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Estimation of CO_2 Emissions of Internal Combustion Engine Vehicle and Battery Electric Vehicle Using LCA

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Abstract: In order to reduce vehicle emitted greenhouse gases (GHGs) on a global scale, the scope of consideration should be expanded to include the manufacturing, fuel extraction, refinement, power generation, and end-of-life phases of a vehicle, in addition to the actual operational phase. In this paper, the CO_2 emissions of conventional gasoline and diesel internal combustion engine vehicles (ICV) were compared with mainstream alternative powertrain technologies, namely battery electric vehicles (BEV), using life-cycle assessment (LCA). In most of the current studies, CO_2 emissions were calculated assuming that the region where the vehicles were used, the lifetime driving distance in that region and the CO_2 emission from the battery production were fixed. However, in this paper, the life cycle CO_2 emissions in each region were calculated taking into consideration the vehicle's lifetime driving distance in each region and the deviations in CO_2 emissions for battery production. For this paper, the US, European Union (EU), Japan, China, and Australia were selected as the reference regions for vehicle operation. The calculated results showed that CO_2 emission from the assembly of BEV was larger than that of ICV due to the added CO_2 emissions from battery production. However, in regions where renewable energy sources and low CO_2 emitting forms of electric power generation are widely used, as vehicle lifetime driving distance increase, the total operating CO_2 emissions of BEV become less than that of ICV. But for BEV, the CO_2 emissions for replacing the battery with a new one should be added when the lifetime driving distance is over 160,000 km. Moreover, it was shown that the life cycle CO_2 emission of ICV was apt to be smaller than that of BEV when the CO_2 emissions for battery production were very large.

Keywords: battery electric vehicle; carbon dioxide; internal combustion engine vehicle; life-cycle assessment; passenger car

1. Introduction

In response to the awareness of human induced climate change in the past decades, the international policy agenda has been driven toward greenhouse gas (GHG) reduction. The transport sector, especially land based passenger transport constitutes the fastest growing source of all GHG emissions. It is recognized as a primary sector [1]. Despite the growing importance of CO_2 regulation in the passenger transport sector, the focal point of current regulations is limited only to a vehicle's operational phase, i.e., tank-to-wheel tailpipe emissions. There is currently no regulatory consideration for the other phases of a vehicle's life cycle.

A prospective unbiased measure to evaluate GHG emissions during a vehicle's life can be a life-cycle assessment (LCA). This considers the CO_2 emissions of vehicles during its operational phase as well as the emissions generated from the fuel extraction, refining, power generation, and its end-of-life phases. LCA studies have gained more attention in recent years as a more holistic view of powertrain solutions for passenger transport with the goal of reducing CO_2 emissions.

Previous LCA studies for conventional internal combustion engine vehicles (ICV) [2–6] and advanced powertrain namely; battery electric vehicles (BEV) [2–6], hybrid electric vehicles (HEV) [3,6] and plug-in hybrid electric vehicles (plug-in HEV) [3,6] already exist. In these studies, the CO_2 emissions were calculated assuming that the region, the lifetime driving distance, and the CO_2 emission from the battery production were fixed at certain conditions which are summarized in Table 1. However, it is commonly understood that the power generation mix for BEV and plug-in HEV, and a vehicle's lifetime driving distance, vary by region. Also, LCA could be affected by the difference of fuel and electricity consumption of vehicles by region due to the difference of the driving conditions, such as vehicle speed ranges, loading weights, etc. It is noteworthy that Delogu et al. [7] conducted LCA of a diesel car considering some kinds of fuel consumption test cycle. The fact that the CO_2 emission from the battery production differs depending on the reference source cannot be overlooked [8–11]. Therefore, it is necessary to analyze the effects of those variations holistically.

This study focused on CO_2 inventory analysis as a preliminary step for future life cycle impact assessment (LCIA) study. Therefore, in this paper, the life cycle CO_2 emissions of gasoline and diesel ICV (GE, DE), and BEV were calculated. The US, European Union (EU), Japan, China, and Australia were selected as the regions of vehicle usage, and the fuel efficiency, the electric efficiency, the CO_2 emission factor of electric power generation and the CO_2 emission for battery production in each region were applied. Also, the effects of variations in driving distance and the CO_2 emission from battery production on the total life cycle CO_2 emissions was evaluated.

Table 1. Assumptions of previous life-cycle assessment (LCA) studies for internal combustion engine vehicle and advanced powertrain vehicle.

Reference	Studied Region	Studied Vehicles	Lifetime Driving Distance [km]	Estimation of Battery Production	Fuel Efficiency/Electric Efficiency	CO_2 Emission Factor of Electricity [kg-CO_2/kWh]	Study Results
Ellingsen et al. [2]	Europe	ICV *1 and BEV *2 from A (mini size) to F (luxury size) segment *3	180,000	Referring to own earlier study [8]	ICV: average of actual ICVs (NEDC) *4 BEV: estimating from the relationship between electric efficiency and weight of actual BEVs	0.521 (European average mix [12])	—The life cycle Climate Change Potential of the F segment BEV was 1.7 times higher than that of the A segment BEV. —The CO_2 emissions in the use phase of BEVs became lower when its electricity was coming from energy source of lower CO_2 emission factor such as renewables.
Mayyas et al. [3]	US	ICV (GE *5, HEV *6, plug-in HEV) and BEV with lightweight technologies	320,000	Referring to some other studies (120 kg-CO_2- /kWh)	Estimation from running resistances and energy for driving force, assuming US driving cycle (55 % FTP-75 *7 and 45 % HFET *8)	0.8515 (US average mix)	—The life cycle CO_2 emissions of BEV and plug-in HEV were region dependent due to regional source of power generation. In the case of the US, HEV showed lower CO_2 emissions than BEV and plug-in HEV.
Messagie [4]	European average and each country	ICV, BEV	200,000	Referring to Peters et al. [13] (55 kg-CO_2- /kWh for LMO battery*2*9)	ICV: European fleet average, augmented by 35% to reflect real driving conditions based on Fontaras et al. [14] BEV: Real driving efficiency based on De Cauwer et al. [15] (average of BEVs from A to C-segments)	0.300 (European average mix [16])	—BEVs showed significant lower CO_2 emissions, compared to ICV in most European countries.
Ou et al. [5]	China	ICV (GE, DE *10, Natural gas), BEV	240,000	Referring to GREET 2.8 [17] (30 kg-CO_2- /kWh)	Referring to some other studies, e.g., 6 L/100 km for GE [18]	0.539 (by natural gas single cycle) 0.485 (by natural gas combined cycle)	—BEV reduces life cycle greenhouse gas emissions by 36%–47% compared to GE.
Sharma et al. [6]	Australia	ICV (GE, HEV, plug-in HEV) and BEV	150,000	Estimation by referring to some other studies	Australian Urban Drive Cycle (AUDC)	1.04 (Australian average mix).	—Regarding larger size vehicles, BEV shows lower greenhouse gas emissions than GE, but higher than HEV and plug-in HEV.

*1 ICV: Internal combustion engine vehicle; *2 BEV: Battery electric vehicle; *3 The size segment has been defined by the European Commission [19]; *4 NEDC (New European Driving Cycle): the fuel efficiency test cycle in Europe; *5 GE: Gasoline engine vehicle; *6 HEV: Hybrid electric vehicle; *7 FTP-75: the fuel efficiency test cycle for city driving in the US; *8 HFET: the fuel efficiency test cycle for highway driving in the US; *9 LMO: Lithium manganese oxide; *10 DE: Diesel engine vehicle.

2. Scope of this Study

2.1. Regions for This Study

The US, EU (the average of member countries), Japan, China, and Australia were selected as the regions for this study considering variations in energy situations (e.g., electricity generation mix, petroleum refinery efficiency) and vehicle driving conditions.

2.2. Vehicles Assessed in This Study

In order to analyze the effect of regional vehicle's lifetime and the CO_2 emissions from battery production, the vehicle type for this study was unified to the compact class (also known as "C-segment" in Europe [19]) for both ICV (GE, DE) and BEV, which had the highest production volumes in the world. Specifications of the vehicles listed in Table 2 were referenced by the publicized information on existing vehicles sold in each region as of April 2018; whereby, fuel efficiency and electric efficiency data were officially provided by the automotive manufacturers. The difference in the fuel efficiency of the same vehicle by region could be caused by different driving conditions, as represented by vehicle speed ranges, loading weights, etc. In order to calculate the CO_2 emissions of BEV in five regions, the electric efficiency of the BEV in the EU was substituted for China and Australia because the selected model in this paper was not actually sold in these regions and their test cycles for energy efficiency were similar to those of the EU [20]. On the other hand, the CO_2 emissions of the selected DE were calculated only for the EU and Japan where they were sold. In Table 2, the fuel and electricity efficiency value in Europe and Japan are based on the NEDC and the JC08 test cycle respectively. Currently, these test cycles are both switched to the WLTC (Worldwide Light-duty vehicle Test Cycle) which reflects real driving conditions more precisely [21], but the data of NEDC and JC08 were used in this study due to limited availability of WLTC data in the market.

Table 2. Specifications of assessed vehicles.

Vehicle		Gasoline Engine Vehicle (GE)	Diesel Engine Vehicle (DE)	Battery Electric Vehicle (BEV)
Weight [kg]		1310	1360	1590
Displacement [cc]		1998	1498	-
Battery capacity [kWh]		-	-	35.8
Output [kW]		88–114	77	100
Torque [Nm]		196	270	290
Fuel / Electric efficiency*1	US (5cycle)	13.2 km/L	-	5.75 km/kWh
	Europe (NEDC)	19.6 km/L	26.3 km/L	7.87 km/kWh
	Japan (JC08)	19.0 km/L	21.6 km/L	8.06 km/kWh
	China (NEDC)	16.1 km/L	-	7.87 km/kWh
	Australia (NEDC)	17.2 km/L	-	7.87 km/kWh

*1: Test cycle in each region is noted in brackets; Note: these specifications were set by reference to Mazda 3 (also known as Axela in some regions) and Volkswagen e-Golf sold in each region as of April 2018.

2.3. Lifetime

The LCA study for automobiles requires the lifetime driving distance of the vehicles as the functional unit. The lifetime driving distances were cited in the LCA literature for ICVs and/or BEVs such as 150,000 km [22], 160,000 km [23], 180,000 km [2] and 200,000 km [4,24] for the EU, 193,120 km [10] and 320,000 km [2] for the US, and 100,000 km [25] and 110,000 km [26] for Japan.

In this study the lifetime driving distance was defined as a variable from 0 km to 200,000 km in the five regions referring to the above literature.

2.4. The Scope of the Assessment

The entire life cycle of vehicles was considered as the scope of this study. The amounts of CO_2 emissions were calculated from phases 1 to 5.

Phase 1 Vehicle production: raw material extraction, material production, vehicle component production and vehicle assembly.

Phase 2 Fuel production/electric power generation: production of fuel for ICVs, generation of electric power for BEVs.

Phase 3 Vehicle usage: fuel combustion in driving ICVs

Phase 4 Maintenance: production of replacement parts

Phase 5 End-of-life (EOL): disposal of the vehicles once its useful life has expired.

The scope of this study excluded disposal and recycling of waste materials in the vehicle production phase, recycling of parts removed from the vehicle in the maintenance phase and recycling of the disassembled powertrain parts from the vehicles in the EOL phase. The scope of this assessment is shown as Figure 1.

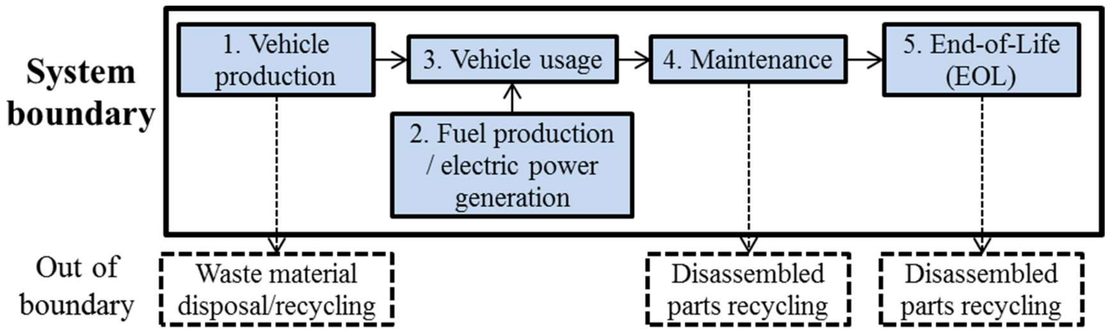

Figure 1. Scope of this study.

3. The Calculation at Each Phase of the Life Cycle

3.1. Vehicle Production Phase

The amounts of CO_2 emissions for the production phase were calculated by splitting them into four items such as (1) chassis, (2) engine and transmission for GE and DE, (3) inverter and motor for BEV, (4) battery for BEV as follows. In this study, the CO_2 emission for the production phase was regarded as the same for all regions.

(1) Chassis parts (body, tires, interiors, etc.) of the GE, DE and BEV were assumed to be identical. The amounts of CO_2 emissions of the chassis parts production in this study were calculated based on database of the Life-Cycle Assessment Society of Japan (JLCA) [27]. According to the database, CO_2 inventory from material extraction to manufacturing of small passenger gasoline engine vehicle, whose vehicle size is similar to that in this study, was 5494 kg-CO_2 and chassis parts account for 76.8% of total vehicle weight. To supplement this, material extraction to vehicle manufacturing was also modeled and the CO_2 inventory was calculated based on database JLCA [27]. For the purposes of this study, CO_2 emissions for production of chassis parts is assumed to be proportionate to their weight as a fraction of the total vehicle weight. Therefore, CO_2 emissions for the production of chassis parts is assumed to be 4219 kg-CO_2 (= 5494 kg-CO_2 × 0.768) in this study.

(2) The amount of CO_2 emissions from the gasoline engine and transmission production was also calculated based on JLCA [27] and assumed to be 1274 kg-CO_2 (= 5494 kg-CO_2–4219 kg-CO_2). As the amount of CO_2 emissions from the diesel engine and transmission production was not described in JLCA [27], it was estimated based on the weight difference of 50 kg (= 1360 kg–1310 kg) between GE and DE shown in Table 2 and the weight of the gasoline engine and transmission of 241 kg cited from JLCA [27]. As a result, the amount of CO_2 emissions from the diesel engine and transmission production was estimated to be 1,539kg-CO_2 (= 1274 kg-CO_2 × (241 kg + 50 kg)/241 kg).

(3) The amount of CO_2 emissions of the motor and inverter production for the BEV was estimated to be 1070 kg-CO_2 and 641 kg-CO_2 cited from Hawkins et al. [28] where the material compositions and the CO_2 emission factor were quoted from the literature and the CO_2 emissions of production of these

parts were calculated considering each production process. Although their results were calculated with CO_2 equivalent values (kgCO_2-eq), these values were regarded as CO_2 values in this study.

(4) The CO_2 emission factor represents the amount of CO_2 emissions per unit battery capacity, which was estimated based on various works in the literature [8–11]. The criteria for selecting the literature included the following three items: (1) The boundary encompassed raw material extraction through to production of a battery system (or battery pack, which was ready to be assembled to vehicles); (2) Each detailed process of battery production was considered (e.g., cathode production, cell assembly, pack assembly); (3) The lithium-ion battery included either mainstream cathode described as lithium nickel-manganese-cobalt oxide (NMC) cathode or lithium iron phosphate (LFP) cathode types. The results of the CO_2 emission factor of battery production are shown in Table 3. The average of the values in the literature was 177 kg-CO_2-eq/kWh with the lowest value (121 kg-CO_2-eq /kWh) and the highest value (250 kg-CO_2-eq /kWh). The summary of the CO_2 emissions of the vehicle production phase is shown in Table 4. These values were regarded as CO_2 values in this study.

Table 3. Review results of works of literature about LCA for battery production.

Literature	Cathode Type*1	CO_2 Emission Factor [kg-CO_2eq/kWh]
Zackrisson et al. [8]	LFP	166
Majeau-Bettez et al. [9]	NMC	200
	LFP	250
Amarakoon et al. [10]	NMC	121
	LFP	151
Ellingsen et al. [11]	NMC	172
Average		177

*1 NMC: Lithium nickel-manganese-cobalt oxide; LFP: Lithium iron phosphate.

Table 4. The amount of CO_2 emissions of vehicle production phase.

Part Name		Reference	Referenced Data of CO_2 Emission [kg-CO_2]	Apply to
Chassis parts (Body, tires, interior, etc.)		JLCA [27]	4219 (76.8 % of overall production)	GE, DE, BEV
Gasoline engine and transmission		JLCA [27]	1274 (23.2 % of overall production)	GE
Diesel engine and transmission		JLCA [27] modified	1539 (20.8% higher than the gasoline engine)	DE
Electric drive unit parts (Elec. parts)	Li-ion battery	CO_2 factor: Average of Table 3 Capacity: Table 2	6337 (177 kg-CO_2/kWh × 35.8 kWh)	BEV
	Motor	Hawkins et al. [28]	1070	BEV
	Inverter	Hawkins et al. [28]	641	BEV

As they were already mentioned above, the chassis parts production and the engine parts production were calculated as CO_2 inventory but the motor, inverter and lithium-ion batteries were calculated as greenhouse gas inventory (CO_2-eq). In terms of the production of the motor, inverter and lithium-ion batteries, the electricity generation for manufacturing is the main source of the greenhouse gas emissions. According to the LCA database "GaBi" [29], from the electricity generation, the greenhouse gases other than CO_2 (e.g., CH_4, N_2O) are contained only around 5 %. So CO_2-eq values were regarded as CO_2 values in this study.

3.2. Fuel Production, Fuel Combustion and Electric Power Generation Phase

In this study, the CO_2 emissions of gasoline and diesel fuel production, combustion of these fuels and electric power generation which were required to drive GE, DE and BEV, were calculated as follows.

(1) The CO_2 emission factors of the fuel production in each region were cited from the LCA database ″GaBi″ [29] ; data was referenced from 2013. Each system boundary for gasoline and diesel fuel is from resource extraction up to service stations. The emission factors of the fuels in "GaBi" [29] are specified with the amount of CO_2 emissions by 1 kg fuel [kg-CO_2/kg], therefore, the density values of fuel (gasoline: 0.727 kg/L, diesel: 0.828 kg/L) [30] were used to convert [kg-CO_2/L] into [kg-CO_2/kg].

(2) The CO_2 emission factors of gasoline and diesel fuel combustion were cited [30] which were 2.28 kg-CO_2/L for gasoline and 2.62 kg-CO_2/L for diesel respectively and they were used in all five regions covered by the study. For both gasoline and diesel fuels, the CO_2 emission factors of fuel combustion [30] are 5 to 8 times greater than those of fuel production [29] which varies from region to region.

(3) The CO_2 emission factors of the electric power generation in each region were cited from ″GaBi″ [29] ; data was referenced from 2013. The system boundary for the electric power generation is from energy resource extraction to transformation of electric energy to low voltage as the grid mix.

Based on the above results, the amount of CO_2 emissions in the phase of fuel production and combustion for ICV (GE and DE) was obtained by the equation below:

$$CO_{2,ICV(FP,\ FC)} = (CF_{FP} + CF_{FC})/E_{ICV} \cdot LD \quad (1)$$

where;

$CO_{2,\ ICV\ (FP,\ FC)}$ = the amount of CO_2 emissions in the phase of fuel production and combustion [kg-CO_2],
CF_{FP} = CO_2 emission factor of fuel production [kg-CO_2/L],
CF_{FC} = CO_2 emission factor of fuel combustion [kg-CO_2/L],
E_{ICV} = fuel efficiency of ICV [km/L],
LD = lifetime driving distance [km].

The amount of CO_2 emissions in the phase of electric power generation for BEV was obtained with the following equation:

$$CO_{2,BEV(EG)} = CF_{EG}/E_{BEV} \cdot LD \quad (2)$$

where;

$CO_{2,\ BEV\ (EG)}$ = the amount of CO_2 emissions in the phase of electric power generation [kg-CO_2],
CF_{EG} = CO_2 emission factor of electric power generation [kg-CO_2/kWh],
E_{BEV} = Electric efficiency of BEV [km/kWh].

3.3. Maintenance Phase

In order to maintain vehicles, some parts need to be replaced at certain intervals. In this study, CO_2 emissions from production of parts for maintenance were assessed considering maintenance intervals as shown in Table 5. The interval for a lithium-ion battery was cited from the warranty distances for a lithium-ion battery of BEVs in the US [31–33] in which similar distances were shown in the EU and Japan. Maintenance intervals for other parts and the amount of CO_2 emissions for their production were cited from the JLCA [27].

Table 5. Assumptions for the maintenance phase.

Part Name	Maintenance Interval [km/Maintenance]	CO_2 Emission [kg-CO_2/Maintenance]	Reference	Applied Vehicles
Tire	40,000	108	JLCA [27]	GE, DE, BEV
Lead-acid battery	50,000	19.5	JLCA [27]	GE, DE, BEV
Engine oil	10,000	3.22	JLCA [27]	GE, DE
Radiator coolant	27,000	7.03	JLCA [27]	GE, DE
Li-ion battery	160,000	6337	Table 4	BEV

3.4. End-of-Life (EOL) Phase

The amount of CO_2 emissions in the phase of a vehicle's end-of-life (EOL) for GE were estimated; referenced from [34] whereby, the EOL treatment consisted of four processes; "Disassembly", "Shredding and sorting vehicles", "Transportation (trucking) of the shredder residue" and "Landfilling of shredder residue". The target parts were body parts, interior parts and exterior parts for the GE. The same boundary used in this literature was applied to DE and BEV in this study. As a result, the amount of CO_2 emissions in the EOL phase was the same for GE, DE and BEV which is shown in Table 6.

Table 6. CO_2 emissions from end-of-life (EOL) treatment (GE, DE and BEV).

Process Name	CO_2 Emission [kg-CO_2]
Disassembly *	-
Shredding and sorting	24
Transport	4
Landfilling	38
Total	65

*: Energy consumption in disassembly is relatively lower than the other treatment [34].

4. Results

4.1. Effects of Lifetime Driving Distance

The calculation results of total life cycle CO_2 emissions for five regions are shown in Figure 2, e.g., (a) EU, (b) Japan, (c) US, (d) China and (e) Australia. The amounts of CO_2 emissions of GE, DE and BEV were calculated in the EU and Japan, while those for GE and BEV were calculated in the US, China, and Australia. For these assessments, the averaged value of the CO_2 emission factor of the battery production of BEV (177 kg-CO_2/kWh) was used as shown in Table 3. In each figure, the point at which lines of GE or DE and BEV intersect each other indicates the driving distance which was defined as "Distance of Intersection Point (DIP)" in this study.

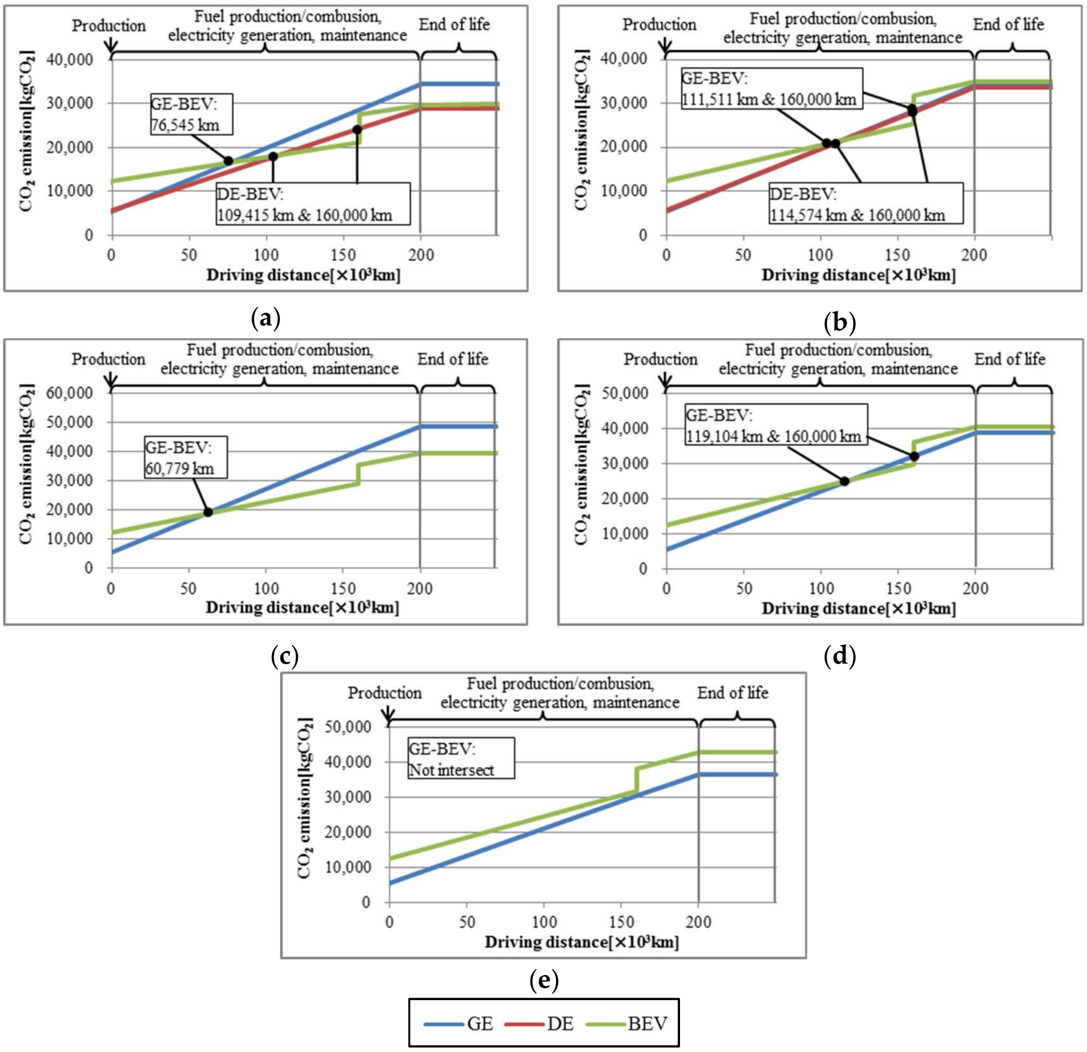

Figure 2. CO_2 emissions during life cycle for GE, DE and BEV. (**a**) European Union (EU); (**b**) Japan; (**c**) US; (**d**) China; (**e**) Australia.

The first observation from the results is that vehicles which exhibit lower CO_2 emissions, i.e., ICVs or BEVs, were dependent on the driving distance. For example, as shown in Figure 2c for the US, GE indicated lower CO_2 emissions than BEV when the driving distance was less than 60,779 km due to the high CO_2 emissions associated with battery production for BEVs, while BEV indicated lower CO_2 emissions when the driving distance was over 60,779 km.

Also, in this study, the battery of a BEV was assumed to be replaced once at 160,000 km. For example, in Figure 2a for EU, the amount of CO_2 emission of DE was lower than BEV when the driving distance was less than 109,415 km (DIP) and more than 160,000 km (battery replacement mileage). One exception was seen in Figure 2e for Australia, where ICV (GE) consistently indicated lower CO_2 emissions than BEV at any driving distance up to 200,000 km.

These results summarized that the longer the vehicle was driven during the vehicle's lifetime distance, the more the BEVs benefited from CO_2 reduction compared to ICV (Australia is only one exception to this point). It was also worth mentioning that the amount of the CO_2 emissions of battery replacement of BEV could alter the amount CO_2 emissions of ICV to become lower than those of BEV. About the end-of-life emissions, it is hard to identify them in Figure 2 because they were very small relative to the emissions of the other phases.

4.2. Regional Difference of the CO_2 Emissions between Internal Combustion Engine Vehicles (ICV) and Battery Electric Vehicles (BEV)

The results shown in Figure 2 indicate that DIP varied by region. For example, for DIPs between GE and BEV, the U.S was the shortest followed by the EU, Japan, and China. Australia had no DIP. In the case of DE and BEV, the DIP in EU was by around 5,000 km less than that of Japan.

The DIP variation in each region was caused by the differences in the set of assumptions that were used in the calculation assumptions. The details will be discussed in Section 5.

4.3. Effects of the CO_2 Emission Factor of Battery Production

Figure 3 represents how the life-cycle CO_2 emissions of BEV could alter at the driving distance of 100,000 km in Japan when the CO_2 emission factor of the battery production deviates from the lowest value (121 kg-CO_2/kWh) to the highest value (250 kg-CO_2/kWh) as shown in Table 3 (emissions data for GE is included as a reference). The amount of total life-cycle CO_2 emissions from BEV varies drastically depending on the CO_2 emission factor of battery production. The lowest emission factor of the battery production showed lower CO_2 emissions of BEV than those of GE but the highest factor brought the opposite result.

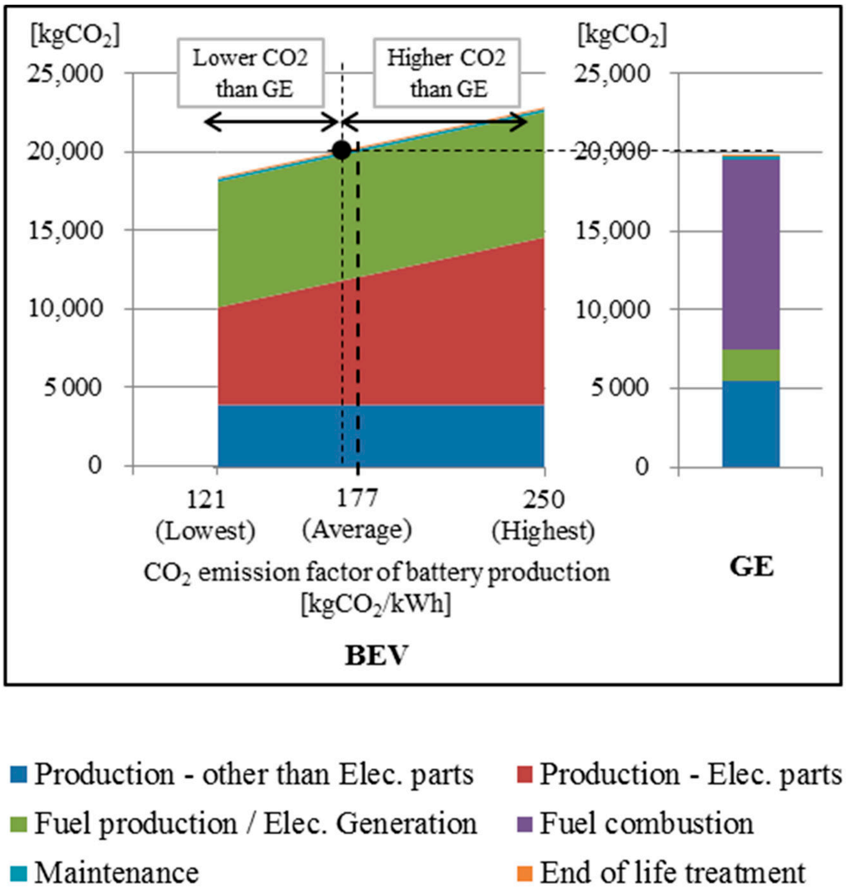

Figure 3. CO_2 emissions of battery electric vehicles (BEV) compared to GE with different CO_2 emission factor of the battery production (Japan, lifetime driving distance 100,000 km).

5. Discussion

5.1. Concern for the Setting of the Lifetime Driving Distance

As noted in Section 4.1, driving distance significantly affects the results of the lifecycle CO_2 of ICV compared to BEV to the degree in which the conclusion may be reversed. Therefore, it is essential to use driving distances referenced from the averaged values of statistical data published, for instance, through governments and research institutes in order to properly assess which vehicle powertrain technology demonstrates lower CO_2 emissions in the region, ICV or BEV.

5.2. Source of the Regional Differences of the CO_2 Emissions between ICV and BEV

Table 7 illustrates the DIP between ICV (GE and DE) and BEV, the fuel efficiency for ICV and electric efficiency for BEV, and the relative emission factor of electric power generation in each area. As mentioned in Section 3.2, as the CO_2 emission factor of fuel production accounts for a small portion of the amount of the CO_2 emissions compared to combustion of fuel. Therefore, it was excluded in Table 7.

Table 7. DIP (distance of intersection point, where the CO_2 emissions from GE or DE and BEV are the same), fuel efficiency, electric efficiency and CO_2 emission factor of electric generation (relative value) in each area. **(a)** DIP for GE and BEV; **(b)** DIP for DE and BEV.

(a)

Area	DIP [km]	Fuel and Electric Efficiency		Relative Value of CO_2 Factor * for Electricity
		GE [km/L]	BEV [km/kWh]	
US	60,779	13.2	5.75	100
Europe (EU28)	76,545	19.6	7.87	72
Japan	111,511	19.0	8.06	110
China	119,104	16.1	7.87	144
Australia	not intersect	17.2	7.87	160

(b)

Area	DIP [km]	Fuel and Electric Efficiency		Relative Value of CO_2 Factor * for Electricity
		DE [km/L]	BEV [km/kWh]	
Europe (EU28)	109,415	26.3	7.87	72
Japan	114,574	21.6	8.06	110

* relative to the value of the US = 100.

Figure 2 shows that BEV has a higher amount of CO_2 emissions than ICV in all regions in the production phase (i.e., the driving distance of 0 km). Then the DIP is determined by the difference in the increased rate of the CO_2 emissions during the driving sequences of ICV and BEV, which is the gradient of CO_2 emission in Figure 2. More specifically, the DIP is shortened with a higher increase rate of CO_2: (fuel efficiency value × [the CO_2 emission factor of fuel production + the CO_2 emission factor of fuel combustion]) for ICVs, and lower increase rate of CO_2: (electric efficiency × the CO_2 emission factor of electric power generation) for BEV. Additionally, another tendency found in Table 7 summarizes the effect of diminishing CO_2 emission factor during electric power generation. It can be implied that the DIPs of GE and BEV become shorter in the four regions except for the US, which suggests that BEV shows a lower amount of CO_2 emissions than GE as the CO_2 emission factor of electric power generation decreases. Since the CO_2 emission factor of electric power generation differs significantly by region—the factor in Australia, for example, is more than twice that of EU—it is a dominant factor in the difference between DIPs by region. As described in Table 7 (b), the DIP between DE and BEV in EU was shorter than that in Japan due to the CO_2 emission factor of the electric power generation in EU being less than that in Japan.

On the other hand, although the CO_2 emission factor of electric power generation in the US was larger than that in the EU, the DIP of the US was shorter than that of the EU. Such causes are attributed by the reason that the fuel efficiency of ICV (GE, DE) and the electric efficiency of BEV in the US were substantially worse than those in other regions.

As explained above, the comparison results of CO_2 emissions between ICV and BEV differ in each region. When more electricity is generated by renewables leading to a smaller CO_2 emission factor of electricity, the amounts of the CO_2 emissions of BEV are lower than those of ICV and the DIP comes at a shorter distance. Besides CO_2 emission factor of electric power generation, the fuel efficiency of ICV and the electric efficiency of BEV also contribute to the variability between regional differences.

5.3. Estimation of the CO_2 Emission Factor of Battery Production

In Section 4.3., it was made clear that the CO_2 emission factor of battery production for BEVs significantly affects the results of the total life-cycle CO_2 emissions. As described in Section 3, the CO_2 emission factor of battery production for BEVs was estimated from previous studies.

Variations in this CO_2 factor in past studies result from a variety of different assumptions used in the calculation of CO_2 emissions. These include battery manufacturing processes, types of battery materials (cathode, anode, electrolyte, battery pack structure, etc.), system boundaries (how many direct/indirect processes relating to manufacturing are included), and public database used for the calculation.

Peters et al. investigated some literature pertaining to battery production, including batteries for stationary systems in the same manner as this study, and calculated the averaged values. The results were, 160 kg-CO_2/kWh for lithium nickel-manganese-cobalt oxide (NCM)-type batteries and 161 kg-CO_2/kWh for lithium iron phosphate (LFP)-type batteries [13]. The difference in averaged values between Peters et al. [13] and this study was approximately 10 %. It was concluded that they analyzed differentials in the factors and concluded that the assessment assumptions were the main causes of the differences.

Ellingsen et al. cited in this study calculated the CO_2 emissions from the battery production based on the electric power consumption for the battery production, etc. provided by a battery supplier [11]. It is desirable that more reliable CO_2 emission data of battery production will become available in the future.

6. Conclusions

In this study, the CO_2 emissions of conventional ICV (GE, DE), and BEV were evaluated using the methodology of LCA.

From the regional vehicle's lifetime perspective, the calculation of CO_2 emissions revealed that as the vehicle was driven longer, the lifecycle CO_2 emission of BEV became lower than that of ICV, except in Australia where ICV emission was lower than BEV until the end of life. Another observation was that regional sources of power generation (coal, contribution from renewable sources, etc.) had a great effect on the CO_2 emissions of BEV. The more the generated electricity came from renewables, the lower the CO_2 emissions of BEV were than those of ICV and the DIP comes at a shorter distance. From the viewpoint of battery production, the CO_2 emission of BEV had a wide variety which results in the lowest emission factor of battery production, which in turn lowered the CO_2 emissions of BEV compared to those of ICV while the highest factor resulted in the opposite conclusion.

This study revealed that the CO_2 emissions of ICV (GE, DE), and BEV are dependent on the regions as well as the CO_2 emissions of battery production. This study suggested that BEV is not only solution for reducing CO_2 emissions globally, but it is important for car manufacturers to introduce ICV as well as BEV to each region in consideration of electricity mixes and so on. In the meanwhile, this study included the limitations listed below.

- This study focused on the regional differences of the CO_2 emission on the fuel production, electric power generation, and fuel combustion phase (i.e., vehicle use stage) but the CO_2 emission on the vehicle and parts production phase is assumed to be the same for all regions.
- As the Joint Research Centre in the EU mentioned [35], the reuse and recycling of lithium-ion batteries is important to mitigate the CO_2 emissions because it can avoid productions of new

materials or parts, but it was out of scope of this study because there are not sufficient data of recycling in each region.

- This study focused on ICV and BEV. A fuel cell electric vehicle fueled by hydrogen is also important to mitigate the CO_2 emissions [36,37] but it was out of scope of this study.
- The CO_2 emissions in the use phase were calculated based on the fuel/electricity efficiency values of type approval test in each region. These values can be different from the values by real driving conditions.
- The uncertainty of cited data from references were taken care of in this study, but this study did not holistically perform a sensitivity check to examine which data could change the results widely other than battery production.

It is essential to assess the CO_2 emissions of ICV, BEV and the other vehicles, considering the change of the regional power generation mix in the future, along with the introduction of advanced ICV technologies and more reliable CO_2 emissions data for battery production with a broader perspective as mentioned in the foregoing limitations of this study.

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