Life Cycle Assessment (LCA) of BEV's Environmental Benefits for Meeting the Challenge of ICExit (Internal Combustion Engine Exit)

Ge Zheng[1], Zhijun Peng[2*]

[1]Department of Computer Science, University of Essex, Colchester, UK

[2]Faculty of Creative Arts, Technologies and Science, University of Bedfordshire, Luton, UK

ABSTRACT

Based on necessary literature review, LC (Life Cycle) emissions, in particular $LCCO_2$ (Life Cycle CO_2) emissions, of BEVs (Battery Electric Vehicles) have been assessed and compared with the most efficient ICEVs (Internal Combustion Engine Vehicles), such as non-plug-in HEVs (Hybrid Electric Vehicles) and diesel cars. By considering CO_2 emissions from vehicle production, vehicle recycle and the entire process of energy flow (from the mining of the energy source to a vehicle being driven), $LCCO_2$ emission models of BEVs and ICEVs were built. For comparing between BEVs and ICEVs in terms of their LC emissions, a new measure named SRPR (Square Root of Power and Range) has been proposed for correctly reflecting the powertrain's main performance. Results show that, although BEVs have much lower ECR (Energy Consumption Rate) than non-plug-in HEV and diesel cars, their $LCCO_2$ are very variable, and are very dependent on $LCCO_2$ of power generation mix of specific country. In some countries where thermal power generation, in particular coal power generation, is still dominant, BEVs' $LCCO_2$ are apparently higher than ICEVs. If a country would like to have their BEVs operating lower $LCCO_2$ than ICEVs, the overall average $LCCO_2$ from their power generation mix should be at least at the level about 320 g/kWh. As a case study, by analysing the power generation development trend and the BEV development trend in China, it suggests that their aim for developing BEVs to have lower $LCCO_2$ than ICEVs in next two or three decades would be very difficult to meet. If they like to put priority on the reduction of $LCCO_2$ of ground vehicles, BEVs could not be widely promoted in China until they made their power generation clean enough, probably at least in next 20 even 30 years. Finally, BEVs' other LC pollutant emissions, such as NOx (Nitrogen Oxides), PM (Particulate Matters), SOx (Sulfur Oxides) would not be a very serious problem if those thermal power generations are equipped with adequate exhaust aftertreatment for removing those pollutant emissions.

INTRODUCTION

As fossil fuel is the primary source of high amounts of CO_2 emissions, about 70% of global CO_2 emissions are from coal-based and petroleum-based power generation plants and transports [1]. The EU proposed a new 2030 Framework under which it aims for making renewable energy to account for at least 27% of total energy consumption and at least a 27% improvement in energy efficiency (relative to a business-as-usual scenario). This is to help reduce GHG (GreenHouse Gas) emissions by 40% in 2030, relative to 1990 levels [2]. The UK's current long-term target is a reduction in GHG emissions at least 80% by 2050, relative to 1990 levels. This 2050 target was conceived as a contribution to a global emissions reduction target aimed at keeping global average temperature at around 2°C above pre-industrial levels [3].

With above background, BEVs (Battery Electric Vehicles) have achieved great development in recent years. In 2020, the global BEV annual production has reached nearly 2.5 million and it is expected to have 70% increase in 2021 [4]. Norway as the biggest BEV country has achieved an unprecedented breakthrough for new BEV car market, where the market share of BEV has reached 53.4% in 2020, and it is predicted the share will pass 70% in 2021 [5]. Based on its superiority on clean electricity, Norway has proposed to stop the sale of new ICEV (Internal Combustion Engine Vehicles) by 2025 [6].

As ICEV's exit (ICExit) has been ruled and suggested by a number of countries, the widespread use of BEVs is still hindered by insufficient technological advancements [7], infrastructure facilities [8], policy support, and that they do not meet the expectations of consumers very well [9]. The key technologies restricting the marketization of BEVs are those for efficient battery energy storage [10] and quick charging at a low temperature [11]. In addition, the high prices of electric motors, batteries, and motor control systems increase the production cost of BEVs compared to ICEVs, which limits the market potential of BEVs to a certain extent [12].

Even for the main advantage of BEVs, as claimed for lower emissions than ICEVs, it is arguable. For non-plug-in vehicles which are totally powered by hydrocarbon liquid fuel, all life or Life Cycle (LC) CO_2 ($LCCO_2$) emissions normally includes those from (a) vehicle manufacturing process, (b) fuel mining, refining and transport, (c) vehicle operation and (d) vehicle recycle. Each of those four parts has very similar level in different country. But for BEVs, although Battery-to-Wheel (Tank-to-Wheel) energy consumption are very similar in different country, Well-to-Electricity (Well-to-Tank) CO_2 emissions can be very different in different country. Then for the same BEV model, the operation may have very different $LCCO_2$ emission rate (g/km).

Therefore, to have a clear picture for analysing emissions of BEVs, all life or LC emissions should be carried out and the Well-to-Electricity (Well-to-Tank) emissions must be considered. As a comparison of only the exhaust emissions between a BEV and a petrol vehicle is misleading, LC system approach is important. Although BEVs have no emissions during operation, there are substantial amounts of emissions in the production processes of electricity and vehicle. [13].

LC Assessment (LCA) is a standardized methodology for the systematic assessment of environmental performance of any product or system, throughout its whole life cycle [14]. Zhao et al. [15] proposed a LC cost and emissions model for BEVs in China. The results showed that until 2031, BEVs are not economically competitive compared with ICEVs in the Chinese market.

Based on LC analysis, the CO_2 balance which is defined as the difference between the quantity of CO_2 emitted from a certain process and the quantity of CO_2 absorbed through the relevant process relating the former process [16] should be considered for some types of energy sources, such as bio-fuel and bio-mass. Very standard LC assessment can be conducted under ISO standard 14040, which generally consists of four steps: goal and scope definition, LC inventory, LC impact assessment and interpretation [17].

LCA of power generation should include analysing both internal and external factors of a power plant that affect energy, economic and environmental performance of power plants [18, 19]. For instance, LCA of thermal power generation can be accomplished by considering the plant construction, the fuel supply, the combustion process, the plant operation and the electricity transmission [20].

In this paper, it is aiming, by based on relevant literature review, to have a LC comparison between BEV and ICEV in terms of their environmental impact. The motivation of this study is to examine whether BEVs are really cleaner than ICEVs. If not, where and how to find a path for developing BEVs and ICEVs in order to reducing LC emissions.

LITERATURE REVIEW

Promotion of BEVs

In recent years, BEVs (Battery Electric Vehicles) have been widely promoted due to their potentials for reducing local CO_2 emissions and other harmful emissions, and meanwhile for lowering vehicle noise level. This provides a significant clean image compared to liquid fuel or combustion engine powered vehicles (Internal Combustion Engine Vehicles - ICEVs) which have been suggested to stop in new car markets in next 10-20 years in a number of countries. While ICVE's exit (ICExit) will be inevitable, how to optimise BEV technology and how it will affect LC (Life Cycle) emissions will be critical for the next step of ground vehicle development including relevant infrastructure.

As those advantages of BEVs are very beneficial for those crowded cities where air pollution and noise have been main concerns, their reduction of emissions have been demonstrated by a number of researches, such as Bickert et al. [21] who analysed BEVs' emissions mainly during vehicle manufacture stage. Their results show BEVs can have obvious saving on emissions during operation stage, although they have higher emissions during production stage than ICEVs (Internal Combustion Engine Vehicles). The research also suggested that BEV's saving on emissions can be feasible for both high and low annual driving range. But the saving magnitude is highly dependent on specifications of local or national electricity production mix.

By a LCA (Life Cycle Assessment), Zhou et al. and Shen et al. examined greenhouse gas emissions of BEVs [22], and demonstrated BEVs could save CO_2 emission in the range of 17–34%, compared to ICEVs. Ou et al. [23] carried out several researches for studying LCA on various vehicle emissions in China and suggested that BEV's applications would significantly contribute to reduction of greenhouse gas and harmful emissions. Their results also showed that those benefits would be magnified with the increase of renewable energy (solar, wind, hydropower, etc.) for power generation. Hawkins et al. [24] built a LCA model for studying the Global Warming Potential (GWP) under the applications of BEVs and ICEVs. In their study, existing Mercedes A-series ICEVs were compared to Nissan Leaf BEVs under European manufacturing and operating conditions, with an assumption of lifetime operating distance of 150,000 km for both ICEVs and BEVs. Their results demonstrated that BEVs can reduce 10–24% of GWP than conventional ICEVs, if BEVs are charged by current European electricity production mix.

Que et al. evaluated Well-to-Tank energy consumption and CO_2 emissions by applying the model of Tsinghua-LCAM (Life Cycle Assessment Method), which is a GREET based LCA tool. Tank-to-Wheel performances were examined with their model by adopting different type of drivetrain configurations of BEVs. Their results shown that LC fuel consumption and $LCCO_2$ emission of BEVs are lower than those of ICEVs (Internal Combustion Engine Vehicles), which have an average fuel consumption about 5 L/100km in China. By including the possible improvement of upstream coal power generation efficiency and the increase of cleaner electricity (solar, wind, hydropower, biofuel), BEVs showed obvious trends of significantly reducing LC fuel consumption and $LCCO_2$ emissions than ICEVs in next several decades [25].

In the research of Zhou et al. [26], they compared LC fuel consumptions and CO_2 emissions of BEV bus and diesel bus, by testing them under Macao driving conditions. Their results suggest that BEVs can reduce Tank-to-Wheel fuel consumption by over 32% and total Well-to-Wheel CO_2 emissions by 19-35%, compared to diesel buses across all tested road and vehicle conditions [26]. Falcao et al. did a similar comparison between BEV and diesel engine powered ICEV by road testing with standard driving cycles and under urban driving conditions in Brazil. With necessary emission analysis, they demonstrated that CO_2 emissions from the tested BEV was 4.6 times lower than the tested diesel vehicle [27].

When BEVs can directly reduce emissions including CO_2 emissions, they can also extend their advantage by working as energy storage system [29, 30], for instance, to be charged at off-peak hours of national grids. With general charging operation of V2G (Vehicle-to-Grid) mode, BEVs can be managed to take charging while an national electricity grid's demand is lower than the supply level [31]. Because generally it is difficult to store those surplus electricity from national grids, optimised BEV charging management would reduce the waste of electricity, then improve energy efficiency of national grids. Although some studies suggested that the arrangement may have a higher emissions factor if the local electricity production is mainly not from renewable sources [33, 34], a research shows that, even with power generation totally by natural gas, off-peak charging mode can save 8% CO_2 emissions, compared to uncoordinated charging operation [35].

Even in those places where the climate conditions are not unfavourable to BEVs, successful applications of BEVs have been reported. For example, BEVs have been adopted very well in Norway and other Scandinavian countries, although intensive heating is required for battery systems to maintain adequate range in those cold areas [28]. To the current world when it has the big pressure to reduce greenhouse gases, BEVs pose both a challenge and an opportunity to optimise national energy structures and national grid managements [32].

As there is still strong debate for the promotion of BEVs to all applications, disadvantages of BEVs are mainly associated with the driving range and the cost of the vehicles. Travellers driving BEVs are still very anxious for finding adequate charging point when commutes a long distance over several hundreds of kilometres, even they do not mind the charging time at each charging point. From published data, it can be found that almost all BEV models have significantly lower driving range than conventional ICEVs. Although most customers do usually drive much shorter daily distance than most BEV's driving ranges, people judge the driving range of BEVs as insufficient by considering some long driving requirements. Meanwhile, BEV's ranges can be reduced very obviously if heating or cooling devices are operated. Some BEV manufacturers have also considered to have big battery stacks in order to increase driving range. But this will increase vehicle weight significantly and also results in the significant increase of vehicle cost.

In terms of the purchase price, it is obvious that BEVs have higher new vehicle price than conventional ICEVs for comparable vehicle size. Regarding Life Cycle Cost (LCC), one example was published by Kara et al. who analysed LCC of 2011 Nissan Leaf by estimating the BEV's life cycle economic impacts under Australian driving conditions, and demonstrated that 2011 Nissan Leaf had a worse LCC compared to its Toyota Corolla counterpart [36]. Another LCC analysis was made by Zhao et al. who examined the economic competitiveness of BEVs in the Chinese market, and suggested that BEV's LCC is about 1.4 times higher than comparable ICEVs [37]. It should be noted that the study of Zhao et al. has considered Chinese government's subsidies to customers for their purchases of BEVs.

Some concern to the rapid increase of BEV production also comes from the more intense use of different metals from the manufacture of conventional ICEVs. Some metals like lithium, manganese and rare earth metals like neodymium which are necessary for lithium-ion batteries and permanent magnet electric machines [38, 39] were not used too much for conventional ICEVs. Those changes have brought some worry about higher environmental impact from BEVs than that of ICEVs, including the much higher CO_2 emissions from production stage of BEVs than that of ICEVs [40, 41].

Not just higher CO_2 emissions from production stage than ICEVs, BEV's Life Cycle CO_2 (LCCO2) emissions are also controversial, although they have no CO_2 emissions during driving stage. Significantly depending on the emissions level (not just CO_2) during electricity production process, BEV's $LCCO_2$ needs also including those losses from electricity transmission, BEV battery charging, BEV electric machines and control systems. Basing on eight Canadian cities, Requia et al. studied $LCCO_2$ of BEVs and found that different power generation profiles across Canada makes serious influence on $LCCO_2$ of BEVs [42]. Mayyas et al. also carried out a study for BEV's LCCO2 but basing on the power generation condition of the USA. Their results demonstrated that ICEVs or non-plug-in HEVs (Hybrid Electric Vehicles) have a lower LCCO2 than BEVs under the grid charging condition and the driving condition in the USA [43].

Finally, there are still a lot works to do for improving the infrastructure to promote the application of BEVs. When more charging points are being built and fast charging technologies is being applied more and more, governments still need to keep adequate purchasing subsidies to BEV buyers for balancing high purchasing price of BEVs. [44].

Further Analysis of BEV's Emissions

When the comparison between BEVs and ICEVs are made for studying their LC emissions, in particular $LCCO_2$ emissions, the first main difference which should be taken into account is that BEVs are more depending on Well-to-Tank energy flow process but ICEVs are more on Tank-to-Wheel energy flow process [47].

To practical cases, when it is claimed that BEVs can save emissions, some uncertainties need to be clarified, such as BEV's market penetration, power generation mix condition (which may be very different in different countries), and increased electricity demand by BEVs (which may need big re-investment of power generation and lead to increased emissions) [45]. Between those factors, the information of power generation mix specifications has been considered as major one to influence BEV's LC emissions [33]. One research carried out by Onat et al. [46] compared CO_2 emissions among BEVs, PHEVs (Plug-in Hybrid Electric Vehicles) and non-plug-in HEVs (Hybrid Electric Vehicles) under different charging and driving conditions in all fifty states in the US, by including local electricity generation mixes, driving modes and vehicle production processes. Their results suggested that considerable difference on CO_2 emissions is existing from different states.

It is believed that BEV's advantages will be realised deeply with further developments of relevant technologies for sufficiently demonstrating BEV's full performances [48]. When electricity production mix has been played a major role to influence the environmental impact of BEVs, it is also necessary to consider other factors, such as BEV's system design etc. [49]. To have a comparative LCA study of BEVs' emissions, not only the exhaust emissions, but all emissions from different life stages such as fuel production, vehicle production, vehicle operation and end of life of vehicles should be considered.

METHODOLOGY

Framework of LCA Study

As different vehicle powertrain types are considered for the LCA study as described in this research, both vehicle's entire Well-to-Wheel energy flow process and vehicle's body cycle are comprised, as shown in Figure 1 below. The Well-to-Wheel process is analysed as two stages of Well-to-Tank and Tank-to-Wheel. The Well-to-Tank is mainly include energy resource extraction, energy refinement and the energy distribution, while the Tank-to-Wheel mainly consider the energy conversion process in a specific vehicle.

In terms of the energy efficiency and emissions during vehicle body cycle, the process can be described as three main stages - vehicle manufacture process, vehicle maintenance and vehicle recycle, as shown in the right hand side of Figure 1.

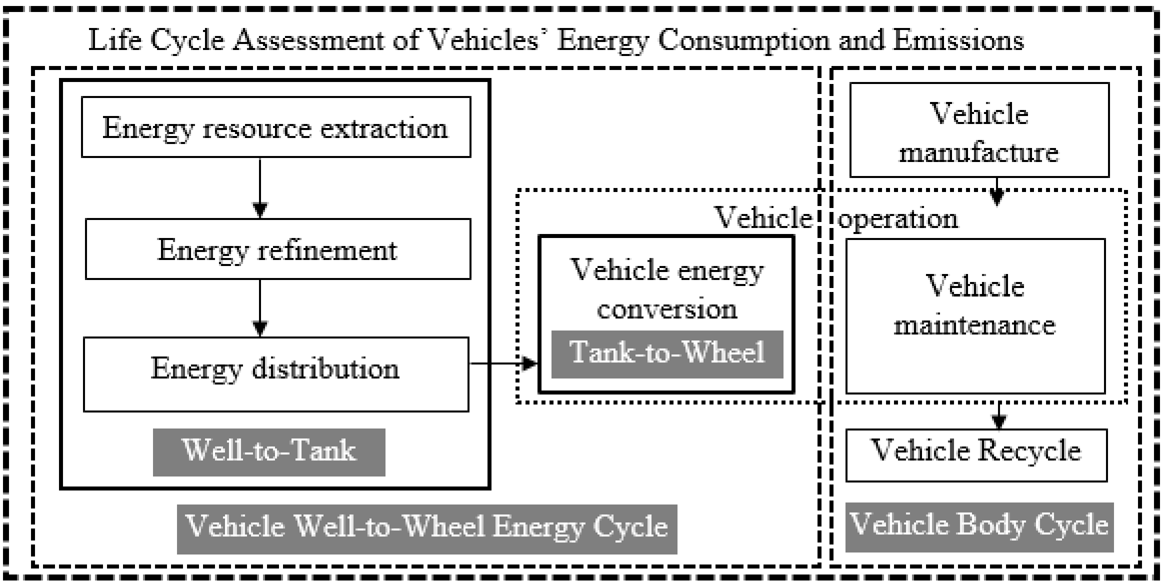


Figure 1 Framework of Life Cycle Assessment (LCA) to BEV and ICEV's energy efficiency and emissions

Studied Vehicle Models

Vehicle Types which are discussed in this paper are mainly including Internal Combustion Engine Vehicle (ICEV) and Battery Electric Vehicle (BEV). Comparisons between these two vehicle types are mainly energy consumption rate, LCCO2 and other relevant harmful emissions.

ICEV is defined as vehicle for which the energy input into the vehicle is pure hydrocarbon fuels. This means that there is no any plug-in of electricity charging for this kind vehicles. Even the vehicle has electric machine for powering the vehicle, the electricity is converted by hydrocarbon fuel or by energy regeneration, such as brake generation or thermal regeneration. For those HEVs (Hybrid Electric Vehicles), if there is no plug-in fitted, they are categorised as ICEV in this paper. Although they have been upgraded with various electric innovation, they are still some kind of ICEV.

BEV is the vehicle for which the energy input into the vehicle is pure electricity. In this study it is defined BEV as pure battery electric vehicles. For BEV, there is no any conventional liquid fuel (fossil fuel or bio-fuel) or gaseous fuel (natural gas etc.) to be used on vehicle for providing power.

In Table 1, the published data regarding main powertrain parameters of six selected BEV and four ICEV (non-plug-in gasoline HEV or diesel cars) models are listed. In the table, two typical non-plug-in HEVs including Toyota Prius and Honda Insight and two diesel ICEVs are listed. The Toyota Prius is the first mass production HEV and the biggest production quantity HEV in the world and Honda Insight is claimed as one of the most efficient HEVs or the most efficient passenger cars fuel by liquid fuel.

The first generation Insight was claimed the most fuel efficient gasoline-powered car available in the US without plug-in capability for the length of its production run and up until December 2015, when it was surpassed by the 2016 Toyota Prius Eco [50]. The Insight earned an EPA (Environmental Protection Agency) fuel economy estimate of 70 mpg_{-US} (3.4 L/100 km; 84 mpg_{-imp}) in highway driving, 61 mpg_{-US} (3.9 L/100 km; 73 mpg_{-imp}) in city driving. With air conditioning it was 68 mpg_{-US} (3.5 L/100 km; 82 mpg_{-imp}) and 60 mpg_{-US} (3.9 L/100 km; 72 mpg_{-imp}). With a CVT (Continuously Variable Transmission), it was 57 mpg_{-US} (4.1 L/100 km; 68 mpg_{-imp}) and 56 mpg_{-US} (4.2 L/100 km; 67 mpg_{-imp}). The second-generation Honda Insight (since 2009) is not better than the first generation in terms of fuel economy because of significant increases in size, weight and power [51].

Table 1 Main parameters of selected vehicle models

(a) ICEV (non-plug-in HEV or diesel cars)

Vehicle model	Power (kW)	Fuel tank (liter)	Range (km)	SRPR	Fuel Consumption (MPG)	ECR (MJ/km)
Toyota Prius	100	45	1067	1.46	67 MPG	1.37
Honda Insight	80	40	1160	1.37	83 MPG	1.1
Nissan Dashqai Diesel	81	55	1437	1.53	74.3 MPG	1.33
VW Golf Diesel	81	50	1211	1.4	68.9 MPG	1.44

(b) BEV

Vehicle model	Power (kW)	Battery capacity (kWh)	Range (km)	SRPR	Electricity Consumption (kWh/100km)	ECR (MJ/km)
BMW I3	125	33	183	0.68	17.75	0.64
Chevrolet Bolt	150	60	383	1.07	17.64	0.64
Ford Focus E 2017	105	33.5	185	0.62	19.57	0.70
Hyundai Ioniq E	88	28	200	0.59	15.4	0.55
Nissan Leaf 2016	80	30	172	0.52	18.7	0.67
Tesla S 60D	279	60	384	1.46	20.13	0.72

As presented in Table 1, a new measure of *SRPR* (Square Root of Power and Range) is introduced for assessing a vehicle's main performances for which customers are concerned for the powertrain performances. This is especially appropriate for BEVs for which both power and range are main interests of customers. Although for traditional ICEVs, the power as the single parameter of powertrain is normally used as the powertrain's main performance for comparing between vehicle models, *SRPR* will be necessary for ICEVs too when a comparison between ICEVs and BEVs is made.

Here, *SRPR* is defined as

$$SRPR = \sqrt{\left(\frac{Power}{100}\right) \times \left(\frac{Range}{500}\right)} \qquad (1)$$

Here 'Power' has the unit of kW and 'Range' has the unit of km. '100' means 100 kW, as a general family passenger car's power. '500' stands for 500 km for representing the range of a general family passenger car's range (compromised between ICEV and BEV). Therefore, for a general passenger car which has 100 kW of power and 500 km of range, the SRPR is 1.0.

Energy Efficiencies and Emissions

Energy efficiencies are relating the comparisons between BEV and ICEV will mainly include the following several definitions which are also demonstrated in Figure 2.

Well-to-Tank efficiency is the ratio of the fuel energy in vehicle fuel tanks to the fuel energy from petroleum wells. For ICEVs, this is mainly the efficiency from petroleum well or biofuel sources to the production of vehicle fuels (gasoline, diesel, natural gas, biofuel), and to transport and finally refill into vehicle tanks. For BEVs, it is the efficiency from energy sources (fossil fuel, biofuel/biomass, solar, wind, tide, geothermal, hydropower, unclear etc.) to produce electricity, then transmit and charge them into vehicle battery stacks. Once electricity is produced and input into national grid, two kinds of losses including electricity transmission losses and charging losses are main factors still to influence efficiency. For both ICEVs and BEVs, details of Well-to-Tank processes can be found in Figure 2.

Tank-to-Wheel efficiency is the ratio of the final useful energy used by vehicle to the fuel energy output from fuel tank. This efficiency is mainly relating vehicle on-board performance. For BEVs, it is the ratio of the final used energy (electricity) amount to the electricity amount output from vehicle battery. This efficiency will determine how much electricity from battery will be required by BEV for covering per unit distance.

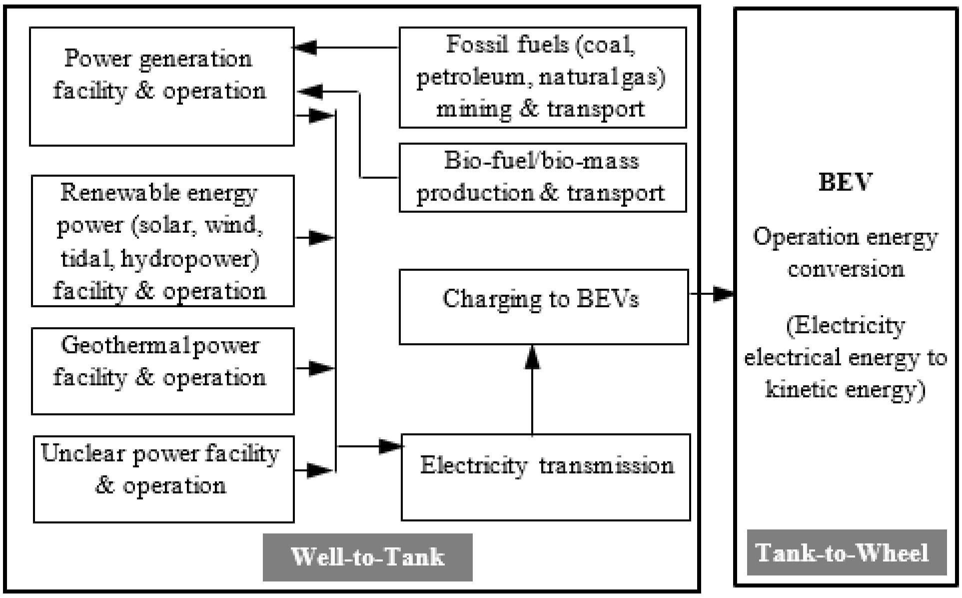
Well-to-Wheel efficiency is Well-to-Tank efficiency timing Tank-to-Wheel efficiency, since Well-to-Wheel is the entire process of energy flow from the mining of the energy source to a vehicle being driven.

$$\eta_{WtW} = \eta_{WtT}\eta_{TtW} \tag{2}$$

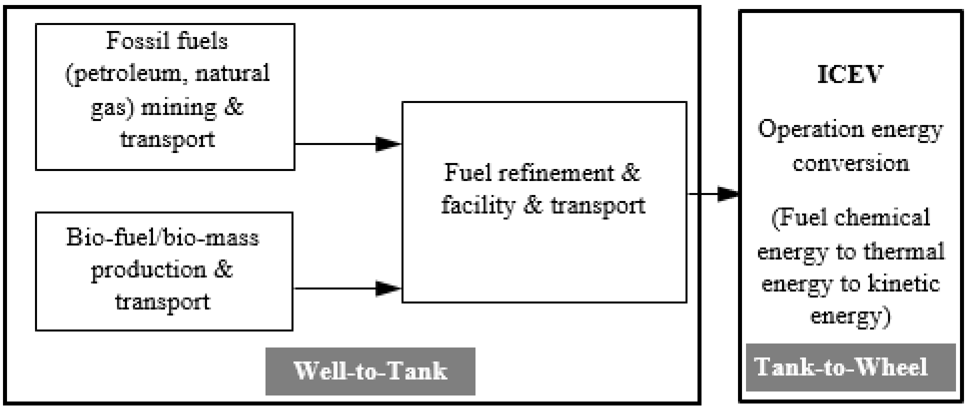
Here, η_{WtW} is Well-to-Wheel efficiency; η_{WtT} is Well-to-Tank efficiency, and η_{TtW} is Tank-to-Wheel efficiency.

Well-to-Tank CO_2 Emissions of BEVs

CO_2 emissions and other harmful emission relating to BEVs mainly rely on the power generation process, electricity transmission and vehicle charging processes. To calculate CO_2 emissions from power generation, a specific country's actual power generation structure which directly contributes to national grid must be considered, because different power generation resources produce very different CO_2 emissions and other harmful emissions. In Table 2, it is listed global and several typical countries' power generation information of 2016. Most of those data are obtained from the published details by the International Energy Agency, in addition to one more set of data collected from Chinese national government's statistics for the global biggest power generation nation.



(a)



(b)

Figure 2 Main factors for considering vehicle Well-to-Wheel energy and emissions of (a) BEV, (b) ICEV

For each power generation source, CO_2 emissions were estimated by using the data published by the Intergovernmental Panel on Climate Change [52], as shown in Figure 3. The results have no obvious difference from published data by [53] which demonstrated that the average CO_2 emissions of electricity from coal, natural gas, wind are 885 g/kWh, 642 g/kWh and 11 g/kWh, respectively.

Table 2 The world's and some countries' power generation sources in 2016

Unit: TWh (10^9 kWh)

	Coal	Gas	Oil	Bio	Nuclear	Hydro	Geo	Solar	Wind	Total
World	9594	5794	931	570	2606	4170	82	338	958	25081
	38.31%	23.14%	3.72%	2.28%	10.4%	16.65%	0.3%	1.35%	3.83%	100%
UK	31	143	2	34.5	72	8.3	0	10.4	37	339
	9.2%	42.3%	0.6%	10.2%	21.3%	2.5%	0	3.1%	10.9%	100%
China	4242	170	10	76	213	1193	0.1	75	237	6218
	68.24%	2.73%	0.16%	1.22%	3.40%	19.2%	0	1.2%	3.81%	100%
	64.21%*	3.09%*	4.96%*		3.47%*	19.43%*	0*	1.02%*	3.84%*	100%
Norway	0.15	2.6	0.03	0.44	0	144	0	0	2.1	150
	0.1%	1.74%	0.02%	0.29%	0	96.44%	0	0	1.4%	100%
India	1105	71	23.4	44	38	138	0	14.1	49	1478
	74.54%	4.79%	1.58%	2.97%	2.56%	9.31%	0	0.94%	3.31%	100%
USA	1354	1418	35	79	840	292	18.6	50	230	4322
	31.37%	32.55%	0.81%	1.84%	19.46%	6.76%	0.4%	1.16%	5.32%	100%

*data.stats.gov.cn and also BP's report [54]
Tide is too small to be ignored.
Oil P – Oil Products, NG – Natural Gas, Bio – Biofuels and Waste, Geo – Geothermal, STW – Solar/Tide/Wind, Hydro – Hydropower

In Figure 3, it can be found that traditionally thermal power generation contributes much higher CO_2 emissions than those renewable energy sources. As it is introduced by [17], in coal power generation plant (in the UK), flue gas is the major contributor towards CO_2 release sharing about 97% (834.7 kg CO_2/MWh) of the total CO_2 emissions (854.7 kg CO_2/MWh) of coal power generation. Although bio-fuel/bio-mass also relies on thermal power generation process, as renewable sources, their CO_2 emissions is much lower than other thermal generation processes. It should be noted that in different countries, CO_2 emissions level from a specific power generation format may be different. This has been reflected from the error bar in Figure 3. While between different countries, the difference of CO_2 emissions from a specific power generation format is not too significant to influence the main results of this study, the same CO_2 emissions for a specific power generation format is used for those listed countries and the world in this study.

In addition, those CO_2 emissions shown in Figure 3 have considered the fuel mining, power generation facility construction and power plant operation. For instance, CO_2 and another GHG (Green House Gas) CH_4 emissions from coal mining has been added with an average value of 15 g/kWh as equivalent CO_2 emissions (actually in the range of 10-20 g/kWh) for coal power generation. For those non-thermal power generations, CO_2 emissions are mainly from facility construction.

Based on the estimate, overall average of CO_2 emissions from all power generation for the world and each of those listed countries are presented in the second column in Table 3. In the third column of Table 3, CO_2 emissions have included those due to power transmission by calculating the average power transmission efficiency of 93%. In the fourth column, the values have further included those losses from charging process (to BEVs) which is generally around 15%, or the charging efficiency as 85%.

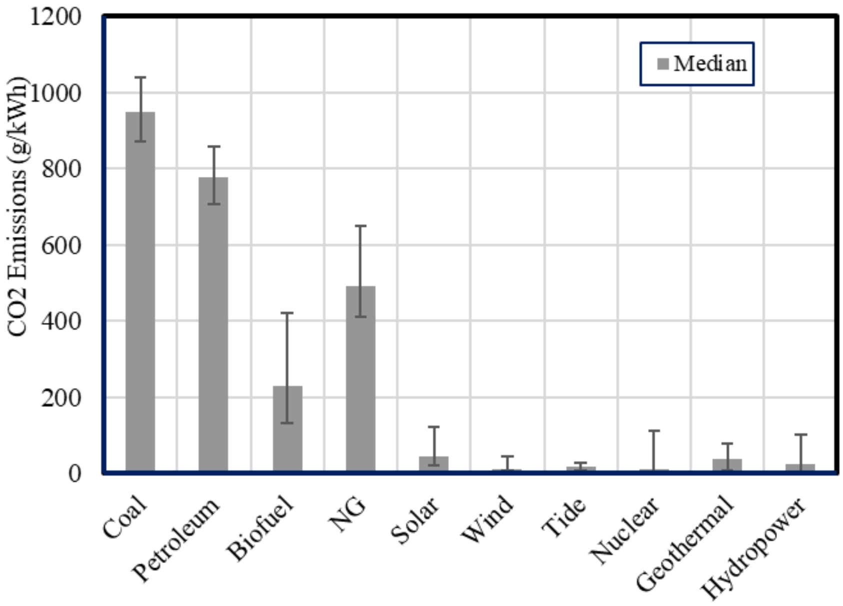


Figure 3 CO_2 emissions from various power generation technologies

Table 3 CO_2 production from power generation, plus from power transmission and charging process (to BEVs) in some countries

(Unit: g/kWh)

	All life CO_2 from Powerplant	CO_2 including power transmission	CO_2 including charging
World	517.80	556.82	655.08
UK	328.04	352.73	414.98
China	671.74	722.30	849.76
	647.97*	696.75*	819.70*
Norway	33.62	36.55	42.53
India	754.04	810.80	953.88
USA	474.70	510.43	600.50

*based on the data of data.stats.gov.cn and also BP's report [54]

The result for the UK shown in Table 3 is obvious lower than the value published by [47] which suggested that the UK power generation mix is about 500 g CO_2/kWh in 2015. Including transmission losses and charging losses, it is about 600 g CO_2/kWh. But for Norway, the research in [47] produced a lower result as about 20 or 30 g CO_2/kWh.

Life Cycle Emissions ICEVs and BEVs

Based on information shown in Figure 1, all life emissions or LC emissions for both ICEVs and BEVs will include Well-to-Tank emissions, Tank-to-Wheel emissions and emissions from vehicle body cycle (production/manufacture, maintenance and recycle).

For ICEVs, Tank-to-Wheel can be easily estimated by using the vehicle fuel consumption rate. The Well-to-Tank emissions can be calculated by considering the fuel mining, refining and transport efficiency which will be regarded as 83% for global average. The value is according to Ou and Zhang [55], who demonstrated that the efficiency of oil extraction and gasoline production were 91.28% and 90.79%, respectively, and that gives Well-to-Tank efficiency 82.87% for ICEVs. In this research, 83% of Well-to-Tank efficiency of ICEVs are assumed suitable for different countries.

In term of BEVs, Well-to-Tank CO_2 emissions will use the values shown in the fourth column in Table 3. Tank-to-Wheel can be estimated by using the actual vehicle's electricity consumption rate.

Based on this, life cycle CO_2 emissions for BEVs should be:

$$\begin{aligned} f_{life-cycle} &= f_{V-production} + f_{V-recycle} + f_{E-generation} \\ &\quad \times \left(ECR + E_{charging-losses} + E_{transmission-losses}\right) \\ &= f_{V-production} + f_{V-recycle} + f_{E-generation}\left(\frac{ECR}{\eta_{charging}\eta_{transmission}}\right) \end{aligned} \quad (3)$$

Here $f_{life\text{-}cycle}$ is BEV's all life CO_2 emission rate, g/km; $f_{V\text{-}production}$ is CO_2 emission rate from vehicle production, based on all life range, g/km; $f_{E\text{-}generation}$ is $LCCO_2$ emission rate from power generation mix, g/kWh; *ECR (Energy Consumption Rate)* is BEV's Energy Consumption Rate, kWh/km; $\eta_{charging}$ is BEV's battery charging efficiency; $\eta_{power\text{-}transmission}$ is power transmission efficiency; $f_{V\text{-}recycle}$ is CO_2 emission rate from vehicle maintenance and recycle, based on all life range, g/km.

In Equation (3), CO_2 emissions during vehicle and maintenance cycle between BEVs and ICEVs are ignored due to being too small value and too small difference between BEVs and ICEVs. In terms of CO_2 emissions from vehicle productions/manufactures, the study in [56] demonstrates that BEVs have much higher value than ICEVs, while B-Class BEV has about 8 ton to 12 ton [56]. From the published data by Low Carbon Vehicle Partnership (Leaded by Ricardo Plc), non-plug-in HEVs (as ICEVs) have an average value of 6.5 tons and BEVs of 8.8 tons [57]. By using general passenger cars' average range of 150k km [24], CO_2 emission rate (per km) from production can be produced.

As car size will influence the CO_2 emissions from production, the coefficient of *SRPR* (Square Root of Power and Range) as introduced in Equation (1) is used to correct the CO_2 emissions from production for different size vehicle.

Finally, it is needed to noted that in this section three main assumptions are made for the estimate of LCCO2 of BEVs and ICEVs: (a) Because the difference of CO_2 emissions from a specific power generation format is not too significant to influence the main results of this study, the same CO_2 emissions for a specific power generation format is used for those listed countries and the world in this study; (b) 83% of Well-to-Tank efficiency of ICEVs are assumed suitable for different countries; (c) CO_2 emissions during vehicle and maintenance cycle between BEVs and ICEVs are ignored due to being too small value and too small difference between BEVs and ICEVs.

Case Study

As different countries have different power generation mix, China is selected as a case study for comparing BEVs and ICEVs under their power generation condition. China is currently the biggest country of BEV production and sale. It is also the biggest country for energy supply, energy demand and power generation. Relevant details of the power generation mix in China can be found in Table 2 and Table 3.

Through the case study, the current progress and the trend in the future in Chinse BEV production sector and market are analysed. Combining their power generation condition, possible benefits and problems for developing BEVs to replace ICEVs are demonstrated.

COMPARISION BETWEEN BEV AND ICEV

With the analysis method as described in last section, LCA estimate of energy efficiency and CO2 emissions and other harmful emissions are carried out with a programme based on Python platform. The results are summarised in the following sections.

Energy Consumption and CO_2 Emissions

As currently the most energy efficient passenger cars fuelled totally by convenient fossil fuel, non-plug-in HEVs (Hybrid Electric Vehicles) and diesel cars is selected to represent ICEVs for comparing with BEVs. Just for Tank-to-Wheel energy efficiency, a comparison between ICEV (non-plug-in HEV and diesel cars) and BEV (Battery Electric Vehicle) is presented in Figure 4.

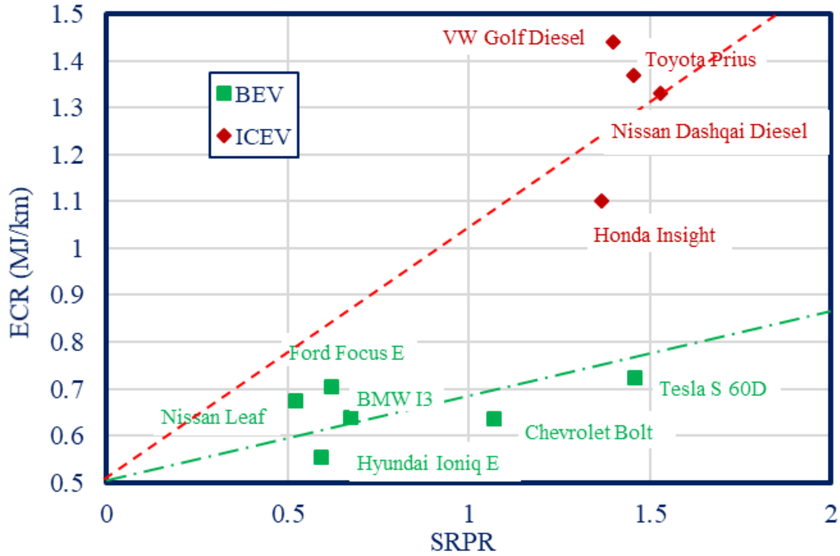


Figure 4 Comparison of Energy Consumption Rate (ECR) between ICEV (non-plug-in HEV and diesel car) and BEV, as function of *SRPR*

From Figure 4, SRPR (Square Root of Power and Range) as defined in last section is used as a measure to assess a vehicle's main performances for which customers are concerned for the powertrain performances. Because BEV powertrain has a higher efficiency then combustion engine powertrain (non-plug-in HEV and diesel cars), BEVs have much lower Energy Consumption Rate (ECR), even compared to the most efficient combustion engine powertrain. From this view point, it can be suggested that BEVs have obvious advantage than non-plug-in HEVs and diesel cars in terms of Tank-to-Wheel energy consumption. This should be one of main factors that BEVs are being widely boosted as the next generation dominant of ground vehicles due to their high energy efficiency.

However, when the energy sources are very different for ICEVs and BEVs, comparable parameters must be used for different vehicles. In Figure 5, the comparison is for $LCCO_2$ emissions for ICEVs and BEVs, based on the electricity production conditions in the UK. From the results in Figure 5, it can be noted that there is almost no difference for all life CO_2 emissions between the most efficient ICEVs (non-plug-in HEV and diesel car) and those popular BEVs, though BEVs are claimed more efficient in terms of Tank-to-Wheel energy consumption.

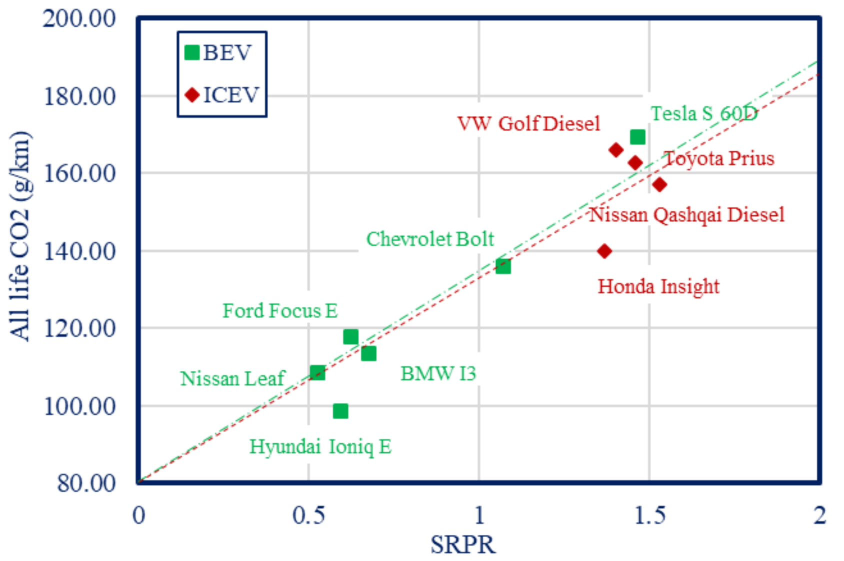


Figure 5 Comparison of all life $LCCO_2$ emissions between ICEV and BEV, based on the power generation condition in the UK

A good case for BEVs is in Norway which has been mentioned in last section as the country with the cleanest electricity. In Figure 6, it can be seen that ICEVs (non-plug-in HEVs and diesel cars) have apparently higher $LCCO_2$ emissions then BEVs, though Tesla S 60D has been close to those HEVs' LC emission level. In Norway, due to very clean power generation with over 98% electricity produced from hydroelectric, BEVs' $LCCO_2$ emissions is much lower than combustion engine power vehicles. If in the future most countries can make their electricity clean enough like those in Norway, it will provide a very helpful development environment for BEVs.

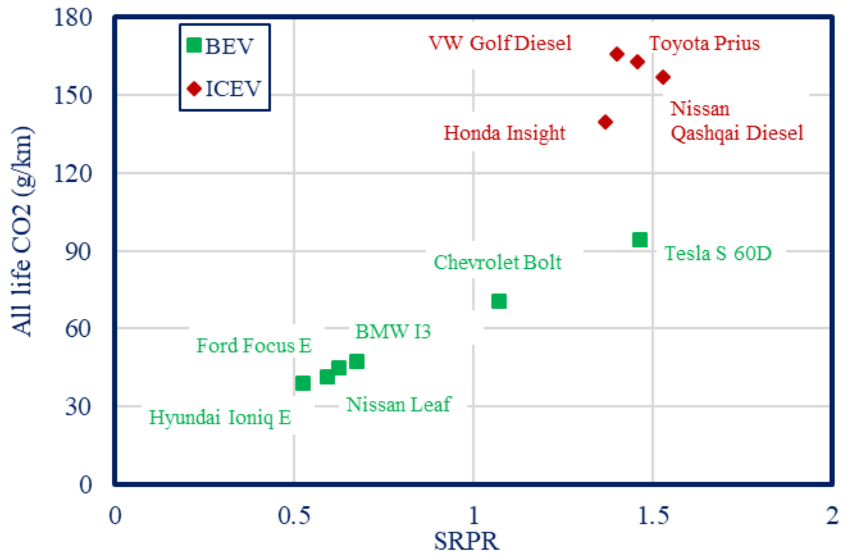


Figure 6 Comparison of $LCCO_2$ emissions between ICEV and BEV, based on the power generation condition in Norway

China as a representative country for still using a lot of coal to produce electricity has much higher CO_2 emissions from power generation mix. Then, BEVs operated in China have much higher $LCCO_2$ emissions, as shown in Figure 7. Compared to the best HEV Honda Insight which produces $LCCO_2$ emissions about 140 g/km, the best BEVs listed in the figure, Hyundai Ioniq E, has $LCCO_2$ about 161 g/km, 21 g/km higher than Honda Insight. Therefore, although China is the biggest country for manufacturing and operating BEVs, at least currently BEVs do not bring any benefit for reducing CO_2 emissions there. Under current power generation condition, more BEV is used in China, more $LCCO_2$ emissions are created.

India is even worse than China for $LCCO_2$ emissions from power generation mix, as shown in Table 3. From those results shown in Figures, it suggests that those countries which have similar conditions as China should keep developing HEVs before obtaining very clean electricity generation mix, rather than BEV, if they take priority on the reduction of $LCCO_2$.

Based the above results, those comparisons shown in Figure 5 to Figure 7 for countries of the UK, Norway and China are very different, while BEV's $LCCO_2$ is very dependent on power generation condition. Finally, for drawing out the picture for all the world, a comparison is as demonstrated in Figure 8. From the comparison, it can be seen that, globally BEVs have more or less higher $LCCO_2$ than those good ICEVs, based on global power generation conditions. Although this result can't negate that BEVs should be developed in some countries/regions for being beneficial to CO_2 emission reduction, most countries whose electricity productions are not so clean should postpone the promotion of BEVs, until their power generations have adequate improvement on $LCCO_2$.

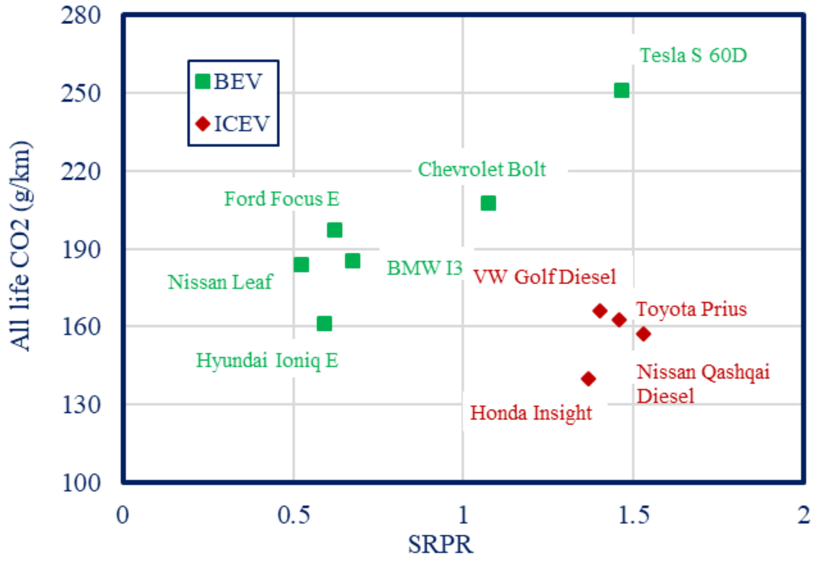


Figure 7 Comparison of $LCCO_2$ emissions between ICEV and BEV, based on the power generation condition in China

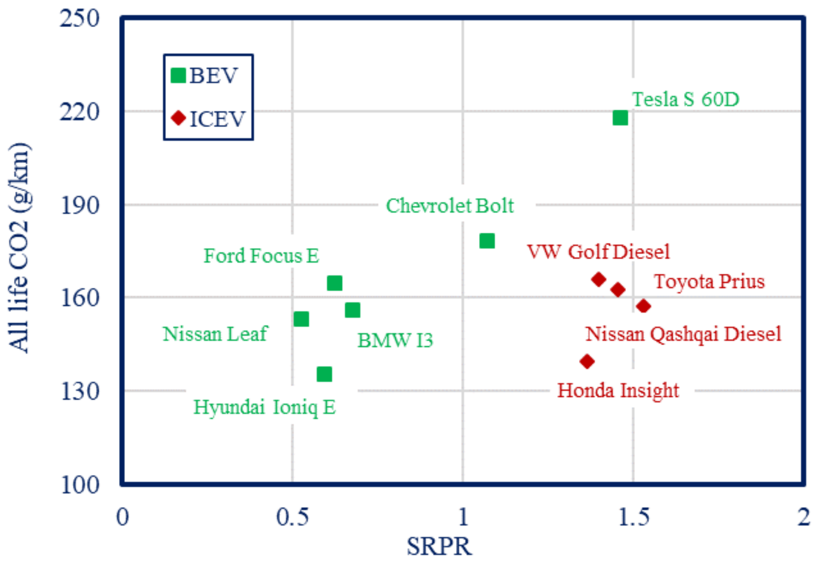


Figure 8 Comparison of $LCCO_2$ emissions between ICEV and BEV, based on the global average condition of power generation

Above results suggest that clean power generation mix must be developed as soon as possible, if BEV is promoted in the world. Although in some countries, it is beneficial for environment, in most big countries, there are still a lot of efforts needing to be made for letting BEVs to have lower $LCCO_2$ than ICEVs.

Evaluation Point for CO_2 Saving of BEV

Comparisons presented in last section demonstrates that the difference of $LCCO_2$ between BEVs and ICEVs is very dependent on $LCCO_2$ level of power generation, and also on energy consumption rates of BEVs. In a specific country, it is critical to find how low $LCCO_2$ from national power generation mix can make a BEV model to have same or lower $LCCO_2$ than some clean ICEV models. In Figure 9, it presents an initial analysis for BEVs' $LCCO_2$ emissions as function of $LCCO_2$ of power generation mix.

In Figure 9, BEV's CO_2 emissions are plotted with one line for 10 kWh/100km and another for 20 kWh/100km. From various information sources, it shows that currently most BEVs' ECR (Energy Consumption Rate) are in the range of 10 to 20 kWh/100km. If not taking into account those losses of electricity transmission and charging, and not taking into account CO_2 emissions from vehicle production, BEV's 10 kWh/100km can meet the EU's 2020 CO_2 regulation for passenger cars (95 g/km), even $LCCO_2$ from power generation mix is around 900 g/kWh. But if BEV's ECR increases to 20 kWh/100km, only $LCCO_2$ of power generation mix less than 460 g/kWh can allow those BEVs to produce less CO_2 than the EU's 2020 regulation.

In the figure, it can be found that Honda Insight can meet the EU's 2020 CO_2 regulation with obvious margin. If a BEV model with 20 kWh/100km wants to have lower $LCCO_2$ emissions than Honda Insight, it needs that the power generation mix's LCCO2 must be lower than 400 g/kWh.

It is noted that the EU 2020 CO_2 regulation for passenger cars and Honda Insight's CO_2 level as shown in Figure 9 did not include Well-to-Tank emissions and those emission during vehicle production. In Figure 10, all emissions parameters have been presented with LC (Life Cycle) values. For instance, losses of electricity transmission and charging and emissions from vehicle production have been taken into account for ICEVs and BEVs' CO_2 emissions. Those purple vertical lines represent $LCCO_2$ of power generation mix in Norway, UK and China, including those CO_2 emissions due to electricity transmission and charging. Honda Insight's emission level and the EU 2020 CO_2 regulation have been demonstrated as life cycle level in Figure 10.

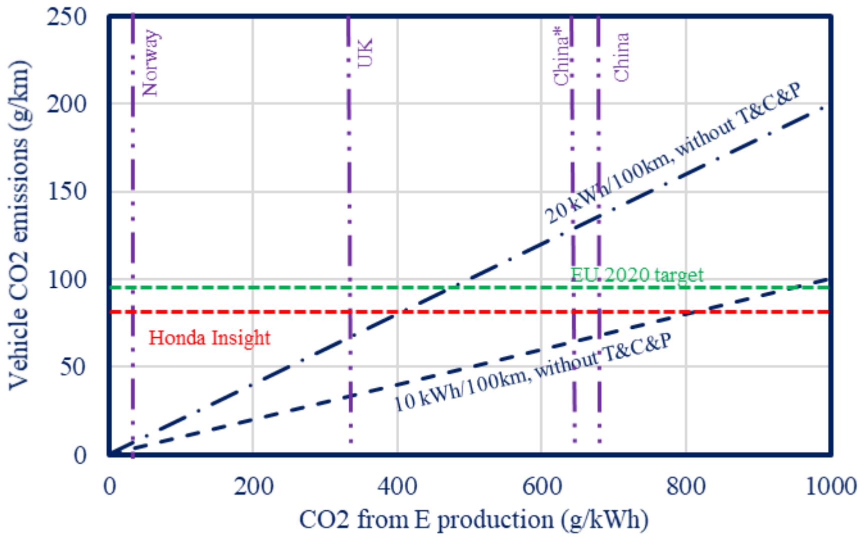


Figure 9 Critical point for saving CO_2 emissions from BEV, just considering vehicle operation (Tank-to-Wheel)
(T&C&P – electricity Transmission and electricity charging and vehicle production)

For considering life cycle condition, in Figure 10, it can be noted that, even 10 kWh/100km BEV can't meet the EU 2020 CO_2 regulation of passenger cars, if operated in China. With the power generation mix of China, BEV must be developed to have an ECR as low as 7 kWh/100km for having similar $LCCO_2$ as Honda Insight. For a BEV which has a general passenger car size or a similar size as Honda Insight, this is apparently impossible with current technology.

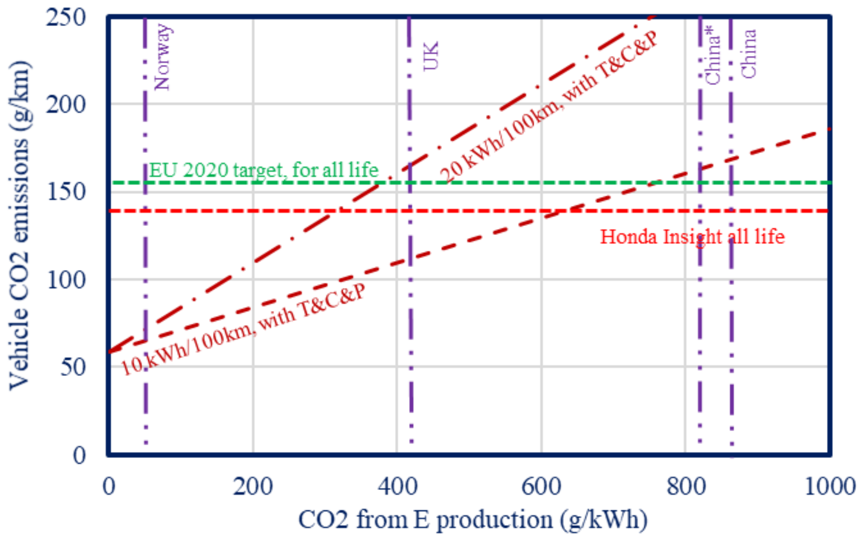


Figure 10 Critical point for saving $LCCO_2$ emissions from BEV, for consideration vehicle production and well-to-wheel

When BEVs themselves with current technology can't get too much reduction of $LCCO_2$ by reducing on-board ECR (Energy Consumption Rate), the only way is to reduce those $LCCO_2$ from power generation mix. In Figure 10, it suggests that for current BEVs with 10 to 20 kWh/100km of ECR, it needs that $LCCO_2$ of power generation mix should be at least around the level of the UK, around 320 g/kWh excluding those losses from electricity transmission and BEV charging process. At this level, most BEVs can meet the EU 2020 CO_2 regulation and those BEVs with ECR lower than 15 kWh/100km can match $LCCO_2$ level of Honda Insight.

For BEVs which have 20 kWh/100km or higher of ECR, such as Tesla S, even the power generation condition of the UK can't make it meet the EU 2020 regulation, and definitely being worse than Honda Insight in terms of $LCCO_2$. This can suggest that a country's power generation mix must achieve a $LCCO_2$ emission as low as the UK's current level (about 320 g/kWh), if they would like to operate BEVs with similar $LCCO_2$ as the cleanest ICEVs.

In accordance with the data published by IEA (International Energy Agency), apart from several small northern European countries where average CO_2 emissions from power generations are very low, most countries, in particular most big countries, have average $LCCO_2$ emissions from power generations mix are higher than that of the UK. Under this condition, at least in next 10 years BEVs have no obvious advantage over ICEVs in terms of $LCCO_2$ in most countries. At least in countryside area (where there is too much concern to vehicle emissions), it will be beneficial if continuously keeping to use those low fuel consumption ICEVs or non-plug-in HEVs.

Those countries like Norway, Switzerland etc. where average $LCCO_2$ emissions of power generation mix is under 100 g/kWh should prompt BEVs with necessary policy as soon and as more as possible. This will provide big advantages for reducing GHG emissions.

CASE STUDY – BEV EMISSIONS IN CHINA

Pollutant Emissions Relating to BEVs in China

Although BEVs have no directly pollutant emissions, their indirect contributions to CO_2 emissions and other harmful emissions can't be neglected. Donateo et al. [24] compared CO_2 emissions as well as other pollutant emissions, including CO, NOx, VOC, THC and particulates, from BEVs and ICEVs based on the analysis on the recharging habits of Italian electric vehicle drivers in Rome. An hourly electricity generation mix was used to obtain the corresponding GHG and pollutant emissions from BEVs. The study demonstrated that the seasonal and periodic variation of electricity generation mixes could have significant impacts on emissions and pollution reduction from BEVs.

In this section a case study will be carried out by focusing on BEV's CO_2 and pollutant emissions in China where there is currently the biggest automobile and BEV manufacture in the world, and it is also the biggest power generation country in the world. As shown in Figure 11, LC emissions of SOx and NOx relating to BEVs are demonstrated, based on Chinese power generation mix which has still over 70% of power generated from thermal power plants (as presented in Table 2).

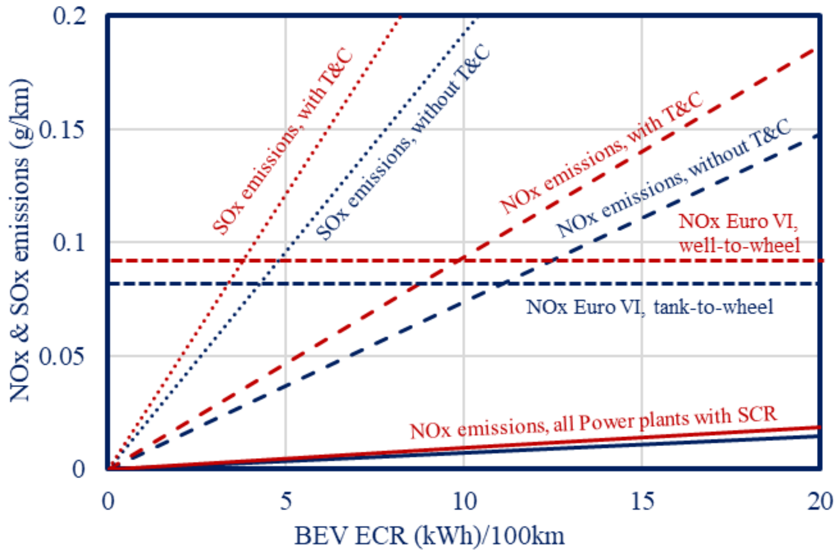


Figure 11 NOx and SOx emissions for BEVs, based on the power generation condition in China

In Figure 11, if considering thermal power plants in China without flue gas aftertreatment of NOx, such as SCR (Selective Catalyst Reduction), it needs that BEVs must have 10 kWh/100km or lower of ECR for the LC NOx emissions to meet Euro VI level (based on Well-to-Wheel value of Euro VI NOx emissions). If considering that in China 80% thermal power plant has been equipped with SCR by 2014 [58], BEVs won't have any problem for LC NOx emissions, compared to ICEVs.

BEV's LC SOx emissions have higher value than NOx emissions, as shown in Figure 11. Although current emissions regulation for vehicles have no limitation to SOx emissions, this is still a problem, in particular when coal has much higher sulphur content than vehicle fuels.

In Figure 12, indirect PM (Particulate Matters) emissions relating to BEVs have been presented. That is based on that those thermal power plants have no aftertreatment facility for removing PM. From the results, it can be seen that, compared to ICEVs, BEVs would have a big problem for indirect PM emissions if electricity was produced from non-aftertreatment thermal power generation stations.

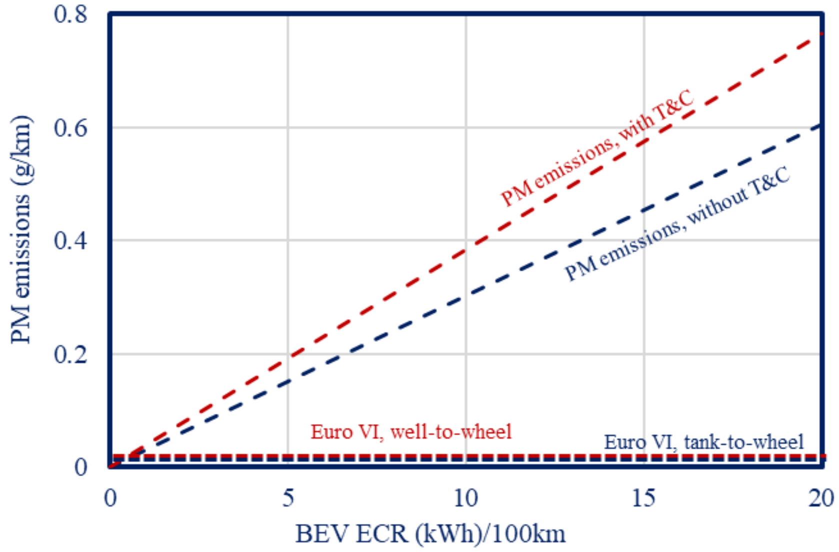


Figure 12 PM emissions for BEVs, based on the power generation condition in China

If all thermal power generation stations are equipped with latest aftertreatment systems for removing PM emissions, then the situation would have significant improvement, as shown in Figure 13. Then if a BEV can have an ECR of 15 kWh/100km or lower, its indirect LC PM emissions could meet Euro VI standard. Obviously, these two conditions of all power plants with latest aftertreatment for PM and BEV's ECR lower than 15 kWh/100km are difficult to have simultaneously. This suggests that BEVs' indirect PM emissions are still a problem at least in China, compared to those efficient ICEVs.

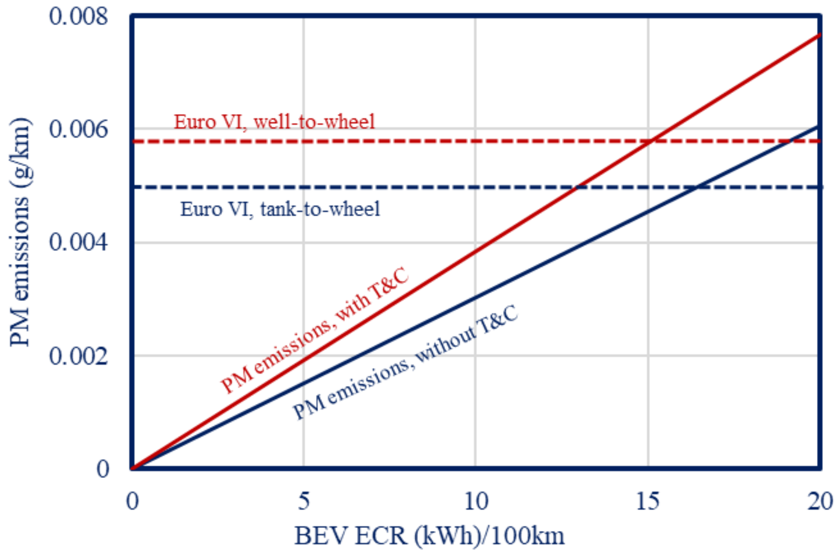


Figure 13 PM emissions for BEVs, based on the power generation condition with aftertreatment in China

From [13], it mentioned that, based on Belgium power generation condition, BEV and CNG (Compressed Natural Gas) vehicles have more or less the same total score of PM, which is the lowest among comparable vehicle technologies [13]. They also suggested that, if the power is mainly generated by coal, the LC value of PM for BEV should be much higher.

Trends of BEV and Power Generation in China

As the biggest power generation country and the biggest vehicle production country, China is taken as a case study in the following section to have more detail analysis about LCCO_2 emissions from BEVs.

Currently, China is not just the biggest ground vehicle manufacture country, but also the biggest BEV manufacture country. It is predicted that by 2045, Chinese vehicle stock will reach the maximum point, with 548 million totally, and 546 million by 2050 (45% are ICEVs) [59]. CO_2 emissions will reach the peak point by 2030 (over 70% are ICEV). Based on those data published by [59], it is estimated that by 2040, BEV development will have a trend as presented in Figure 14. Then the consumed electricity by BEVs in China will have a quick increase after 2020.

By 2050, BEVs in China will need over 1200 TWh electricity. This will take nearly 17% of Chinese all power generation in 2050, which will be over 7000 TWh, compared to 5812 TWh of 2017, as shown in Figure 15. From this view point, the quick increase of BEV stock in China won't result in very big burden for the country's power generation.

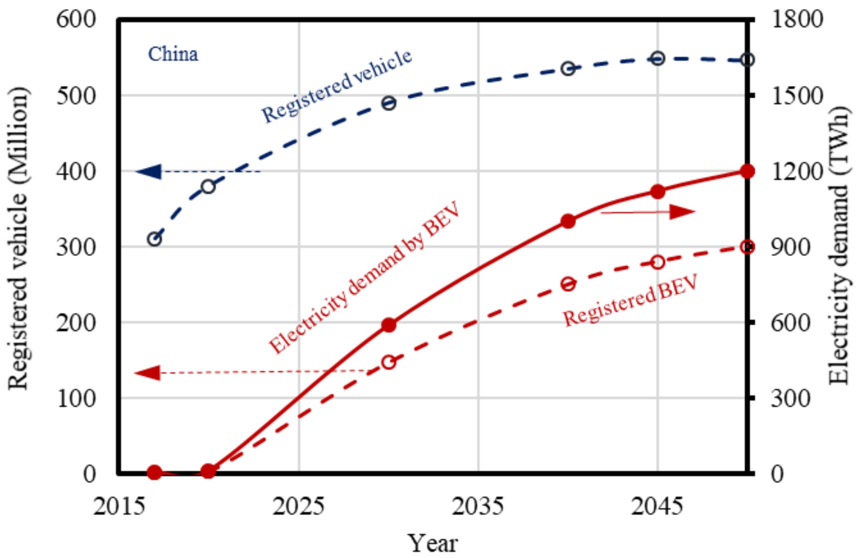


Figure 14 Prediction of BEV increase and electricity demand by BEV in China

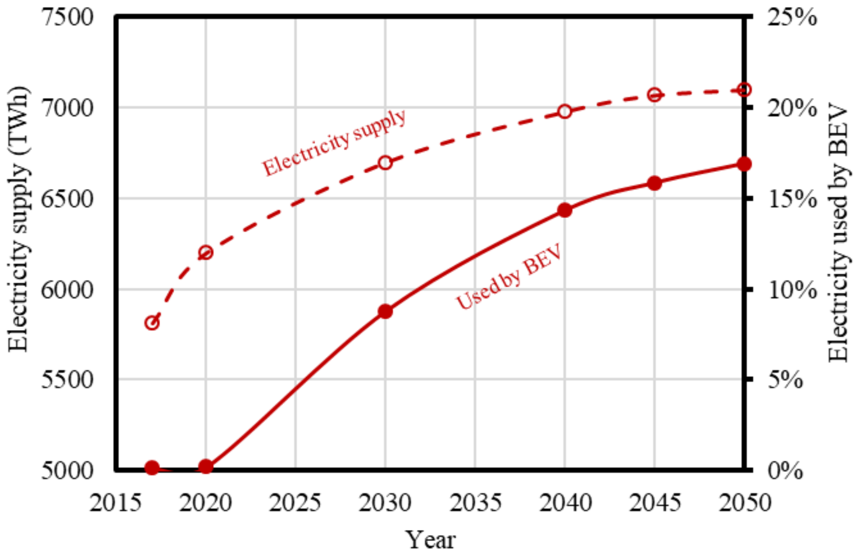


Figure 15 Prediction of total power generation increase and percentage used by BEV in China

Before 2016, thermal power generation has taken over 72% of Chinse total electricity production, in which coal thermal power generation has an absolutely dominated position. As shown in Figure 16, BP (British Petroleum) has predicted that by 2035, Chinese coal power generation will reduce to 42% [54]. Based on BP's model, $LCCO_2$ emissions from power generation mix in China will have a trend as demonstrated in Figure 17.

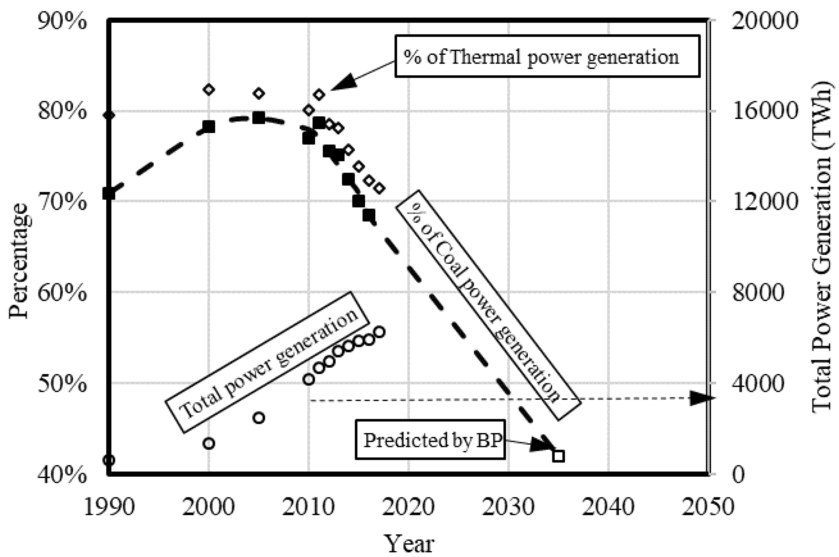


Figure 16 Required reduction of coal power generation in China

Then by 2058, Well-to-Tank CO_2 emissions of BEVs based on Chinese power generation mix could reduce to 415 g/km (including those due to losses of electricity transmission and charging to BEVs), similar as the point of the current level of the UK as shown in Table 3, or the point at which BEVs' $LCCO_2$ emissions can be similar as that of current Honda Insight. This is really not an optimistic result, when it will need about 37 years.

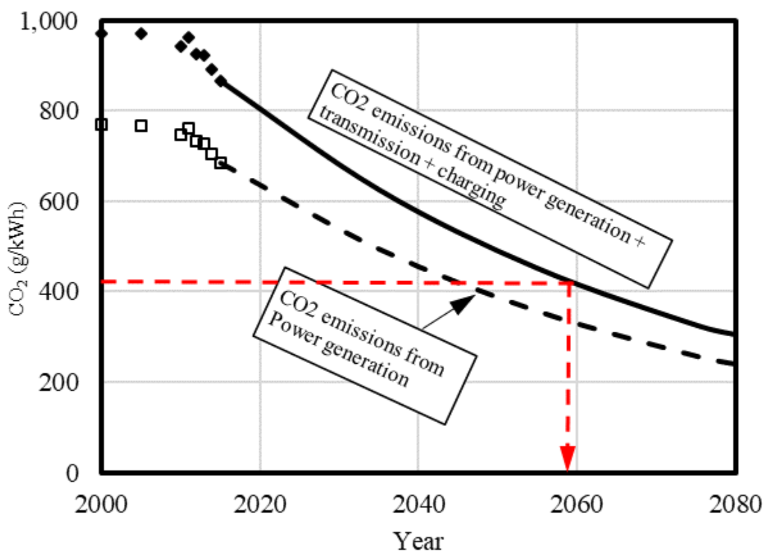


Figure 17 Prediction of CO_2 reduction of power generation in China and the point when BEV can save CO_2 emissions compared efficient ICEVs

From the above result, it suggests that the research and development on BEV technology for reducing BEV's ECR must be significantly enhanced. Meanwhile, the $LCCO_2$ emissions of power generation mix must be quickly improved. Otherwise, BEVs won't be helpful (compared to those most efficient ICEVs) for reducing LC emissions, in particular $LCCO_2$ emissions, in China and those countries which have similar LC emissions from power generation mix.

CONCLUSION

With the rapid promotion BEVs (Battery Electric Vehicles) and possible ICExit (Internal Combustion Engine vehicle Exit) from new passenger car markets in next ten to twenty years, Life Cycle (LC) emissions, in particular $LCCO_2$ emissions, of BEVs have been assessed and compared with those most efficient ICEVs including non-plug-in HEV (Hybrid Electric Vehicles) and diesel cars. Based on those results, the following conclusions have been obtained.

- By analysing several typical countries (including Norway, UK, US, China and India) for their power generation mix, it is found that $LCCO_2$ emissions of power generation mix are very different in different country. Those countries which have more thermal power generation, in particular coal power generation, have very high $LCCO_2$ emissions.

- By considering CO_2 emissions from vehicle production, maintenance and vehicle recycle, Well-to-Tank and Tank-to-Wheel operations, $LCCO_2$ emission models of BEVs and ICEVs were built. Energy losses from electricity transmission and vehicle electric charging have been included in the models for BEVs.
- For comparing between BEVs and ICEVs in terms of their LC emissions, a new measure named SRPR (Square Root of Power and Range) has been proposed for correctly reflecting the powertrain's main performances of both BEVs and ICEVs.
- By comparing current BEVs and efficient ICEVs (non-plug-in HEVs and diesel cars), it is found that, although BEVs have much lower on-board ECR (Energy Consumption Rate) than non-plug-in HEV and diesel cars, their $LCCO_2$ emissions are very variable, and are very dependent on $LCCO_2$ emissions of power generation mix of specific country.
- In those countries which have very clean electricity production, such as Norway, their BEVs' $LCCO_2$ emissions are much lower than ICEVs. But in those countries where thermal power generation, in particular coal power generation, is still dominant, BEVs' $LCCO_2$ are much higher than efficient ICEVs.
- If a country would like their BEVs producing lower $LCCO_2$ than ICEVs, $LCCO_2$ from their power generation mix should be at least about 320 g/kWh, similar level as that of the UK.
- BEVs' other LC pollutant emissions, such as NOx, PM, SOx would not be a very serious problem if those thermal power generations are equipped with adequate aftertreatment for removing those pollutant emissions.
- By analysing the power generation development trend and the BEV development trend in China, it suggests that the aim would be very difficult to meet for letting BEVs having lower $LCCO_2$ than ICEVs in next two or three decades. If they would like to use BEV totally replace ICEVs by 2040, a lot of works are necessary for reducing BEV's ECR and for reducing $LCCO_2$ of their power generation mix. If they like to put priority for developing passenger cars on the reduction of $LCCO_2$, they should keep developing HEVs, rather than BEVs, under current power generation conditions.

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NOMENCLATURE

$E_{charging\text{-}losses}$	energy loss rate via charging
$E_{transmission\text{-}losses}$	energy loss rate via transmission
$f_{E\text{-}generation}$	$LCCO_2$ rate from electricity generation
$f_{life\text{-}cycle}$	$LCCO_2$ rate
$f_{V\text{-}production}$	CO_2 rate from vehicle production
$f_{V\text{-}recycle}$	CO_2 rate from vehicle recycle
$\eta_{charging}$	vehicle electric charging efficiency
$\eta_{transmission}$	electricity transmission efficiency
η_{TtW}	Tank-to-Wheel efficiency
η_{WtT}	Well-to-Tank efficiency
η_{WtW}	Well-to-Wheel efficiency

BEV	battery electric vehicle
CO	carbon monoxide
CO_2	carbon dioxide
CVT	continuously variable transmission
ECR	energy consumption rate
EPA	Environmental Protection Agency
EU	European Union
GHG	greenhouse gas
GWP	global warming potential
HEV	hybrid electric vehicle
ICEV	internal combustion engine vehicle
ICExit	internal combustion engine exit
IEA	International Energy Agency

ISO	International Organization for Standardization
LC	life cycle
LCA	LCassessment/analysis
LCAM	LCassessment method
LCC	LCcost
LCCO2	LCCO2
NOx	nitrogen oxides
PHEV	plug-in hybrid electric vehicle
PM	particulate matters
SRPR	square root of power and range
SOx	sulphur oxides
THC	total hydrocarbon
UK	United Kingdom
US	United States
V2G	vehicle to grid
VOC	volatile organic compound