Potential of Plug-In Hybrid Electric Vehicles' for Emission Reduction in China: the problem of energy sources and travel behavior

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Abstract

To investigate the lifecycle energy consumption and emissions of Plug-in Hybrid Electric Vehicles (PHEVs) in China, this paper undertakes a "Well-to-Wheel" (WTW) lifecycle energy consumption and carbon emission analysis for China 2020 using the latest GREET 1.8c.0 model from the US Department of Energy. A variety of energy mixes and two travel patterns for PHEVs are compared in terms of their energy consumption and emissions. The study finds that PHEVs could have substantial potential in terms of energy consumption and GHG emission reductions in China. This benefit in turn could deteriorate if travel distances increased, which will happen as China's car ownership rises and vehicle operating costs go down.

Keywords: Plug-in Hybrid Electric Vehicles (PHEV), Lifecycle Analysis, GREET 1.8c.0, Electric Vehicles Charging.

1. Introduction

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

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

Also, the integration of ICE within PHEVs provides an effective improvement in vehicle performance when compared to EVs, which further facilitates market penetration of electric technology, if PHEVs are seen as a transition between ICEs and EVs.

Nevertheless, PHEVs also face many challenges. Although the batteries required are not as costly as those required by pure EVs, the capacity still needs to be high and that means higher production costs than conventional ICE cars. The battery capacity is one of the main problems that hybrid and pure electric vehicles face, as the (electric) driving range depends on the battery. Also, as already mentioned above, the reduction in carbon emissions depends on how the electricity is generated. Finally, people's travel behavior is an issue that is seldom mentioned but has an important role to play in carbon emission reduction, not just in the case of ICE vehicles but also in the case of PHEVs.

This paper investigates PHEVs' lifecycle energy consumption and carbon emissions for the case of 2020 China using the 'Greenhouse Gas, Regulated Emissions and Energy Use in Transport' (GREET) Model, which is essentially a lifecycle emission assessment model from the US Department of Energy that covers the fuel lifecycle of feedstock recovery and transport; fuel production, distribution and final consumption of vehicle engines.[1] The answers to a simple questionnaire conducted in China are also used to make assumptions about travel behavior and energy consumption of PHEVs, although there are some caveats regarding their usefulness.

2. Methodology and Data

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

2.1 Well-to-Pump Stage

The energy recovery and refining data input onto GREET for WTP simulation were

[1] The version used here is GREET 1.8c.0.

retrieved from the latest nationwide statistics and research reports, as well as from interviews with experts. The exact source of each piece of information is further detailed below.

Because this study focuses on the energy consumption and emissions of PHEVs, both electricity generation and gasoline production pathways are specifically reviewed, while other alternative vehicle fuels such as diesel, natural gas based fuels, hydrogen and biomass-based fuels are not included, although they can also be used by the dual-power-train systems of PHEVs.

2.1.1 Gasoline pathway

The two key questions when modeling the gasoline pathway are how is the gasoline produced (energy feedstock[2] types) and how it is processed and transported.

The recovery efficiency of petroleum energy feedstock has improved for all the three major oil companies in China over the last 30 years. However, given that many oil and gas fields in China are approaching their late-stage of extracting life, the efficiency improvement rate could decline gradually in the next few years. The recovery efficiency assumptions for 2020 are therefore conservative. The crude oil recovery energy efficiency gap between China and the US in this study is assumed to remain at 5%, or in other words, the crude oil recovery energy efficiency in China in 2020 is assumed to be 93%, against 98% in the US (Zhang et al, 2007, p.37).

Since 1999, Chinese domestic gasoline production has met domestic demand. Therefore, this study only considers the refining efficiency of Chinese refineries. The two main oil companies, China National Petroleum Corporation (CNPC) and China Petroleum and Chemical Corporation (Sinopec), jointly supply 90% of the gasoline in China. Therefore

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

the domestic fuel production energy efficiency of 87% is assumed, in contrast with 92% for the US (GREET 1.8c.0, 2009) estimates for CNPC and Sinopec 2020 levels.

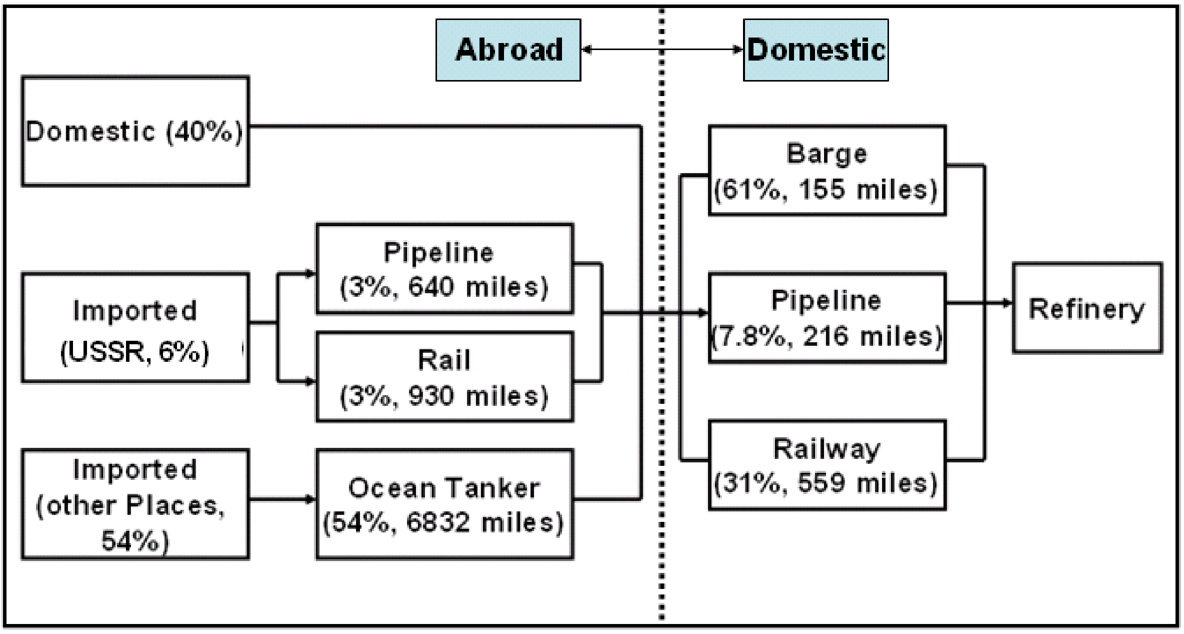
Apart from the energy efficiency of oil recovery and gasoline production, its energy feedstock and fuel product transport also play an important role in the lifecycle. In China the distances that the fuel needs to be transported are large and this causes relatively high energy consumption and emissions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

Figure 1 summarizes the shares of oil sources for China, as well as the transport modes used and the average distances.

Currently, China's imported crude oil accounts for more than 40% of national demand and this figure could reach 60% to 80% by 2020 (Zhang et al, 2007, p. 36, Table 3.1). The imported crude oil is largely transported by ocean tankers (90%), except for the crude oil from former USSR countries, which is usually delivered through pipelines (NDRC, 2006a). There is also some oil imported from South East Asia and Russia, which is transported by railway. Taking into account transport routes and distances from Middle East (38.5%), Asia-Pacific (17.4%), west Africa (19%), north Africa (1.9%), southeast Africa (2.7%), Latin America (6.7%) and Europe (0.2%), we can assume an average transport distance of 11,000 km by ocean tankers.

Domestic and imported crude oil *within* China is transported by three modes: pipeline (61%), barge (7.8%) and railway (31%). According to the National Development and Reform Committee (NDRC) statistics (NDRC, 2006b), the average distance that crude oil was transported in China in 2005 was 390 km. The majority of barge-based crude oil transport in China takes place along the East China Sea and the Yangzi River, and the average transport distance is between 100 and 400 km (Ministry of Communications and Transportation-MOC, 2005a). Because barge fleets in China are comprised largely of small boats fueled by residual oil, energy consumption is 2-5 times higher than in the US. The oil transported by railway has increased relatively slowly compared with the increase in crude oil demand. The average transport distance by railway ranges from 860 km to 960 km. Most trains are fueled by diesel (61%) and electricity (39%).

Figure 1 Crude Oil Transport Pathway in China 2020



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

Since domestic gasoline meets and will continue to meet national demand in 2020, this analysis only considers the transport of gasoline within China. The main transport modes for fuel products currently are pipeline (15%), railway (50%), barge (25%) and highway (10%) (Jia, 2003a). These shares are assumed the same for 2020. A considerable amount of gasoline has to be transported long distances by railway, from the north-east and north-west to the eastern provinces. The average transport distance by train is around 800 to 1000 km (China Logistics Association, 2005).

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

2.1.2 Electricity Pathway

At present, China's national grid is operated by two state-owned companies: State Grid Corporation of China (SGCC) and China Southern Power Grid (CSPG). In both cases electricity is mainly generated in coal power stations. The new generation clean-coal technologies, such as Integrated Gas Combined Cycle (IGCC), are currently only used to produce 1.25% of overall coal-based electricity. Following coal, hydropower ranks second. The shares of natural gas, residual oil and nuclear-based electricity generation are minor. Wind and biomass-based electricity generation are at their trial phase in some provinces only, including Inner Mongolia and Tibet (China National Statistics Bureau, 2006)

According to data from the National Development and Reform Commission (NDRC) in China, the shares of capacity installation and electricity generation in China in 2020 will be as depicted in Table 1 (Wang, 2005, in Zhang, 2007a, p. 94).

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

Table 1 National Grid Energy Feedstock Share in China 2020

	Coal	Oil	Natural Gas	Hydropower	Nuclear	Wind & Biomass
Installed Capacity	59.0%	1.2%	6.3%	25.0%	4.2%	4.3%
Generation Share	**63.0%**	**1.0%**	**6.8%**	**19.0%**	**6.7%**	**3.5%**

Source: Wang (2005), in Zhang (2007, p.94)

2.2 Pump-to-Wheel Stage

Two essential assumptions are needed for Pump To Wheel (PTW) simulation: the selection of a reference plug-in vehicle for modeling and the share between electricity and petroleum energy consumption during vehicle operation. In theory, the share between electricity and gasoline use is determined by kilometers traveled per charge, which further relates to the vehicle's electric operation range, and the required frequency of recharging. This in turn can be linked to driving behavior. A combination of a high-charging frequency rate and a low-driving distance per charge could offer nearly an all electric driving of PHEVs. This pattern would, for example, illustrate the driving behavior of workers commuting short distances by car and recharging the vehicle's batter at home every night.

To address the share of electricity and petroleum consumption, the concept of "Utility Factor" (UF) has been introduced in recent PHEV fuel economy studies (Elgowainy et al, 2009a) to represent the percentage of a PHEV's electricity consumption over its entire energy consumption during vehicle operation. Normally, a daily charging basis is assumed and so a Daily Kilometers Traveled (DKT) becomes the key factor that needs to be identified. For this, daily travel behavior information is required. However, there is currently no such a nationwide level survey available for China. This study hence has conducted a non-representative simple travel and attitudinal survey[3]. The results of this survey are used with much caution and a number of caveats highlighted when deriving conclusions.

[3] If resources had permitted the survey would have been representative. The costs of surveying a large enough sample to make it representative of the whole Chinese population and the costs of conducting the survey face-to-face, by telephone or post were prohibitive in the order of hundreds of thousands of pounds.

2.3 The Survey

The survey was conducted on the 'Auto.Sohu' website and the results reported in this paper correspond to responses posted in the period 24 February to 26 March 2010. Being an Internet based questionnaire, millions of Chinese people without access to the Internet were automatically excluded. Also, the survey was voluntary and only those willing to spend time answering the questions were included in the sample. Given the nature of the website and the survey, respondents were likely to be males interested in cars, which poses an additional selection bias. The best way forward would be to conduct a nationwide representative travel survey in China, but given the costs of such a task, financial support from the Chinese government or some other organization, together with additional human resources, would be required. Unfortunately, this falls beyond the scope of the authors' resources to conduct the present study.

The survey consisted of 30 questions, designed to elicit: 1) people's attitudes to EVs and PHEVs in terms of relative prices with respect to ICE vehicles (for both the cost of the vehicle and the operation cost), performance expectancy and other concerns; 2) their travel behavior including mode of transport used, daily travel distance, speed and driving/parking habits, and; 3) personal socio-economic information including income, gender and home/work addresses.

331 usable responses were collected and are used in this paper. The histogram in Figure 2 illustrates the distribution of DKT across the survey's observations. The majority of daily distances for all transport modes, including bus, car, metro, cycle and walk, and trip purposes, including commuting, shopping, recreation, and also work-related trips, as well as all other trips (such as attending doctor's appointments, etc) are concentrated from 20 km to 60 km.

Figure 2 Frequency Distribution of Daily Kilometers Traveled

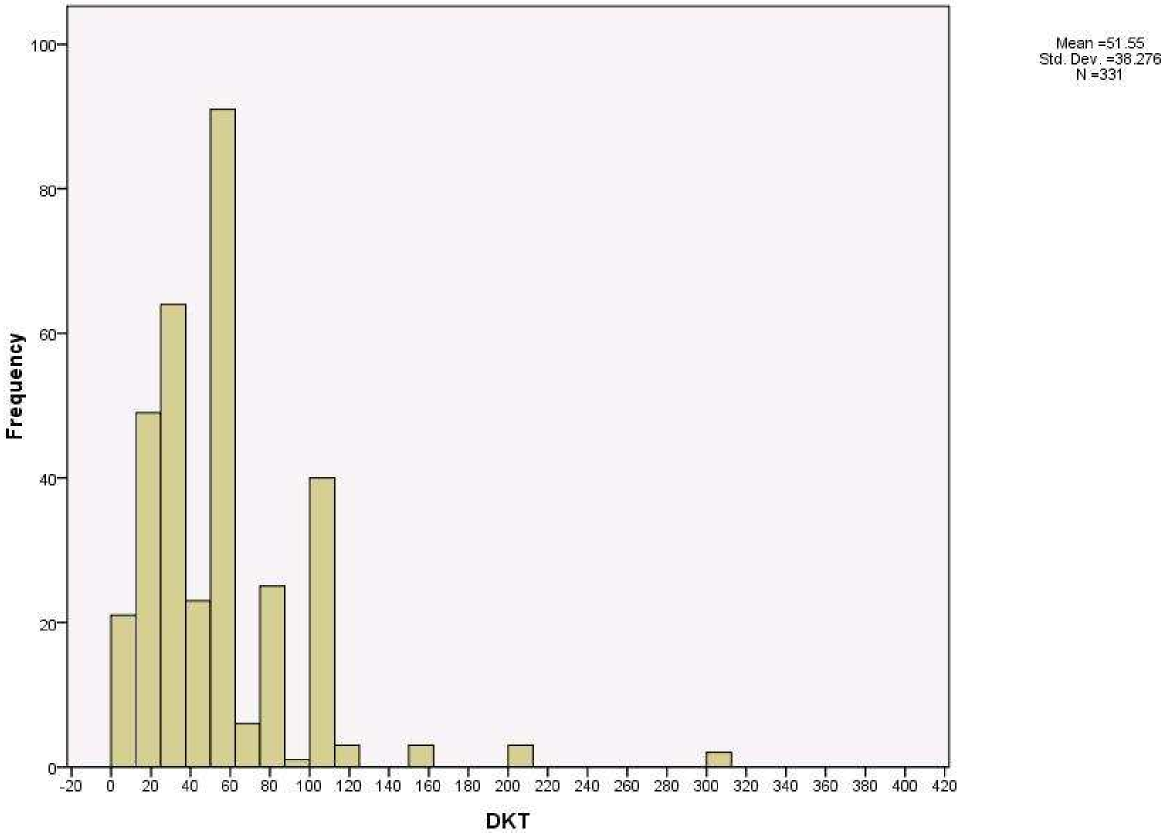


Figure 2 is a snapshot of a very small and not necessarily representative group of Chinese people. The geographical distribution of the respondents is also uneven. For example, 22% of the responses came from Beijing, where only 1.09% of the Chinese population lives; and almost 17% of the responses came from Shanxi, where only 2.85% of the population lives.

The histogram in Figure 3 illustrates the distribution of DKT by car across the survey's observations. All trip purposes are still included but the only transport mode considered in this case is the private car. As it can be seen, the average distance is higher, now concentrated between 25 and 70 km. The number of responses was obviously limited by the number of respondents who actually own or have access to a car. It should be born in mind that car ownership in China is still very low, with only 36 in 100 households owning a car in capital Beijing (Beijing Statistics Bureau, 2009, section 9 – Transport, Post and Telecommunications), in contrast with the UK, where 76% of all households have regular access to at least one car (UK Department for Transport, 2009, Table 9.15, p.166).

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

3. Data Analysis

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

Needless to say, and there is no need to ask this to any potential buyer, the higher the battery capacity and maximum possible speed the more attractive the PHEV will be, *ceteris paribus*. One (heroic) assumption we make in this study is that drivers will expect the battery capacity to meet at least their daily travel requirements (or DKT), without the need of recharging the battery until they are back home in the evening[4]. With this in mind, the DKT by car at present by the survey respondents are assumed to be the minimum required battery capacity and used for modeling lifecycle assessment in this study.

3.1 Utility Factor

As already explained above, PHEVs can run on conventional oil-based fuels and electricity from the grid.

Since their storage capacity is limited, PHEV batteries can only supply electricity to drive

[4] This assumption is actually a standard assumption in the literature. Even the documents produced by the Society of Automotive Engineers (SAE) in the US assume that batteries are only recharged once a day (Bradely and Quinn, 2010).

the vehicle for a limited number of kilometers. As a result, PHEVs operate in two modes: ‘a charge-depleting mode where the stored battery energy contributes to the propulsive energy consumed by driving the vehicle, and a charge-sustaining mode, where the net energy from the battery is essentially zero’ (Bradley and Quinn, 2010, page number to be added when the paper comes out).

The UF can be defined as the ratio of the number of kilometers driven under charge-depleting mode to the total number of kilometers driven:

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

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

Following Elgowainy et al (2009), in order to identify the UF for various PHEV models (or battery energy storage capacities), the survey observations are categorized in 12 groups in terms of DKT, as shown in Table 2. Only the responses from car drivers are taken into account for these calculations, as DKT by other modes would not be a good estimate of drivers’ behavior.

Table 2 can be read as follows. The first two columns indicate the limits of the range of DKT. For example, the first range corresponds to respondents who travel between 0 and 10 km per day. The ‘Frequency’ column is simply the number of respondents who gave that answer. The ‘Share’ column is the percentage of respondents with a DKT falling in that range. The rest of the columns give the UF for different R_{CD}. For example, when the R_{CD} is 10 km, drivers with DKT between 0 and 10 km will be able to drive all those km on charge depleting mode. In fact, as long as the R_{CD} is higher than the DKT the PHEV will be able to drive on charge depleting mode alone. When the R_{CD} is 50 km but the DKT are between 80 and 90, drivers will be able to drive the first 50 km on charge depleting mode but they will drive the remaining 30 to 40 km on conventional fuel. The PHEV Utility Factor on the last row indicates the percentage of total DKT by survey respondents that can be driven on electricity. If the R_{CD} is 10 km only 32.28% of DKT by all respondents can by driven on charge depleting mode, whereas if the R_{CD} is 70 km then 94.63% of DKT by all survey respondents can be done on charge depleting mode.

It should be noted that the R_{CD} denotes the charge depletion range on the assumption of a PHEV operating on an ICE-battery combination mode rather than purely on electricity, as one important characteristic of PHEVs is that they combine both sources of energy, oil-based fuels and electricity.

Table 2 Utility Factors for PHEV with R_{CD} of 20, 40, 60, 80, 100 and 120 km

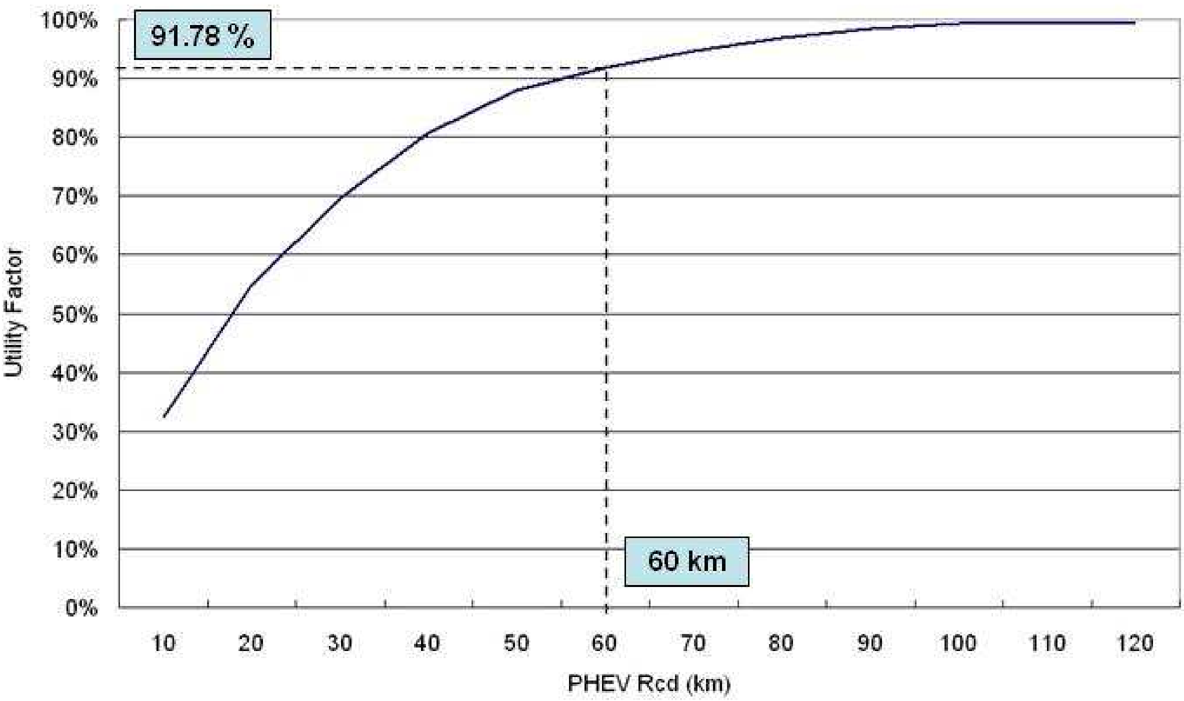
DKT (min - max, km)		Frequency	Share	20	40	60	80	100	120
0	10	12	5.15%	5.15%	5.15%	5.15%	5.15%	5.15%	5.15%
10	20	33	14.16%	14.16%	14.16%	14.16%	14.16%	14.16%	14.16%
20	30	32	13.73%	10.99%	13.73%	13.73%	13.73%	13.73%	13.73%
30	40	17	7.30%	4.17%	7.30%	7.30%	7.30%	7.30%	7.30%
40	50	59	25.32%	11.25%	22.51%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

Source: Calculations by the authors, using survey responses

Figure 3 shows the daily distance UF curve for PHEVs if these were to be driven by the survey respondents, and if the respondents did not change their DKT as a result of driving a PHEV rather than a conventional ICE vehicle.

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

Figure 3 Utility Factors of Different R_{CD}



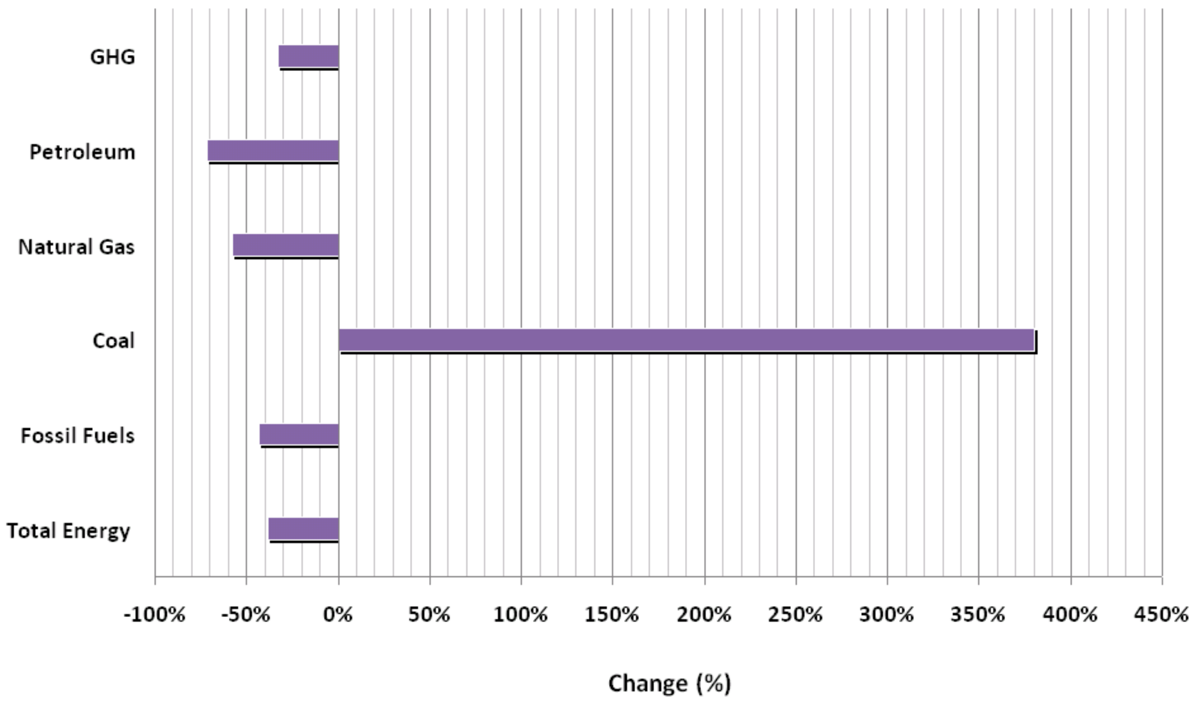
Source: calculations carried out by the authors using survey responses

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

4. Life Cycle Assessment Results

Figure 5 graphically summarizes the lifecycle energy consumption and emissions for PHEVs with R_{CD} of 60 km relative to ICE vehicles. GHG emissions are 26% lower and total energy consumption is 34% lower. Assuming that grid electricity in China continues to be mainly generated in coal power stations, coal consumption obviously increases. One clear conclusion from these estimates, which is further discussed below, is that for PHEVs to be truly environmentally friendly and make significant improvements on energy consumption and GHG emissions, the electricity to power them needs to be generated using clean technologies.

Figure 4 Lifecycle Energy Consumption and Emissions for PHEVs with R_{CD} of 60km relative to ICE Vehicles in China 2020 for the travel survey sample



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

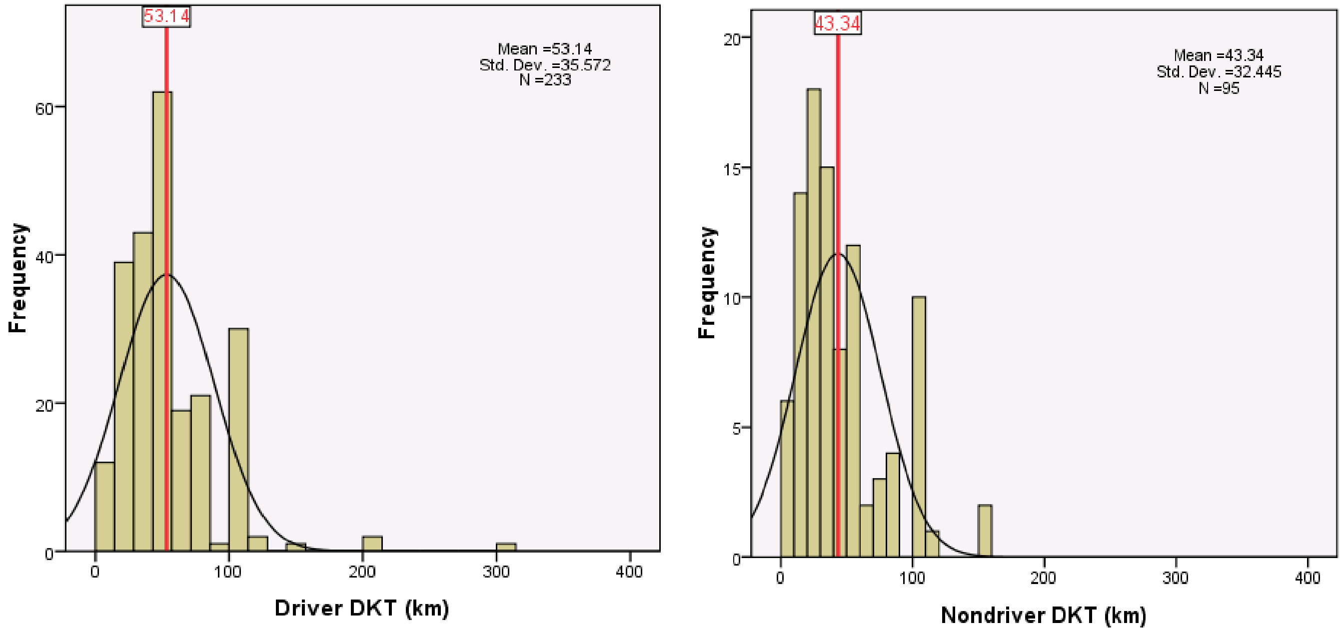
Note: For the year 2020 fuel economy for PHEVs driving in charge depleting mode is assumed to be 15.14 km/l and fuel economy for ICE vehicles is assumed to be 10.8 km/l. GREET always assumes PHEVs to have a fuel economy 40% better than that for ICE vehicles.

5. The Effects of Travel Distance Increase

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

That car ownership increases travel distances is a well-documented fact in the transport studies literature. Not surprisingly, this is exactly the case for the small sample of survey respondents used in this study. Figure 5 shows daily distances traveled by drivers and non-drivers.

Figure 5 DKT Distributions between 'Driver' and 'Nondriver'

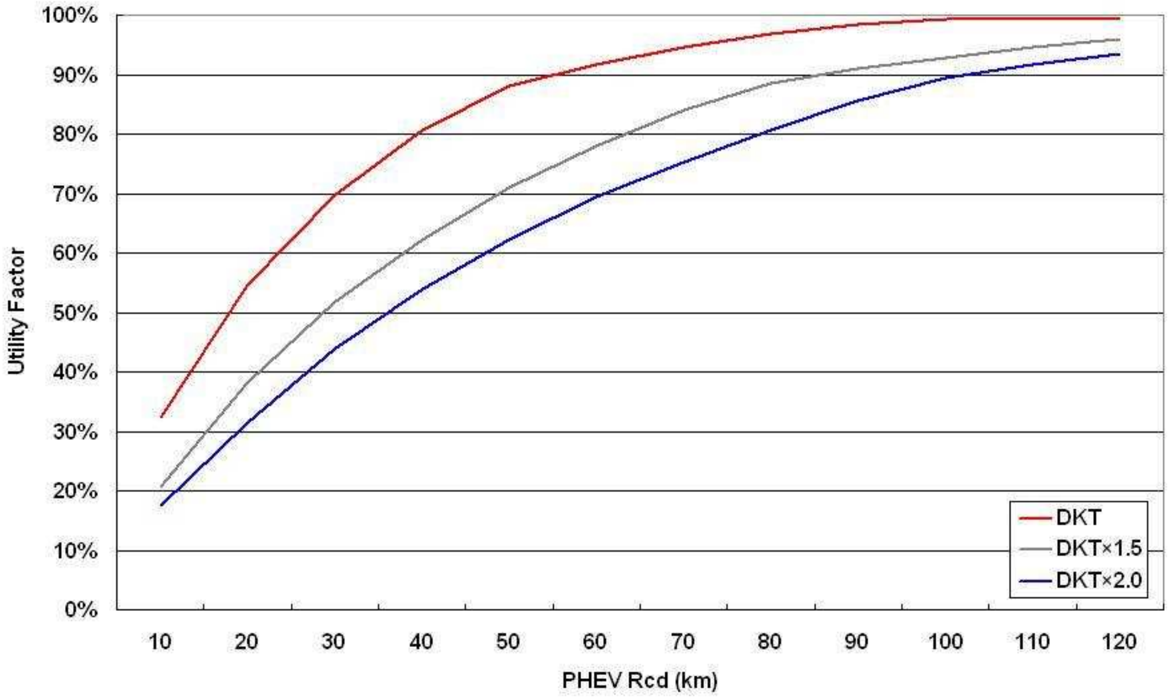


Source: graphs produced by the authors using survey responses

As it can be seen on Figure 5 the 'driver' group has a higher average daily travel distance with a greater standard deviation compared with the 'non-driver' group. Having said that, it is worth highlighting that, perhaps because there is not widespread penetration of the private car in China yet, daily distances traveled by non-drivers are only 18.4% lower than those traveled by drivers.

Figure 6 presents the daily distance UF curve for various PHEVs with R_{CD} of 10 km to 120 km for average daily distances of 53.14km, 79.71km and 106.28km, which is the average, 1.5 times and twice the average travel distance of the 'drivers' in our small sample.

Figure 6 Daily Distance UF Curves for DKT, 1.5 DKT and 2 DKT



Source: calculations produced by the authors

Lower vehicle operating costs cause a 'rebound effect' and this is also a well-documented fact in the transport studies literature (Evans, 2008; Gorham, 2002, Portney et al, 2003).

6. Conclusions

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

For our small sample, PHEVs have large potential for reducing petroleum fuel use, compared to ICE vehicles. The potential for reducing GHG emissions could be larger if electricity in China were generated using cleaner technologies rather than coal.

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

References:

Bradley T H & Quinn C W, 2010, Analysis of Plug-in Hybrid Electric Vehicle Utility Factors, Journal of Power Sources (2010), doi:10.1016/j.jpowsour.2010.02.082

British Petroleum, 2009, BP Statistical Review of World Energy – June 2009, British Petroleum Company, retrieved on 11th April, 2010 from http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/2009_downloads/statistical_review_of_world_energy_full_report_2009.pdf

China Logistics Association, 2005, China Logistics Yearbook of 2005, China Goods and Materials Press, Beijing

China National Statistics Bureau, 2006, China Statistics Yearbook-2006, China Statistics Press, Beijing.

Elgowainy A, et al, 2009a, Well to Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles, Argonne National Laboratory, U.S. Department of Energy

Elgowainy A, et al, 2009b, Well to Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles, Argonne National Laboratory, U.S. Department of Energy

Evans, C. (2008), Putting Policy in Drive: Coordinating Measures to Reduce Fuel Use and Greenhouse Gas Emissions from U.S. Light-Duty Vehicles, MSc Dissertation, Master of Science in Technology and Policy, Massachusetts Institute of Technology, June.

Gorham, R. (2002), Air Pollution from Ground Transportation: An assessment of causes, strategies and tactics, and proposed actions for the international community, The Global Initiative on Transport Emissions: A Partnership of the United Nations and the World Bank, Division for Sustainable Development, Department of Economic and Social Affairs, United Nations. http://www.un.org/esa/gite/csd/gorham.pdf

GREET 1.8c.0, 2009, Greenhouse Gas, Regulated Emissions and Energy Use in Transport, Argonne National Laboratory, US Department of Energy, Chicago

Jia J, 2003a, Pipeline Transport Development for Fuel Products in China, Journal of Integrated Transport, (2003-12): p.43-p.45

Jia J, 2003b, Pipeline Transport Development for Fuel Products in China, Journal of Integrated Transport, (2003-12): p.43-p.45

Liu J, 2010, Sohu New Energy Vehicles Online Survey: http://auto.sohu.com/20100224/n270407525.shtml

Ministry of Communication and Transportation of China (MOC) (2005a). Economic Analysis for China’s Water Transport Operation in 2004 and 2005

Ministry of Communication and Transportation of China (MOC) (2005b). Economic Analysis for China’s Water Transport Operation in 2004 and 2005

National Development and Reform Committee (NDRC) (1990-2006a). China Energy Statistics Yearbook 1985-2005, China Statistics Press, Beijing, 2006

National Development and Reform Committee (NDRC) (1990-2006b). China Energy Statistics Yearbook 1985-2005, China Statistics Press, Beijing, 2006

National Development and Reform Committee (NDRC) (1990-2006c). China Energy Statistics Yearbook 1985-2005, China Statistics Press, Beijing, 2006

Nobuyuki H, 2009, Natural Gas in China – Market Evolution and Strategy, International Energy Agency, Working Paper Series, retrieved on 11th, April, 2010 from http://www.iea.org/Papers/2009/nat_gas_china.pdf

Portney, P. R., Parry, I. W. H., Gruenspecht, H. K. and W. Harrington (2003), 'Policy watch - The economics standards of fuel economy', Journal of Economic Perspectives, Vol. 17, N°4, pp. 203-217.

Rousseau A, et al, 2007, Research on PHEV Battery Requirements and Evaluation of Early Prototypes, Argonne National Laboratory, U.S. Department of Energy

Wang M Q, 2006, Energy and Greenhouse Gas Emission Impacts of Fuel Ethanol, prepare for Ford Motor Company

Wang J, 2005, The Development of China's Energy Industry, presentation Institute of Nuclear and New Energy Technology of Tsinghua University, National Development and Reform Committee, Beijing

Wang M Q 2004. Allocation of Energy Use in Petroleum Refineries to Petroleum Products – Implications for Life-cycle Energy Use and Emission Inventory of Petroleum Transportation Fuels, International Journal of LCA, 9(1): 34-44

UK DfT (2009), Transport Statistics Great Britain 2009 Edition, Department for Transport, London: TSO. http://www.dft.gov.uk/pgr/statistics/datatablespublications/tsgb/2009edition/

Wang Q, 2006, Energy Economy Policy Research for Sustainable Development-2006 Energy Data Report, Energy Research Association of China, Beijing

Zhang A, Shen W, Han W, et al, 2008b, Lifecycle Analysis for Alternative Vehicle Fuels, Tsinghua University Press, Beijing

Zhang A, Shen W, Han W, et al, 2008a, Lifecycle Analysis for Alternative Vehicle Fuels, Tsinghua University Press, Beijing

Appendixes

Appendix 1 PHEV-CD-60km Parameters

Simulation Options	
Fuel Consumption in CD Mode (Btu_fuel/km)	601.304
Electricity Consumption in CD Mode (Wh/km)	134.410
MPG Change in CS Mode relative to ICE vehicles (%)	140.00%
Operational charge-sustaining range (km)	60
Share of kilometers traveled for CD Mode (%)	91.9
Share of kilometers traveled for CS Mode (%)	8.1
Electric Charger Efficiency (%)	85
Test Prius-Hymotion PHEV	
Vehicle Configuration:	pre-transmission parallel
Vehicle Class:	Mid-size
Vehicle Test Mass:	1661kg
Front Area:	2.2m2
Drag Coefficient:	0.29
Transmission	5-speed manual
Accessory Load Electrical	200watt average
Electric Machine:	75kw peak at base speed of 3000rpm
Battery Model	SAFT-JCS VL41M
Capacity	41Ah at 3/c
Operating Voltage	194-288V
Continuous Current	150A for 30sec at 30°C
Discharge Power	65kw for 30sec at 50% SOC at 30°C

Sources: Rousseau A, et al, 2007