo, Y., Hubacek, K., Suh, S., Minx, J., Kudoh, Y., Tasaki, T., Nakamura, S., (2011), *"Role of Motor Vehicle Lifetime Extension in Climate Change Policy"*, Environmental Science & Technology, 45 (4), pp. 1184–1191

[37] Kagawa, S., Hubacek, K., Nansai, K., Kataoka, M., Managi, S., Suh, S., Kudoh, Y.,

(2013), *"Better cars or older cars?: Assessing CO2 emission reduction potential of passenger vehicle replacement programs"*, Global Environmental Change, 23 (6), pp. 1807–1818

[38] Becker T.A., Sidhu I., Tenderich B., (2009), *"Electric Vehicles in the United States, A New Model with Forecasts to 2030"*, Center for Entrepreneurship & Technology (CET) Technical Brief, University of California, Berkeley, United States

[39] Wang G., (2010), *"Advanced vehicles: Costs, energy use, and macroeconomic impacts"*, Journal of Power Sources, 196, pp. 530-540

[40] Donateo T., Licci F., D'Elia A., Colangelo G., Laforgia D., Ciancarelli F., (2015), *"Evaluation of emissions of CO2 and air pollutants form electric vehicles in Italian cities"*, Applied Energy, 157, pp. 675-687

[41] Wu, Y., Yang, Z., Lin, B., Liu, H., Wang, R., Zhou, B., Hao, J., (2012), *"Energy consumption and CO2 emission impacts of vehicle electrification in three developed regions of China"*, Energy Policy, 48, pp. 537–550

[42] Shen, W., Han, W., (2013), *"Well-to-Wheel Analyses for Energy Consumption and Greenhouse Gas Emissions of Electric Vehicles Using Various Thermal Power Generation Technologies in China"*, in: SAE-China, FISITA (Ed.), Proceedings of the FISITA 2012 World Automotive Congress (2012), pp. 101–115

[43] Lang, J., Cheng, S., Zhou, Y., Zhao, B., Wang, H., Zhang, S., (2013), *"Energy and Environmental Implications of Hybrid and Electric Vehicles in China"*, Energies 6, pp. 2663–2685

[44] Shen, W., Han, W., Wallington, T.J., (2014), *"Current and Future Greenhouse Gas Emissions Associated with Electricity Generation in China: Implications for Electric Vehicles"*, Environmental Science & Technology 48 (12), pp. 7069–7075

[45] Leontief, W.W., (1936), *"Quantitative Input and Output Relations in the Economic Systems of the United States"*, The Review of Economics and Statistics, 18, pp. 105–125

[46] Leontief, W., (1970), *"Environmental Repercussions and the Economic Structure: An Input-Output Approach"*, The Review of Economics and Statistics, 52, pp. 262–271

[47] Liu, Z., Geng, Y., Lindner, S., Zhao, H., Fujita, T., Guan, D., (2012), *"Embodied energy use in China's industrial sectors"*, Energy Policy, 49, pp. 751–758

[48] Hubacek, K., Guan, D., Barrett, J., Wiedmann, T., (2009), *"Environmental implications of urbanization and lifestyle change in China: Ecological and Water Footprints"*, Journal of Cleaner Production, 17:14, pp. 1241–1248

[49] Hertwich, E.G., (2011), *"The Life Cycle Environmental Impacts of Consumption"*,

Economic Systems Research 23 (1), pp. 27–47

[50] Wiedmann, T., Minx, J., Barrett, J., Wackernagel, M., (2006), *"Allocating ecological footprints to final consumption categories with input–output analysis"*, Ecological Economics 56 (1), pp. 28–48

[51] Turner, K., Lenzen, M., Wiedmann, T., Barrett, J., (2007), *"Examining the global environmental impact of regional consumption activities — Part 1: A technical note on combining input–output and ecological footprint analysis"*, Ecological Economics 62 (1), pp. 37–44

[52] Feng, K., Davis, S.J., Sun, L., Li, X., Guan, D., Liu, W., Liu, Z., Hubacek, K., (2013), *"Outsourcing CO_2 within China",* Proceedings of the National Academy of Sciences (PNAS), 110, pp. 11654–11659

[53] Guan, D., Su, X., Zhang, Q., Peters, G.P., Liu, Z., Lei, Y., He, K., (2014), *"The socioeconomic drivers of China's primary PM $_{2.5}$ emissions"*, Environmental Research Letters, 9 (2), p.9

[54] Miller, R.E., Blair, P.D., (2009), *"Input-Output Analysis: Foundations and Extensions"*, Second Edition, Prentice-Hall, Englewood Cliffs, New York, United States

[55] Hao, H., Ou, X., Du, J., Wang, H., Ouyang, M., (2014), *"China's electric vehicle subsidy scheme: Rationale and impacts"*, Energy Policy, 73, pp. 722–732

[56] Huo, H., He, K., Wang, M., Yao, Z., (2012), *"Vehicle technologies, fuel-economy policies, and fuel-consumption rates of Chinese vehicles",* Energy Policy, 43, pp. 30–36

[57] Hao, H., Wang, H., Ouyang, M., (2011), *"Fuel conservation and GHG (Greenhouse gas) emissions mitigation scenarios for China's passenger vehicle fleet",* Energy, 36 (11), pp. 6520–6528

[58] Huo, H., Zhang, Q., He, K., Yao, Z., Wang M. (2012), *"Vehicle-use intensity in China: Current status and future trend"*, Energy Policy, 43, pp. 6-16

[59] Helveston, J.P., Liu, Y., Feit, E.M., Fuchs, E., Klampfl, E., Michalek, J.J., (2015), *"Will subsidies drive electric vehicle adoption? Measuring consumer preferences in the U.S. and China",* Transportation Research Part A: Policy and Practice, 73, pp. 96–112

[60] Hubacek K., Sun L., (2005), *"Economic and societal changes in China and their effects on water use: a scenario analysis"*, Journal of Industrial Ecology, 9, pp. 187-200, [1–2, special issue on Consumption & the Environment edited by E. Hertwich]

[61] Guan D., Hubacek K., Weber C.L., Peters G.P., Reiner D., (2008), *"The drivers of Chinese CO2 emissions from 1980 to 2030"*, Global Environmental Change: Human

and Policy Dimensions, 18 (4), pp. 626–634

[62] United Nations, (1999), *"Handbook of input-output table compilation and analysis"*, Studies in Methods, Handbook of National Accounting, Series F, No. 74. Handbook of National Accounting. New York, United Nations, available at: http://unstats.un.org./unsd/publication/SeriesF/SeriesF_74.pdf

[63] China's State Council, (2014), "*Energy Development Strategy Action Plan (2014-2020)"*, available at: http://www.gov.cn/zhengce/content/2014-11/19/content_9222.htm in Chinese (accessed August 2015)

[64] National Bureau of Statistics, (2013), "*China Energy Statistical Yearbook 2013"*, China Statistics Press, Beijing

[65] IPCC, (2006), *"IPCC Guidelines for National Greenhouse Gas Inventories"*, Intergovernmental Panel on Climate Change, Japan

[66] Huo, H., Zheng, B., Wang, M., Zhang, Q., He, K.-B., (2014), *"Vehicular air pollutant emissions in China: evaluation of past control policies and future perspectives"*, Mitigation and Adaptation Strategies for Global Change, 20 (5), pp. 719–733

[67] Chalvatzis K.J., (2009), "*Electricity generation development of Eastern Europe: A carbon technology management case study for Poland*", Renewable and Sustainable Energy Reviews 13 (6-7), pp. 1606-1612

[68] Huo H., Zhang Q., Yao Z., Wang X., Zheng B., Streets D. G., Wang Q., Ding Y., (2011), "Modeling vehicle emissions in different types of Chinese cities: Importance of vehicle fleet and local features", Environmental Pollution 159, pp. 2954-2960

[69] Ou, X., Yan X., Xiliang Z., (2010), *"Using coal for transportation in China: Life cycle GHG of coal-based fuel and electric vehicle, and policy implications"*, International Journal of Greenhouse Gas Control 4, pp. 878-887

[70] Ou, X., Xiaoyu Y., Zhang X., (2011) *"Life-cycle energy consumption and greenhouse gas emissions for electricity"*, Applied Energy, 88, pp. 289-297

[71] Schill W.-P., Gerbaulet C., (2015), *"Power system impacts of electric vehicles in Germany: Charging with coal or renewables?"*, Applied Energy, 156, pp. 185-196

[72] Zafirakis D., Chalvatzis K.J., Kaldellis J.K., (2013), "*"Socially just" support mechanisms for the promotion of renewable energy sources in Greece"*, Renewable and Sustainable Energy Reviews 21, pp. 478-493

[73] Beijing Municipal Science and Technology Committee (BMSTC), (2010), "Pilot Program of Subsidies for Private Purchase of New Energy Vehicles in Beijing", available at: http://news.cntv.cn/20101130/104651.shtml, in Chinese (accessed May 2016)

[74] Wu, Y., Yang, Z.D., Lin, B.H., Liu, H., Wang, R.J., Zhou, B.Y., Hao J.M., (2012), *"Energy consumption and CO2 emission impacts of vehicle electrification in three developed regions of China"*, Energy Policy, 48 (2012), pp. 537–550

[75] Xu X., Zhao T., Liu N., Kang J., (2014), *"Changes of energy-related GHG emissions in China: An empirical analysis from sectoral prospective"*, Applied Energy, 132, pp. 298-307

[76] Yuan X., Li L., Gou H., Dong T., (2015), *"Energy and environmental impact of battery electric vehicle range in China"*, Applied Energy, 157, pp. 75-84

[77] Zafirakis D., Chalvatzis K.J., (2014), "*Wind energy and natural gas-based energy storage to promote energy security and lower emissions in island regions"*, Fuel 115, pp. 203-219

[78] Zafirakis D., Chalvatzis K.J., Baiocchi G., Daskalakis G., (2013), "*Modeling of financial incentives for investments in energy storage systems that promote the large-scale integration of wind energy*", Applied Energy 105, pp. 138-154

[79] Aziz M., Oda T., Kashiwagi T., (2015), *"Extended utilization of electric vehicles and their reused batteries to support the building energy management system"*, Energy Procedia 75, pp. 1938-194

[80] Zafirakis D., Chalvatzis K.J., Baiocchi G., (2015), "*Embodied CO 2 emissions and cross-border electricity trade in Europe: Rebalancing burden sharing with energy storage*", Applied Energy 143, pp. 283-300

[81] Takeshita Takeshita T., (2012), *"Assessing the co-benefits of CO2 mitigation on air pollutants emmissions from road vehicles"*, Applied Energy, 97, pp. 225-23