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Cradle-to-Grave Lifecycle Environmental Assessment of Hybrid Electric Vehicles

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Abstract: Demand for sustainable transportation with a reduced environmental impact has led to the widespread adoption of electrified powertrains. Hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) produce lower greenhouse gas (GHG) emissions during the use phase of their lifecycle, compared to conventional internal combustion engine vehicles (ICEVs). However, a full understanding of their total environmental impact, from resource extraction to end-of-life (EOL), of a contemporary, real-world HEV and PHEV remains broadly elusive in the scientific literature. In this work, for the first time, a systematic cradle-to-grave lifecycle analysis (LCA) of a Toyota Prius XW50, as a HEV and PHEV, was used to comprehensively assess its environmental impact throughout its entire lifecycle using established lifecycle inventory databases. The LCA revealed that the gasoline fuel cycle (extraction, refinement, and transportation) is a major environmental impact "hotspot". The more electrified PHEV model consumes 3.2% more energy and emits 5.6% more GHG emissions within the vehicle's lifecycle, primarily owed to the manufacturing and recycling of larger traction batteries. However, when factoring in the fuel cycle, the PHEV model exhibits a 29.6% reduction in overall cradle-to-grave life energy consumption, and a 17.5% reduction in GHG emissions, in comparison to the less-electrified HEV. This suggests that the higher-electrified PHEV has a lower environmental impact than the HEV throughout the whole lifecycle. The presented cradle-to-grave LCA study can be a valuable benchmark for future research in comparing other HEVs and PHEVs or different powertrains for similarly sized passenger vehicles.

Keywords: lifecycle; vehicles; environmental impact; hybrid; electric

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1. Introduction

The transportation sector accounts for approximately 30% of total global energy consumption and 37% of global CO_2 emissions, with the highest reliance on fossil fuel than any other sector [1]. Within the transportation sector, road vehicles, such as cars, represent the largest share in energy consumption and GHG emissions. This had led to considerable technological developments in vehicle drivetrain technology aimed at reducing the environmental burden of road vehicles, in addition to meeting future energy demands. Drivetrain electrification has been widely adopted in the automotive industry to reduce GHG emissions during the usage phase of a vehicle's lifecycle. There exist three levels of drive train electrification: hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), and battery electric vehicle (BEV). HEVs were the inaugural electrified vehicles to hit the mass global market. Such vehicles augment a conventional internal combustion engine (ICE) with electric motors, switching between the two to save fuel and GHG emissions. On the other end of the scale, BEVs are powered solely by electric motors, using electricity stored in an on-board battery. They represent the highest degree of propulsion electrification. PHEVs sit between HEVs and BHEVs on the scale of drivetrain electrification. They retain the use of an ICE but use a higher-capacity chargeable battery, in comparison to HEVs. This permits the PHEV to drive for prolonged periods under fully electric propulsion while the ICE is switched off.

Technological advancements in battery technologies, particularly in lithium-ion batteries, led to significant improvements in energy storage capacity, longer driving range, and reduced charging times. These advancements, along with decreasing costs, led to rapid market growth of all forms of electric vehicles. Government incentives and regulations intended to promote the usage of electric vehicles further contributed to the rapid market expansion of electric vehicles, positioning the technology firmly as the future of transportation. At the time of writing, BEVs experience the highest rate of market expansion. However, due to their relatively high costs, in comparison to ICE-powered vehicles (ICEVs), in addition to factors such as structural deficiencies, and consumer range anxiety, HEVs and PHEVs remain the most widely sold forms of electric vehicles, accounting for a 77% share of global electric vehicles [2].

According to the European Environmental Agency (EEA) [3], it is estimated that HEVs emit 20–35% fewer CO_2 emissions during the usage phase of their lifecycle compared to a comparable ICE-powered vehicle. PHEVs, depending on the battery size, electric range, and charging patterns, can offer up to 50% savings in CO_2 emissions over ICE-powered vehicles. However, a higher degree of drivetrain electrification is met with an increased manufacturing effort to produce larger batteries. The use of heavy and rare-earth metals, the electricity mix used for the charging of batteries (in PHEVs and BEVs), and the recycling of batteries are highly energy-intensive operations that need to be carefully considered to fully understand the net environmental effects of higher degrees of drivetrain electrification.

To comprehensively assess the net impact of electric vehicles, researchers have conducted lifecycle assessment (LCA) studies of vehicles with a range of drivetrain configurations. These studies vary greatly in detail and scope of the analysis performed, often yielding different results and conclusions. Samaras et al. [4] compared the lifecycle GHG emissions of a conventional ICEV, the Toyota Corolla, with a comparable HEV (Toyota Prius), and three unnamed PHEVs differing in battery capacity and electrical ranges (30, 60, and 90 km). The results indicated a 32–42% reduction in GHG emissions for PHEVs, in comparison with the Toyota Corolla ICEV. The HEV vehicle showed a smaller reduction, at 7–12% over the ICE-powered vehicle. The LCA of this study solely evaluated the manufacturing and usage stages of the vehicle's lifecycle. Other significant lifecycle stages, including gasoline production, transportation, vehicle maintenance, and EOL, were not accounted for in the LCA. Consequently, a comprehensive environmental impact evaluation of the vehicle's entire lifecycle could not be carried out. Another limitation of this study was that the LCA was conducted solely within the context of the United States. Wang et al. [5] conducted a cradle-to-grave LCA to assess the emissions of ICEVs, BEVs, and hydrogen fuel cell vehicles (FCVs), based on contemporary (2009, at the time of writing) data, and projected (2020) data. The study reported an 8.6% lower total lifecycle energy consumption of BEVs, in comparison to conventional ICEVs. At the same time, the total lifecycle carbon emissions of BEVs were 16.16% higher than ICEVs, owing to a high degree of fossil fuels in the energy-generation mix. Although the LCA study assessed a wide range of drivetrain options (ICEVs, BEVs, and five types of FCVs), it did not include HEVs and PHEV, which are the most prevailing types of EVs used worldwide. Additionally, the LCA was constrained within the industrial and energy mix conditions of the People's Republic of China, which has a higher share of fossil-fuel-based energy generation than the global average.

Qinyu et al. [6] evaluated the lifecycle GHG emissions of theoretical unnamed BEVs and an ICEV through a cradle-to-gate LCA. The study reported that a BEV has approximately 50% higher CO_2 emissions than ICEVs, within the cradle-to-gate lifecycle phase. This was owed to the manufacturing of traction batteries, which results in significant GHG emissions under heavy fossil-fuel-based energy-mix scenarios. The cradle-to-gate LCA was bound between materials extraction and vehicle manufacturing. Consequently, the full lifecycle environmental impact of these two drivetrain technologies could not be fully established or compared.

Aaron et al. [7] conducted an LCA to assess the CO_2 emissions of real-world ICEVs, HEVs, and BEVs. The study reported a 90% reduction in well-to-wheels (WTW) lifecycle CO_2 emissions in BEVs, in comparison to conventional ICEVs. The WTW LCA only considered the fuel cycle aspect of the total lifecycle. As a result, vehicle and battery manufacturing, maintenance, and EOL were omitted within the LCA scope. In addition, the study lacked the inclusion of PHEV vehicles. A similar well-to-wheel LCA was conducted by Elgowainy et al. [8], which compared the WTW fuel-cycle energy consumption and GHG emissions of unnamed PHEVs with HEVs. The study reported an approximately 46% reduction in well-to-wheel GHG emissions in gasoline-powered PHEVs, in comparison to conventional ICEVs. Further reductions could be achieved by using alternate fuels, particularly biomass-based fuels, providing the energy mixed used for their manufacturing does not predominantly consist of fossil-fuel-based sources. However, like the previous study (Aaron et al.), the researchers did not incorporate the manufacturing process, maintenance, and EOL, within the scope of the LCA. Recently, Wang et al. [9] conducted a WTW LCA of unnamed HEVs, PHEVs, and BEVs within the context of Chinese industrial conditions. The study reported a 44.7% disparity in WTW petroleum energy consumption between an HEV and PHEV, owing to lower utilization of the ICE within the PHEV. However, like the aforementioned publications, the WTW LCA did not take into account energy-intensive lifecycle stages, such as vehicle and battery manufacturing, maintenance, and EOL. As a result, the overall environmental burden of vehicular drivetrain technologies could not be assessed or compared through WTW LCA alone.

Gao et al. [10], conducted a cradle-to-grave LCA of real-world ICEVs (Toyota Corolla), HEVs (Toyota Prius), PHEVs (Toyota Prius Plug in), BEV (Nissan Leaf), and FCV (Honda Clarity). Surprisingly, the study reported the lowest lifecycle energy consumption and GHG emissions within the HEV vehicle, with the second least degree of drivetrain electrification. This was owed to high crude-to-gasoline pathway efficiency (82.6%). In comparison, the lifecycle energy consumption and GHG emissions of vehicles with higher degrees of electrification, such as the PHEVs, FCVs and BEVs, were not encouraging, owed to the low-efficiency pathway for electricity generation within the well-to-pump (WTP) fuel cycle phase. However, a comprehensive breakdown of the energy consumption and GHG emissions calculations throughout all stages of the vehicle lifecycle, from material extraction (to produce gasoline, as well as vehicle component manufacturing), to EOL, was lacking.

Pipitone et al. [11] recently reported cradle-to-grave LCA on fictitious (with specifications modelled on real-world vehicles) ICEVs, HEVs, and BEVs. The study indicated that vehicles with higher drivetrain electrification, such as BEVs, exhibit higher environmental impact, primarily due to the manufacturing process of lithium-ion batteries, particularly within a fossil-fuel-prevalent energy mix. However, the LCA did not incorporate the highly energy in tensive fuel cycle phase, undermines comparisons between the three powertrain technologies. As a result, the LCA could not highlight any potential savings in energy consumption and environmental emissions due to the reduced gasoline consumption of electrified drivetrains.

Petrauskiene et al. [12] conducted a cradle-to-grave LCA comparing real-world ICEVs, HEVs, and BEVs within a Lithuanian context. The study revealed that, under the 2015 energy mix, greater drivetrain electrification of BEVs and HEVs exhibited a higher degree of environmental impact when compared to diesel-powered ICEVs. However, within a 2020–2050 energy mix, where a higher share of renewable power is anticipated, this trend reverses, where BEVs are expected to have the least environmental impact.

Table 1 summarizes the reviewed LCA literature, their scope, limitations, and the conclusion on whether increased drivetrain electrification reduces environmental impact or not. It is evident that conclusions vary between different researchers, owed to differences in datasets, as well as the scope and system boundary of the LCA performed. It is also evident that there is a lack of a comprehensive cradle-to-grave LCA of a contemporary, real-world HEV and PHEV. As a result, the net environmental impact of the said drivetrain technologies remains elusive. To bridge this knowledge gap, we have employed a comprehensive cradle-to-grave LCA methodology that encompasses the entire lifecycle of a real-world, contemporary HEV and PHEV, from raw material extraction to EOL, under contemporary industrial practices, conditions, energy mixes and industrial infrastructure. Using this method, the total lifecycle environmental impact of HEV and PHEV drivetrain technologies was assessed. The LCA methodology presented here could be adopted for future investigations aimed at evaluating the net lifecycle environmental impact of a range of drivetrain technologies, with particular emphasis on degrees of drivetrain electrification. In addition, it can also be employed to examine the influence of regional infrastructure and energy generation mixes on the relative environmental performances of vehicular and drivetrain technologies. Lastly, by utilizing the LCA framework established within this study, researchers and engineers can identify specific environmental impact hotspots within the full vehicular lifecycle.

Table 1. Summery of reviewed literature, taking the stand point whether higher drivetrain electrification reduces environmental impact or not.

Publication	Scope of LCA	Subject of LCA	Limitations	Reduction of Environmental Impact through Higher Electrification?
Samaras et al. [4]	Cradle-to-gate	ICEV, HEV, PHEV	(1). Lifecycle of Gasoline fuel not included in the LCA scope (2). Transportation, vehicle maintenance, EOL not included in the LCA scope (3). LCA is bound by the conditions of the US	Yes
Wang et al. [5]	Cradle-to-grave	ICEV, BEV, five types of FCVs	(1). HEVs and PHEVs not included in the LCA (2). LCA was bound by the conditions of Chin (3). The LCA did not study real-world vehicles	Yes (energy consumption), No (GHG emissions)
Qinyu et al. [6]	Cradle-to-gate	ICEV, BEV	(1). HEVs and PHEVs not included in the LCA (2). The LCA did not study real-world vehicles (3). Cradle-to-gate scope did not take into account vehicle usage, maintenance, and EOL.	No
Aaron et al. [7]	Well-to-wheel	ICEVs, HEVs, BEVs	(1). LCA scope limited to WTP stage (2). PHEVs not included in the LCA	Yes
Elgowainy et al. [8]	Well-to-wheel	ICEV, HEV, PHEV	(1). LCA scope limited to WTP stage (2). PHEVs not included in the LCA (3). The LCA did not study real-world vehicles	Yes
Wang et al. [9]	Well-to-wheel	HEV, PHEV, BEV	(1). LCA scope limited to WTP stage (2). LCA was bound by the conditions of China (3). The LCA did not study real-world vehicles	Yes
Gao et al. [10]	Cradle-to-grave	HEV, PHEV, BEV, FCV	(1). Lack of comprehensive breakdown of environmental impact calculations within all lifecycle stages	No

Table 1. *Cont.*

Publication	Scope of LCA	Subject of LCA	Limitations	Reduction of Environmental Impact through Higher Electrification?
Pipitone et al. [11]	Cradle-to-grave	ICEV, HEV, BEV	(1). The LCA did not study real-world vehicles (2). The LCA was bound by the conditions of European continent (3). PHEVs not included in the LCA (4). The LCA did not take into account the WTW fuel cycle	No
Petrauskiene et al. [12]	Cradle-to-grave	ICEV, HEV, BEV	(1). PHEVs not included in the LCA (2). The LCA is bound by the conditions of Lithuania	No (2015 setting), Yes (2020–2050 setting)

The goal, scope, methodology, and underlying assumptions of the LCA is elucidated in Section 2. Subsequently, Section 3 presents the results and discussion in a systematic bottom-up manner, starting from the upstream stage (resource extraction) to the final downstream stage (EOL).

2. Materials and Methods

In this study, the environmental impact of HEV and PHEV drivetrain technologies was assessed through the application of the LCA methodology, as prescribed by ISO 14040. This methodology compromises four steps: goal and scope (1), lifecycle inventory (2), lifecycle impact assessment (3), and interpretation of results (4).

2.1. Goal and Scope

The goal of the presented study is to assess the environmental impact of HEV and PHEV drivetrain technologies. This was achieved by quantifying the energy consumption and GHG emissions throughout the entire lifecycle of a Toyota Prius XW50, in HEV and PHEV configuration. It is assumed the vehicle will travel 250,000 km during the usage phase of its lifecycle. This is the functional unit of the LCA. The choice of the XW50 Prius was based on its widespread popularity. Additionally, the HEV and PHEV configurations possess similar technical specifications, as summarised in Table 2, differing mostly in the size of the lithium-ion batteries used within the hybrid drive system. As the two models are broadly similar, differing mostly in battery capacity, a direct comparison on the environmental impact of HEV and PHEV drivetrain configurations can be made.

Table 2. Specification of HEV and PHEV models subject to cradle-to-grave LCA. Data obtained from [13].

Vehicle Parameter	Toyota Prius XW50 HEV	Toyota Prius XW50 PHEV
Fuel type	Gasoline	Gasoline
Powertrain	2ZR-FXE gasoline engine + dual motor-generator system	2ZR-FXE gasoline engine + dual motor-generator system
Curb Weight (kg)	1575	1605
Power Output (hp)	123	123
Hybrid Fuel-Cell Battery	Lithium Ion	Lithium Ion
Mass of Hybrid Fuel-Cell Battery (kg)	39	151
Battery Capacity (kWh)	1.31	4.4
Range Under Full Electric Mode (km)	N/A	24

The LCA analysis performed in this study encompasses all stages of a vehicle's lifecycle. This is known as a cradle-to-grave LCA, which defines the scope of the analysis. The cradle-to-grave scope is the most extensive form of LCA, with the broadest boundaries. This holistic approach ensures that all significant factors are accounted for and not overlooked. For instance, due to a higher degree of electrification, PHEVs are designed to consume less fossil fuel, and emit fewer GHG emissions than HEVs during the usage phase of the lifecycle. However, achieving these savings through a greater degree of drivetrain electrification demands a greater degree of manufacturing effort to produce larger batteries. Therefore, it is imperative to adopt a cradle-to-grave approach to evaluate which of these contrasting factors prevail, to gain an accurate assessment on the net environmental impact.

2.2. Lifecycle Inventory

The lifecycle inventory is a list of environmental exchanges throughout the lifecycle of a product or process. The product lifecycle is first split into discretised stages using a lifecycle flow model. The list of inputs and outputs, which represents the inventories, are then identified, and quantified within all stages of the product lifecycle. Figure 1 illustrates a cradle-to-grave lifecycle flow model of an HEV and PHEV, from resource extraction to EOL. The cradle-to-grave lifecycle can be divided into two phases, the fuel cycle, and the vehicle cycle.

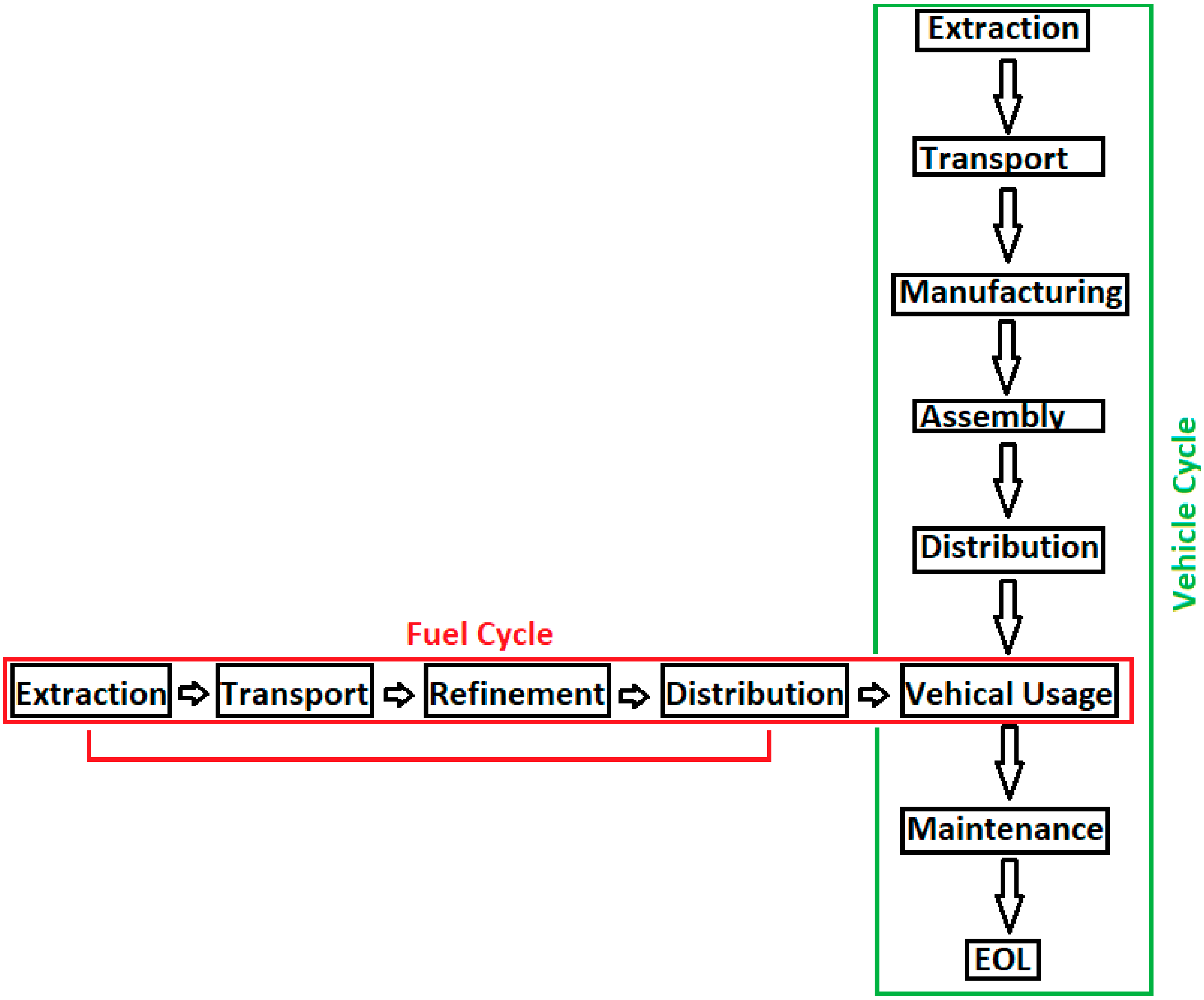

Figure 1. Illustration of cradle-to-grave lifecycle model of HEVs and PHEVs.

The fuel cycle concerns the manufacturing, transportation, and usage of automobile fuel. It is further decomposed into two phases, well-to-pump (WTP) and pump-to-wheels (PTW). The WTP phase encompasses the extraction of raw materials such as petroleum, the transportation of the said materials to refineries, refining process (into gasoline), and distribution to petrol pumps (refuelling stations). The PTW phase concerns the consumption of gasoline during the operational phase of the vehicle. Combining WTP with PTW yields the well-to-wheels (WTW) fuel cycle, which is the complete lifecycle of a vehicle's fuel. The input inventories within all stages of the WTW fuel cycle are electrical and fossil-fuel energy, which are required for the operation of various machinery and processes. The output inventory is GHG emissions.

The vehicle lifecycle phase concerns the manufacturing, operational usage and of end-of-life (EOL). It encompasses the extraction of materials required for the manufacturing of vehicular components, the manufacturing of vehicular components, their assembly into a complete vehicle, distribution to 4S shops, maintenance, and EOL. The input inventories include electrical and fossil-fuel-based energy, as well as material inputs required within the manufacturing process. The list of material inputs for the manufacturing of HEV and PHEV vehicular components is summarized in Table 3. This was obtained by multiplying the mass fraction of each material with the total mass of the vehicle (excluding batteries and fluids). Table 4 summarizes the material inputs for the manufacturing of vehicular batteries, and their amount within the HEV and PHEV model. Table 5 summarizes vehicular fluid inputs, and the amounts used in the HEV and PHEV model. The output inventory within all stages of the vehicle lifecycle is GHG emissions.

Table 3. Material input inventory for the manufacturing of HEV and PHEV vehicular components (excluding lithium-ion batteries). Data obtained from [14].

	Mass Amount in HEV (kg)	**Mass Amount in PHEV (kg)**
Total mass of Vehicle Components (excluding batteries and fluid)	1378	1301
Steel	899.8	865.2
Cast Iron	77.2	67.6
Forged Aluminium	27.6	22.1
Cast Aluminium	67.5	59.9
Copper	57.9	58.5
Glass	35.8	37.7
Plastic	148.8	139.2
Rubber	23.4	22.1
Other (Magnesium + PET)	40	28.6

Table 4. Material input inventory for the manufacturing of HEV and PHEV starter (lead-acid), and propulsive (lithium-ion) batteries. Data obtained from [14].

Lead-Acid Battery	**Amount in HEV and PHEV (kg)**	**Lithium-Ion Battery**	**Mass Amount in HEV (kg)**	**Amount in PHEV (kg)**
Lead	11.7	Lithium Iron Phosphate	10.8	50.43
Sulfuric Acid	1.35	Graphite	4.78	22.05
Plastic Polypropylene	1.04	Adhesive	0.819	3.78

Table 4. *Cont.*

Lead-Acid Battery	Amount in HEV and PHEV (kg)	Lithium-Ion Battery	Mass Amount in HEV (kg)	Amount in PHEV (kg)
Glass Fibre	0.357	Copper	5.77	16.5
Water	21.3	Forged Aluminium	8.93	28.8
Other	1.36	Lithium Hexafluorophosphate	0.663	2.78
		Ethylene carbonate ester	1.91	8
		Dimethyl carbonate ester	1.91	8
		Polypropylene	0.858	2.57
		Polyethylene	0.156	0.453
		Steel Thermal Insulation	0.741 0.117	2.11 0.453
		Glycol	0.507	1.51
		Other	1.8	4.564

Table 5. Vehicle fluid input inventory for HEV and PHEV. Data obtained from [14].

Fluid Type	Amount in HEV (kg)	Amount in PHEV (kg)
Lubricant	4.4	3.9
Brake Fluid	1	0.9
Transmission Fluid	0.9	0.8
Coolant	11.6	10.4
Wiper Fluid	3	2.7
Fuel Additive	15.2	13.6

2.3. Lifecycle Impact Analysis

The environmental impact of the HEV and PHEV drivetrain technology was assessed using energy consumption and GHG emissions as impact categories. The cradle-to-grave lifecycle flow model, as illustrated in Figure 1, was modelled using the GREET 2019 LCA software package, developed by Argonne National Laboratory [15]. The list of input inventories, as summarized in Tables 3–5 were inputted into the GREET model. Based on the comprehensive and verified database, the GREET software package calculates the energy consumption and GHG emission intensity within each stage of the cradle-to-grave lifecycle. Table 6 summarizes the energy and GHG emissions intensities within each stage of the cradle-to-grave lifecycle [16]. The energy consumption and GHG emission intensities (normalization factors) obtained from GREET, for each stage of the lifecycle, were multiplied by the total amount used within the lifecycle (normalization quantity), to obtain the environmental impact, as defined in Equation (1).

$$E_i = N_f\, N_C \tag{1}$$

where E_i is the environmental impact, such as energy consumption or GHG emissions, N_f the normalisation factor, such as energy consumption or GHG emission intensity, N_C the normalisation quantity, such as the total lifecycle energy equivalent consumed.

Table 6. Definition of energy consumption intensity and GHG emission intensity within each lifecycle stage.

		Lifecycle Stage	Energy Consumption Intensity (SEI)	GHG Emissions Intensity (GEI)
Cradle-to-grave lifecycle	Fuel Cycle	Resource Extraction	Energy equivalent (MJ) required to produce a unit MJ equivalent of gasoline (MJ/MJ)	Mass amount (g) of GHG emitted, to produce a unit MJ equivalent of gasoline (g/MJ)
		Transportation		
		Refinement		
		Distribution		
		Usage	Energy equivalent (MJ) of gasoline consumed per km travelled during the usage phase of the lifecycle (MJ/km)	Mass amount (g) of GHG emitted per km travelled during the usage phase of the lifecycle (g/km)
	Vehicle Cycle	Vehicle Body Manufacturing	Energy (MJ) required to produce a unit kg of material required for the manufacturing of vehicular components (MJ/kg)	Mass amount (g) of GHG emitted for every kg of produced material required for the manufacturing of vehicular components (g/Kg)
		Vehicle Battery Manufacturing		
		Vehicle Fluid Manufacturing		
		Assembly	Energy (MJ) require per unit kg of vehicle assembly (MJ/kg)	Mass amount (g) of GHG emitted per unit kg of vehicle assembly
		Transportation	Energy (MJ) required to move unit kg (MJ/kg)	Mass amount of GHG emitted per unit kg moved (g/kg)
		Maintenance	Energy (MJ) required to replace unit kg of material (MJ/kg)	Mass amount of GHG emitted per kg of material replaced (MJ/kg)
		End-Of-Life	Energy (MJ) required per unit kg of recycled material (MJ/kg)	Mass amount (g) of GHG emitted per unit kg of recycled material (g/kg)

3. Results and Discussion

3.1. Fuel Cycle

The first part of the cradle-to-grave LCA consisted of the fuel chain. The fuel chain consists of an upper and lower stream phase, known as well-to-pump (WTP) and pump-to-well (PTW), respectively.

3.1.1. WTP

Figure 2 plots the energy equivalent of inputs required within all four stages of the WTP fuel cycle to produce a unit MJ of gasoline. The results highlight the refinement stage as the most energy intensive within the upstream WTP fuel cycle. It accounts for 70% of the total WTP fuel cycle energy consumption. This is followed by extraction (20%), transportation (6.7%), and distribution (8.6%). Within the extraction, transportation, and refining stages, electrical energy accounts for slightly over half of all energy inputs. This is due to high reliance on electrical equipment within the extraction, refining, and transportation stages, such as pump motors, drilling rigs, compressors, and railway-based transportation that employ electrical locomotives. These results are based on the average energy global energy mix, obtained from GREET 2019, where fossil-fuel based power generation prevails. This is particularly the case in highly industrialized economies like the People's Republic of China, the largest automotive manufacturer globally, which primarily relies upon coal-based power stations for electricity generation. A total of 83% of WTP fuel cycle electrical demand is generated from fossil-fuel-based power sources. The fossil-fuel-based energy sources include coal (47%), oil (34%) and natural gas (0.18%). This is illustrated by the pie chart in Figure 3, which reveals the global average energy mix. The remainder 17% of electricity generated stem from non-fossil-fuel-based sources such as nuclear and renewable sources. It is therefore clear that the WTP fuel cycle phase is highly dependent on coal-based energy sources.

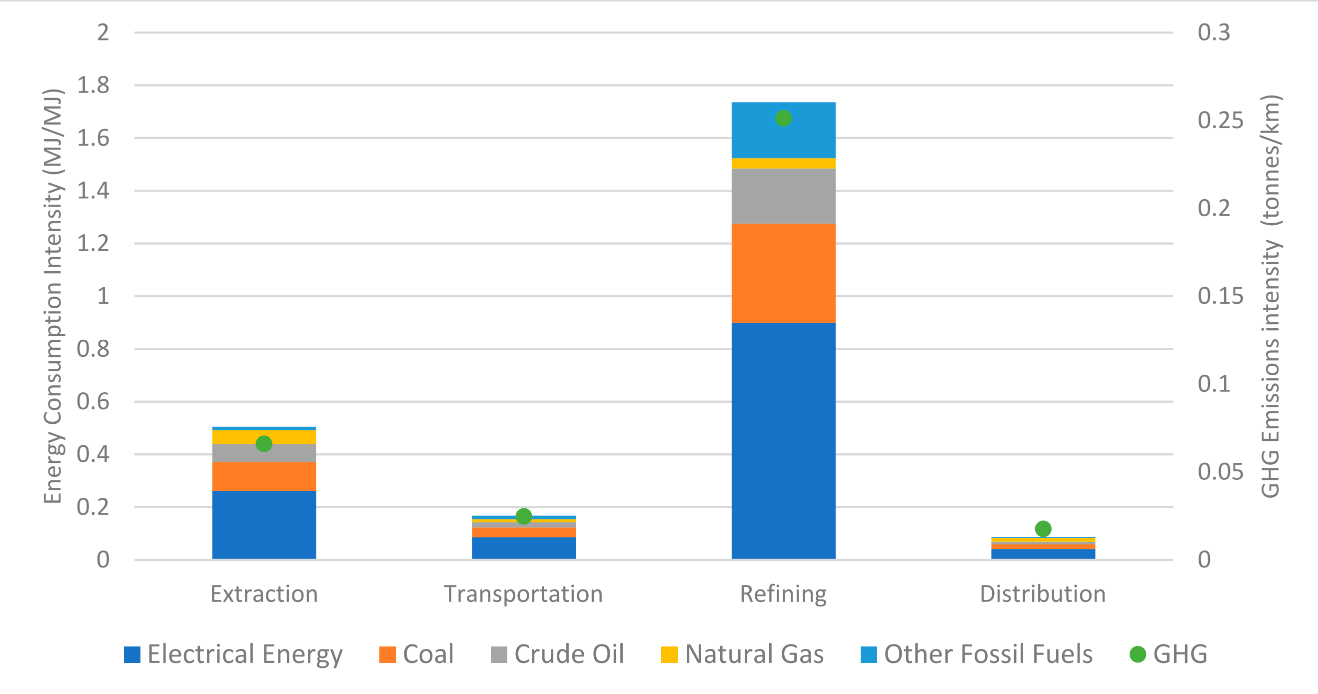

Figure 2. Energy inputs required to produce unit MJ of gasoline within WTP fuel cycle.

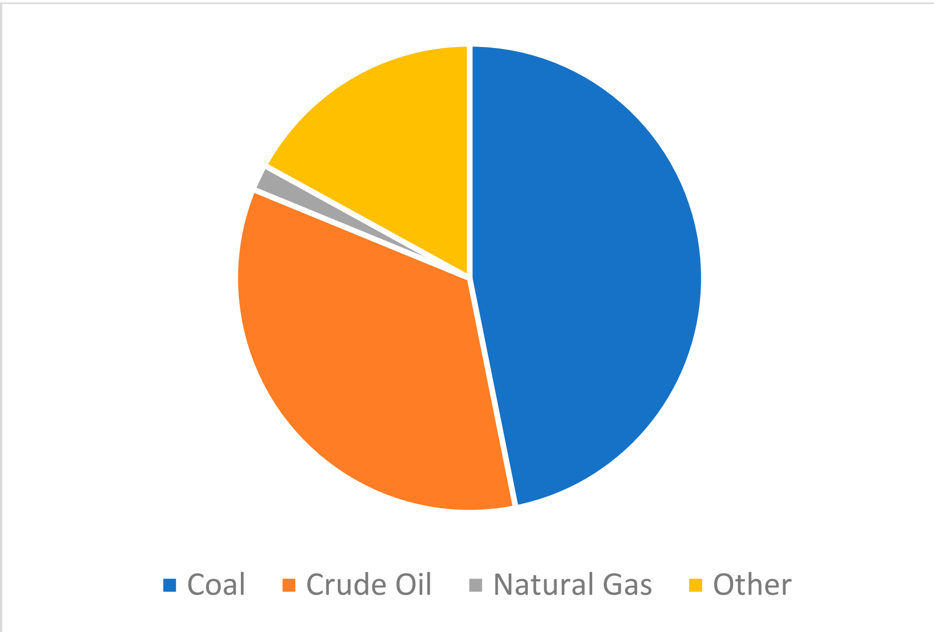

Figure 3. Global energy mix, obtained from GREET 2019.

The points within Figure 2 plot the equivalent GHG emissions emitted per MJ of gasoline produced, within all four stages of the WTP fuel cycle phase. The results show a strong correlation between energy intensity and GHG emissions, with the refining stage consuming the most energy as well as emitting the most GHGs. The corresponding increase in GHG emissions from increased energy consumption can be attributed to the use of fossil fuel, namely, coal-based energy sources for electricity generation. In addition, much equipment in the extraction and refining stage requires direct fossil fuel inputs, such as fuel oil, which results in GHG emissions. CO_2 emissions remain the most dominant form of GHG emissions, accounting for 66%, 67%, 78%, and 86% of all GHG emissions within the extraction, transportation, reining, and distribution stages, respectively.

Based on these results, the total WTP fuel cycle energy consumption and GHG emissions were calculated using Equation (1) defined earlier. The service life of a vehicle was assumed to be 250,000 km. According to Toyota, the average fuel consumption for the HEV and PHEV model is 86 and 156 MPG (EPA standard) [17]. Assuming the specific range (MPG) remains constant throughout the entire use phase of the vehicle lifecycle, the total gasoline consumption after driving 250,000 km is expected to be 1816 and 1001 US gallons for the HEV and PHEV models, respectively. According to the EPA [18], 1 US gallon of gasoline is equivalent to 121 MJ of potential energy. Thus, the HEV and PHEV models are expected to consume 219,736, and 121,121 MJ equivalent of gasoline during the usage stage of the lifecycle, respectively. These are the normalisation quantity for the calculation of WTP energy consumption and GHG emissions. Using Equation (1), the WTP energy consumption and GHG emissions were obtained, presented in Figure 4. The 58% lower WTP energy consumption of the PHEV can be attributed to its higher degree of electric locomotion, resulting in a lower demand for gasoline fuel.

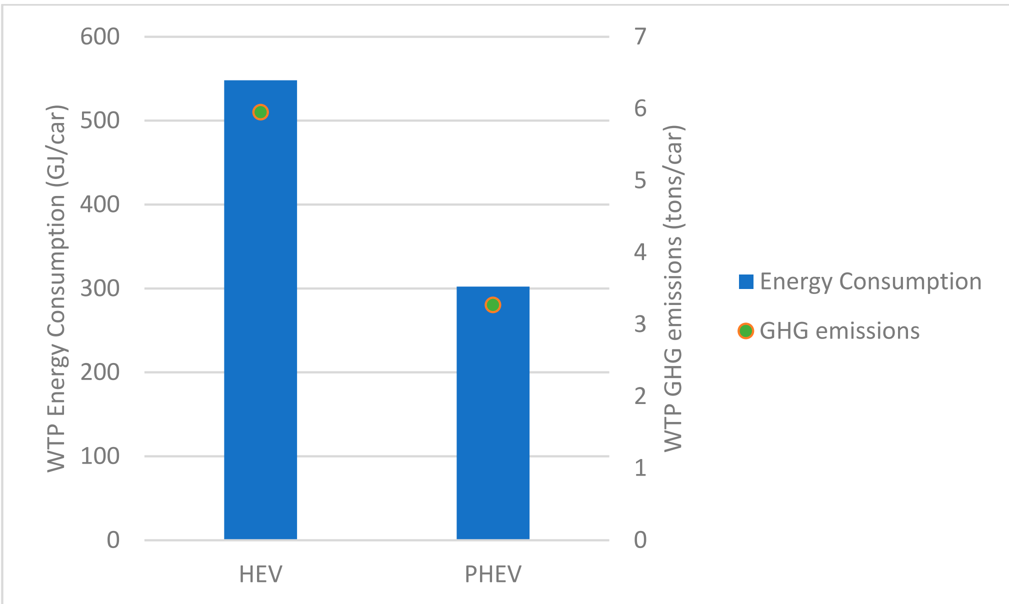

Figure 4. WTP energy consumption and GHG emissions.

3.1.2. PTW

Using the energy consumption and GHG emissions intensities obtained from the GREET model, plotted in Figure 5, the total PTW energy consumption and GHG emissions were calculated using Equation (1). This is presented in Figure 6. The results indicate that the PHEV model consumes 14.7% less energy than the HEV. This resulted in an even larger disparity in GHG emissions between the two models, where the PHEV model emits 25% fewer GHGs. This is owed to a higher degree of electrification, resulting in a lower utilization of the ICE during usage. It is worth noting that the reduction in GHG emissions offered by the more electrified PHEV model is higher than the reduction in energy consumption. This is owed to additional demand in electrical energy that is drawn from the national grid to charge the rechargeable batteries. This demand is predominantly met by coal-powered energy sources within the national grid. As a result, 16% of the PTW energy consumption within the PHEV model stems from coal-based energy sources. In contrast, the energy consumed within the HEV's PTW fuel cycle is exclusively derived from the combustion of gasoline, due to its lack of a rechargeable battery.

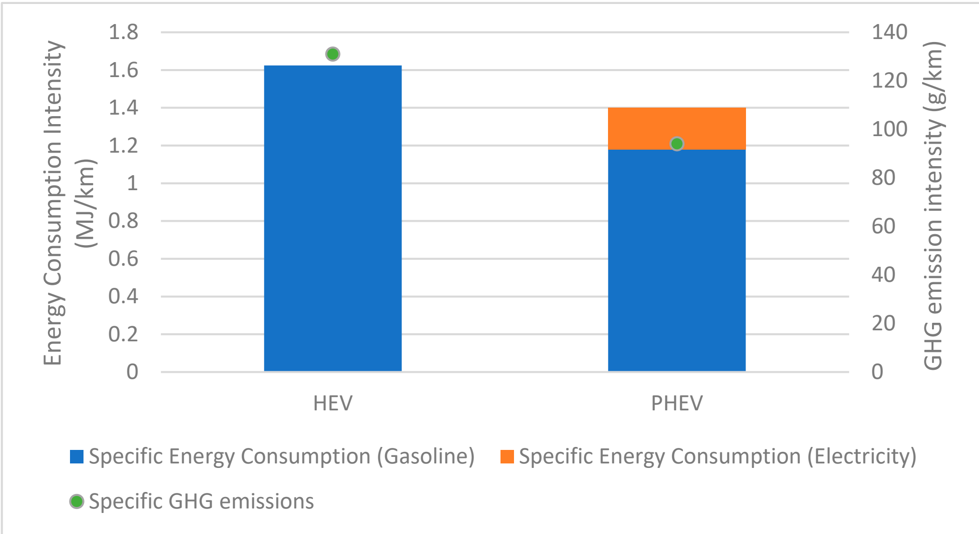

Figure 5. PTW energy consumption and GHG emission intensities.

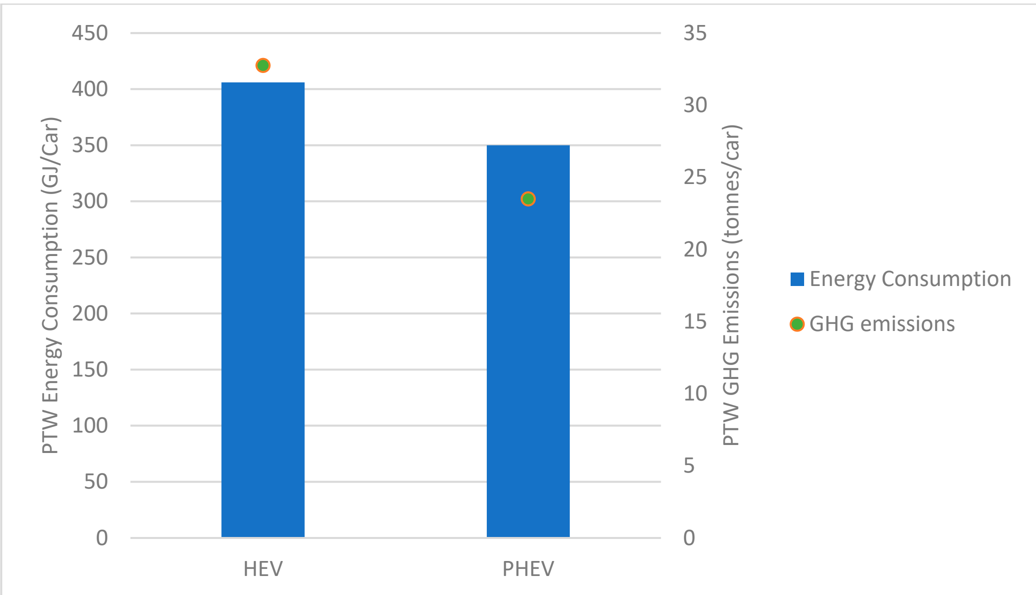

Figure 6. PTW energy consumption and GHG emissions.

3.1.3. WTW Energy Consumption

Consolidating WTP and PTW energy consumption and GHG emissions, a comparison of the total WTW fuel cycle is presented in Figure 7. The results shows that the PHEV model consumes 37.5% less energy and emits 35% less GHGs than the HEV model. This is attributed to the higher degree of electrification, resulting in a lesser gasoline consumption. These findings agree with those reported by Elgowainy et al. [8], and Wang et al. [9], though it must be stated that the aforementioned researchers utilized different datasets and energy mixes within the LCA than the presented study, in addition to studying different models of vehicles. It is worth noting that the PTW/WTW energy consumption ratio is higher within the PHEV model, where 53.7% of the total WTW fuel cycle energy is consumed at the PTW phase. In comparison, only 43% of the total WTW fuel cycle is consumed in the HEV's PTW phase. This is due to additional electrical energy inputs in the PHEV model for the recharging of batteries. This additional demand for electrical energy is met from the national grid, whereas the HEV model charges exclusively charges its traction batteries through the ICE, and therefore does not require any other energy inputs during the PTW fuel cycle phase besides gasoline.

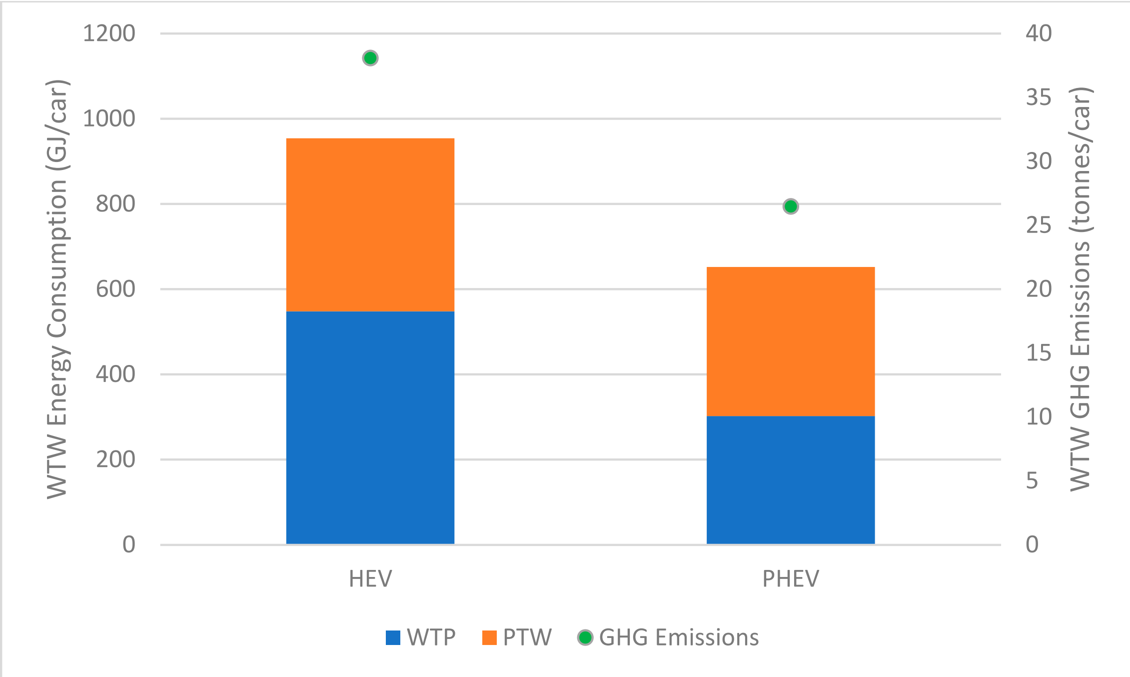

Figure 7. WTW energy consumption and GHG emissions.

3.2. Vehicle Lifecycle

3.2.1. Vehicle Component Manufacturing

Table 7 summarizes the energy consumption and GHG emission intensity associated with the extraction, transport, and manufacturing of materials used for the manufacturing of vehicular components. Using Equation (1), the total energy consumption and GHG emissions associated with the manufacturing of vehicular components were calculated, presented in Figure 8. The results indicate a 10.7% reduction in energy consumption and an 8.9% reduction in GHG emissions within the PHEV model. This can be attributed to the lower use of energy-intensive materials, such as ferrous alloys, aluminium, PET, and magnesium [19].

Table 7. Specific energy consumption and GHG emissions of materials used for the manufacturing of vehicle components. Data obtained from GREET.

Material	Energy Consumption Intensity (MJ/kg)	GHG Emission Intensity (g/kg)
Steel	56.82	7305
Iron	17.64	1327
Forged Aluminium	208.08	2170
Cast Aluminium	221.28	2301
Copper	43.48	4025
Glass	21.78	2134
Plastic	114.8	7640

Table 7. *Cont.*

Material	Energy Consumption Intensity (MJ/kg)	GHG Emission Intensity (g/kg)
Rubber	43.67	4200
Magnesium	394.51	37852
PET	96.44	6219

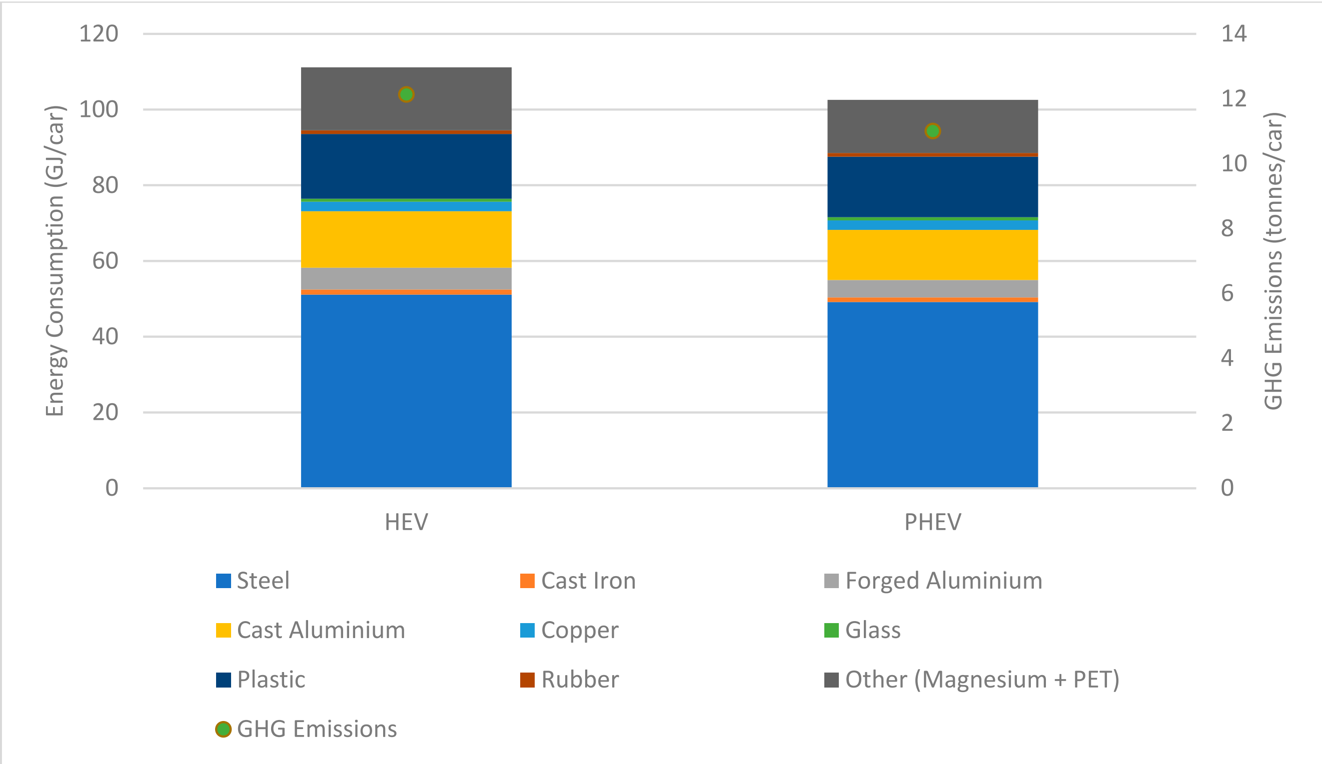

Figure 8. Energy consumption and GHG emissions associated with the manufacturing of vehicle components.

Figure 9 plots the energy consumption and GHG emissions associated with the manufacturing of vehicle batteries. The results indicate a large disparity in the energy consumption (by 3.3 times) and GHG emissions (by 3.2 times) between the PHEV and HEV model. This is attributed to the much larger lithium-ion battery employed on the PHEV model, at 154 kg compared to 39 kg in the HEV model.

3.2.2. Vehicle Fluid Manufacturing

Figure 10 plots the energy consumption and GHG emissions associated with the manufacture of vehicle fluids. The results indicate an 11.1% higher energy consumption in the HEV model, and the same amount higher GHG emissions. This is attributable to the higher degree of electrification of the PHEV model. This results in a lower use of the ICE and the CVT transmission, which correspondingly demands less coolant, lubrication, and transmission fluid. Additionally, the PHEV model can employ regenerative breaking to a higher extent than the HEV model. This reduces the demand for brake fluids used to operate the hydraulically operated brake discs.

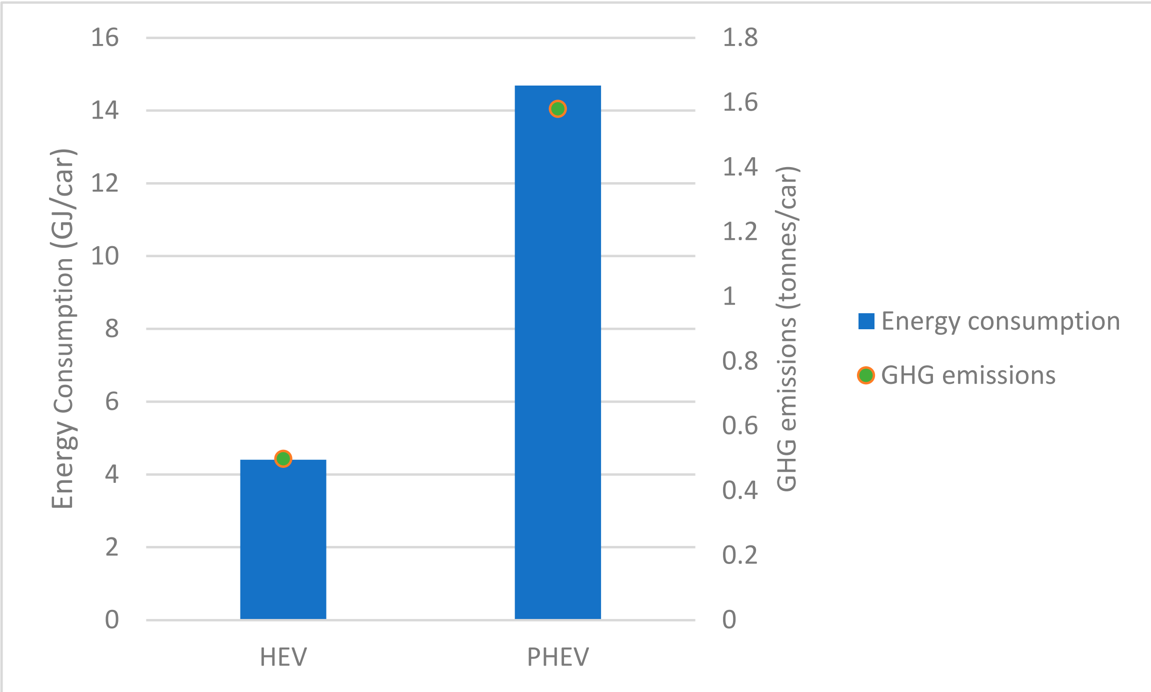

Figure 9. Energy consumption and GHG emissions associated with the manufacturing of vehicle batteries.

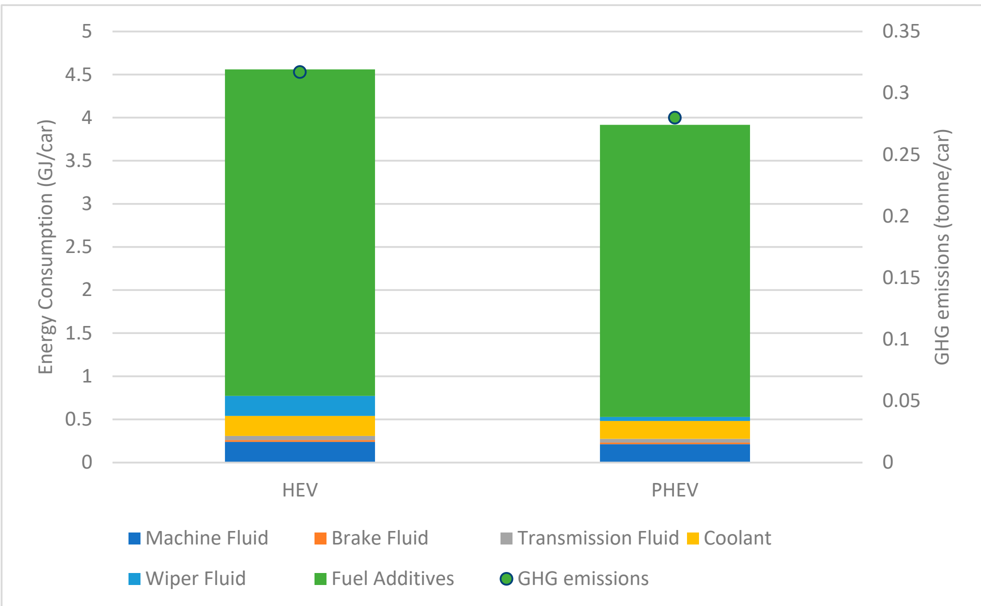

Figure 10. Energy consumption and GHG emissions associated with the manufacturing of vehicle fluids.

3.2.3. Vehicle Assembly

The assembly process assembles all vehicle components and subcomponents. It consists of multiple processes that consume energy directly, such as heating, painting, welding, material handling, electrical machinery, and processes that consume energy indirectly, such as HVAC and lighting (of the factory floor). Figure 11 presents the energy consumption and GHG emissions from the assembly process. The results indicate an 8% disparity between the HEV and PHEV models. The slightly higher energy consumption of the PHEV model is attributed to a higher vehicle mass.

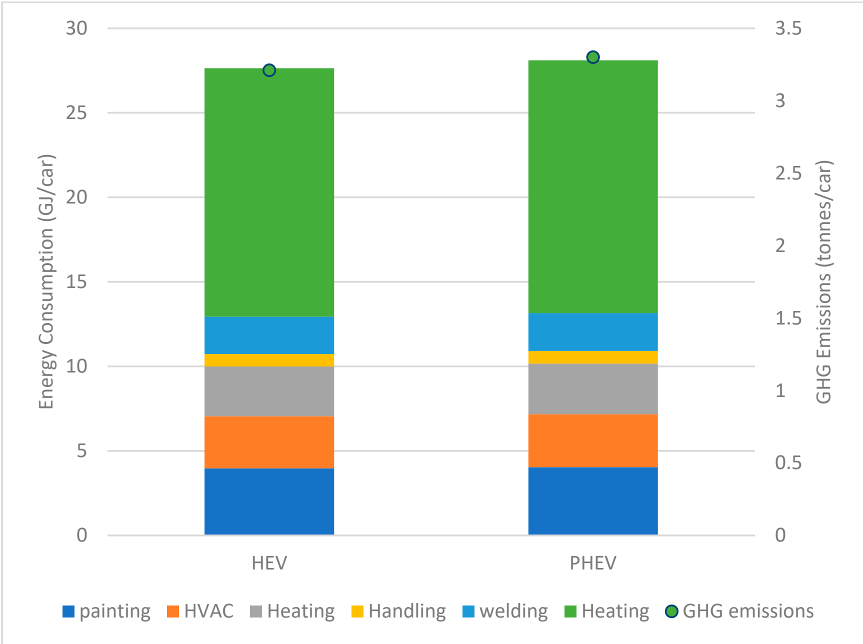

Figure 11. Energy consumption and GHG emissions associated with vehicle assembly.

3.2.4. Transportation to 4S Shops

The transportation of a fully manufactured car to 4S shops is assumed to be achieved by the use of an articulated heavy-duty car transporting truck, with a travel distance of 1500 km. According to GREET, the specific energy consumption and GHG emissions associated with the transportation of by car transporting articulated trucks are 4.95 MJ/kg and 510 g/kg, respectively. Based on these assumptions, the calculated energy consumption and GHG emissions are presented in Figure 12. The results indicate a small (1.7%) disparity in energy consumption and GHG emissions between the two models.

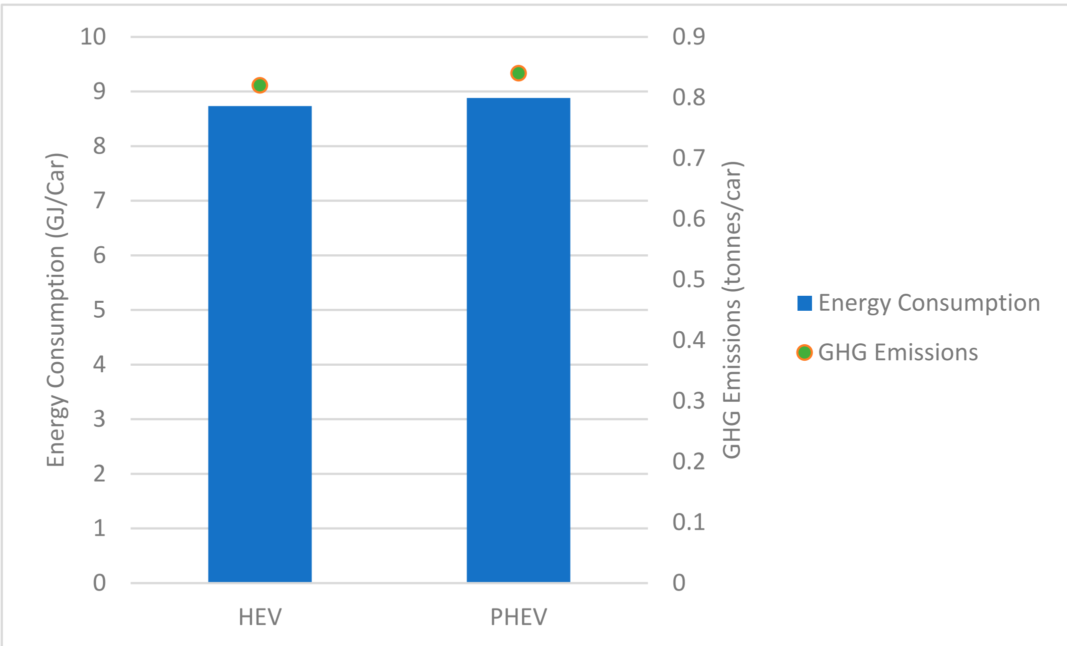

Figure 12. Energy consumption and GHG emissions associated with transportation to 4S shops.

3.2.5. Maintenance

Vehicle maintenance is defined as the replacement of vehicle fluids and tires. Assuming normal driving conditions, tire replacement is assumed to occur every 60,000 km [20]. This results in three replacements during the vehicle's full lifecycle. Lubrication oil requires changing every 6000 km, accounting to a total of 39 changes. Wiper and brake fluids require two changes, and transmission fluid require three changes within the full lifecycle. According to Toyota, the lithium-ion batteries do not require replacement or maintenance during the entire lifecycle of a car. This claim was independently verified by Gaines et al. [21]. Therefore, lithium-ion batteries are assumed as maintenance/replacement free. From these assumptions, the energy consumption and GHG emissions associated with the maintenance stage were calculated, as presented in Figure 13. The results indicate an 11.3% disparity in energy consumption, and an 8.64% disparity in GHG emissions, favouring the PHEV model. This is attributed to a higher degree of electrification, resulting in a lesser reliance on lubrication oil and transmission fluid.

3.2.6. End-of-Life

The EOL stage of the vehicle lifecycle compromises crushing and battery recycling. The energy consumption and GHG emission intensity associated with EOL is summarised in Table 8. Using Equation (1), the total energy consumption and GHG emissions during the EOL stage were calculated. This is presented in Figure 14. The results show a considerable disparity in energy consumption (3.3 times) and GHG emissions (3 times) between the PHEV and HEV model. This disparity is owed partly to the higher vehicular mass of the PHEV model, but mostly from the much higher battery mass.

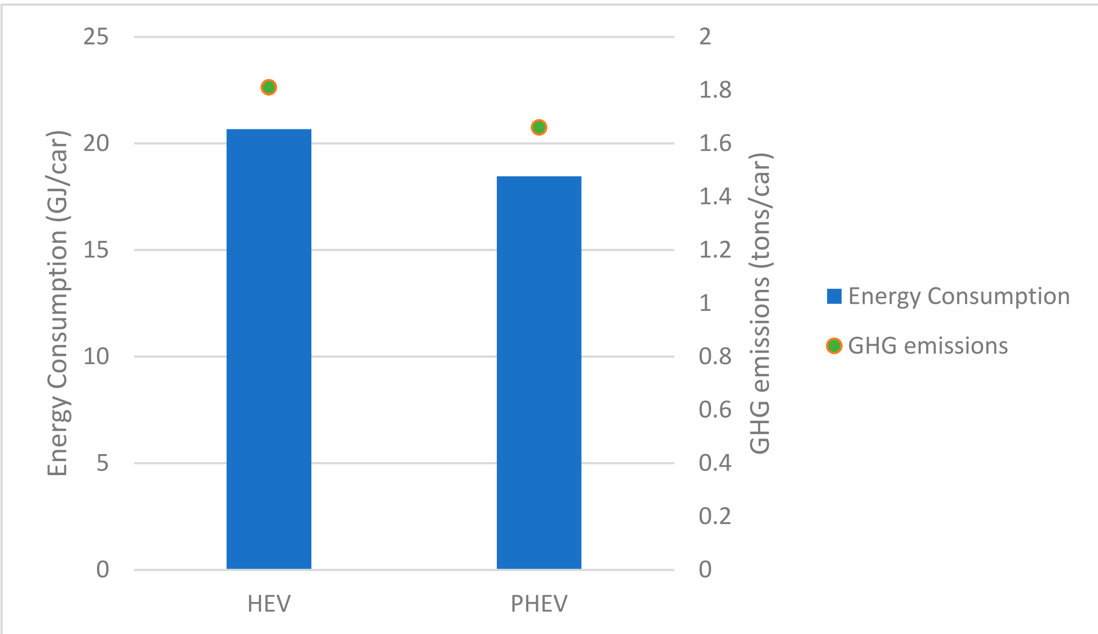

Figure 13. Energy consumption and GHG emissions associated with vehicle maintenance.

Table 8. Specific energy consumption and GHG emissions. Data obtained from GREET.

	Body Crushing	Battery Retraction
Specific Energy Consumption (MJ/kg)	1.12	84.6
Specific GHG Emissions (g/kg)	100	8212

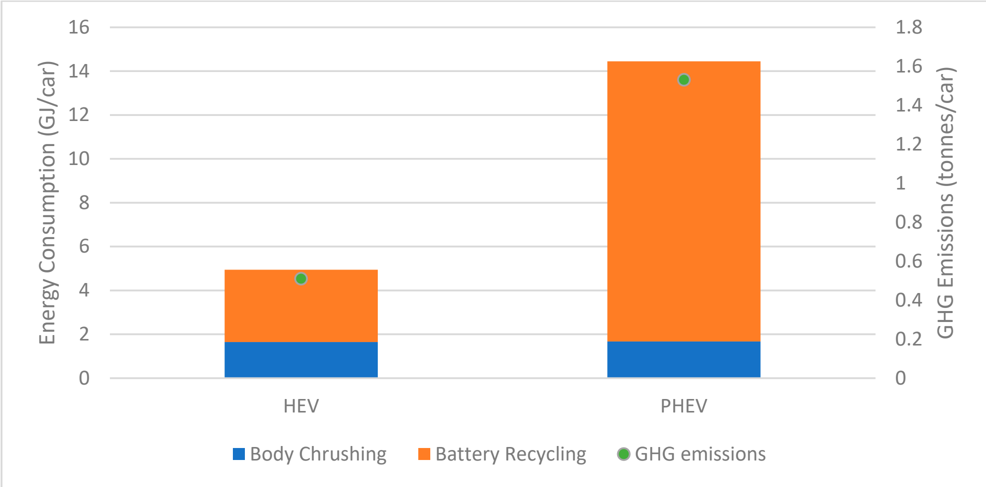

Figure 14. Energy Consumption and GHG emissions associated with the vehicle's EOL.

3.2.7. Summary of Vehicle Lifecycle

Figure 15 consolidates all the results from the vehicle lifecycle phase to yield the energy consumption and GHG emissions. The results indicate the PHEV model consumes 3.2% more energy, and emits 5.6% more GHG emissions than the HEV model throughout the vehicle lifecycle phase. This disparity can be considered minor, given large disparities in energy consumption and GHG emissions during battery manufacturing and EOL stages of the vehicle lifecycle. This can be owed to mitigating design strategies employed on the PHEV models, which use lower amounts (by mass) of energy-intensive materials such as steel, cast iron, aluminium, magnesium, and PET. Other mitigating factors include lower mechanical maintenance and fluid requirements, owing to higher degree of electrification.

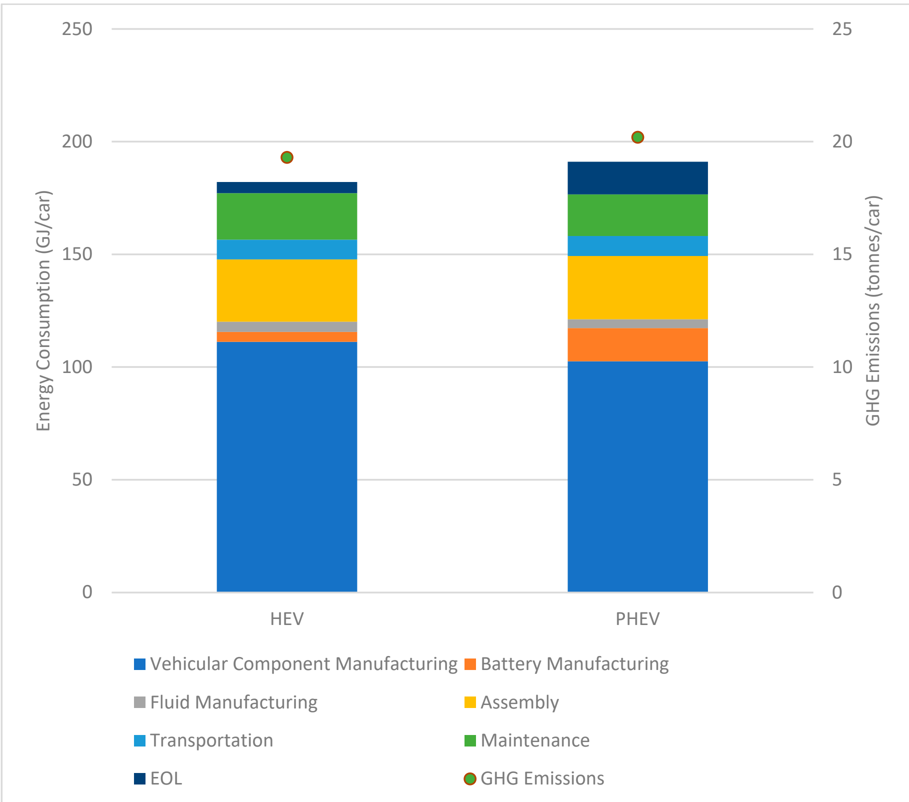

Figure 15. Energy consumption and GHG emissions during vehicle lifecycle.

3.3. Cradle-to-Grave Lifecycle

Consolidating the vehicle and fuel lifecycle phases presented prior, the total cradle-to-grave lifecycle was obtained, presented in Figure 16. The results indicate that most of the energy is consumed at the fuel cycle phase of the lifecycle, accounting for 87 and 77% of total cradle-to-grave energy consumption within the HEV and PHEV models, respectively. It is also clear that the disparity in energy consumption is at the highest in the WTW fuel cycle phase, with a 33% disparity in fuel consumption between the HEV and PHEV model. This is attributed to significantly lower gasoline consumption of the PHEV model during usage. On the other hand, the disparity in energy consumption at the vehicle lifecycle phase is comparatively small, at 3.2%. It can thus be concluded that a small increase in energy consumption at the vehicle lifecycle phase, mostly attributed to the manufacturing and recycling of a larger battery, can result in a substantial reduction in the overall cradle-to-grave energy consumption. However, it should be noted that these finding are based on the average global energy mix, where coal-powered power generation prevails. For this reason, increased energy consumption leads to a corresponding increase in GHG emissions, as the increased demand is often met by the fossil-fuel based power station. By increasing the amount of renewable, non-fossil-fuel-based sources in the energy mix, increased demands for electricity, either for the recharging of batteries or for manufacturing processes, can be met without a directly proportional increase in GHG emissions.

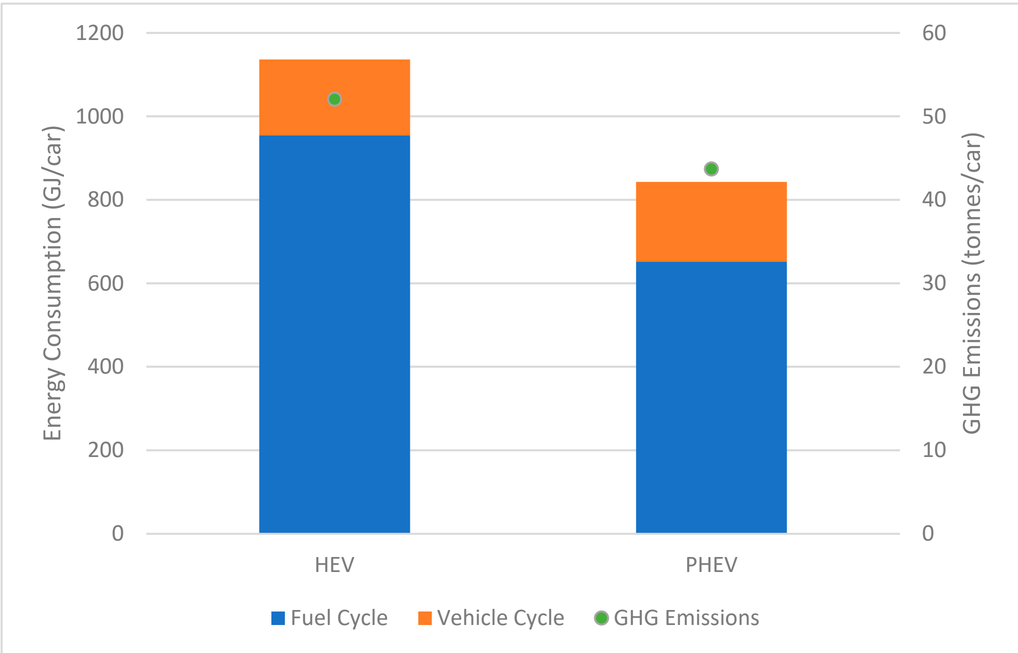

Figure 16. Cradle-to-grave lifecycle energy consumption and GHG emission.

Conversely, the disparity in energy consumption and GHG emissions during the lifecycle phase is relatively minor, at 3.2% and 5.6%, respectively. A marginal increase in energy consumption during the lifecycle phase, mainly due to the production and recycling of a larger battery, can yield a substantially reduced environmental impact within the whole cradle-to-grave lifecycle.

These findings suggest that increased drivetrain electrification results in a reduction in environmental impact. This trend contradicts those reported by Gal et al. [10], Qinyu et al. [6], Pipitone et al. [11], and Petrauskiene et al. [12]. This reversal may be attributed to differences in data sets, LCA subject matter, ranges of impact categories, as well as technological advancements in battery and vehicular manufacturing, particularly battery manufacturing and recycling. Consequently, the total lifecycle environmental impact of Evs can be expected to have decreases over the last decade. Additional factors such as improved vehicular technology, resulting in improved fuel economy, changes in energy mixes with a higher share of non-fossil-fuel based energy sources, and lower use of energy-incentive materials can collectively contribute to decreasing the environmental impact of Evs. In comparison to the LCA of HEVs and PHEVs reported by Samaras et al. [4] in 2008, in this study, the disparity in total lifecycle GHG between the vehicle types is much greater. In addition to differences in datasets, the scope of the LCA reported in this study is much broader, by encompassing notable lifecycle stages (such as gasoline production), which were not accounted for in the aforementioned publication. Furthermore, the thorough and transparent breakdown energy consumption and GHG emission calculations within the presented study, particularly in vehicle and battery manufacturing, makes the methodology adopted here more comprehensive and adaptable for future researchers in their quest to obtain a thorough understanding of the environmental impact of various vehicle technologies.

4. Conclusions

At present, there exists a gap in knowledge concerning the environmental impact of a contemporary real-world HEV and PHEVs, throughout the entirety of their lifecycles. The presented research study bridges this gap by presenting a comprehensive cradle-to-grave LCA comparison between Toyota Prius XW50 HEV and PHEV. The LCA investigation systematically quantified the energy consumption and GHG emissions across all stages of the vehicle's lifecycle: from resource extraction to EOL. From this investigation, the following original conclusions were attained:

(1) The WTW fuel cycle phase is the largest contributor to the overall cradle-to-grave lifecycle energy consumption, accounting for 87% and 77% within the HEV and PHEV models, respectively. This can be attributed to the substantial energy intensity of petroleum extraction and refinement, particularly within the context of a fossil-fuel (primarily coal)-dominated energy mix. Increasing the proportion of renewable energy sources in the energy mix can potentially reduce energy consumption, as well as GHG emissions within the fuel cycle phase. This, in turn, would lead to a corresponding reduction in the overall environmental impact.

(2) Throughout the PTW fuel cycle phase, the PHEV model demonstrates a 14.7% reduction in energy consumption, and a 25% reduction in GHG emissions compared to the HEV model. This is attributed to a higher degree of drivetrain electrification, which reduces reliance on the ICE.

(3) Throughout the vehicle lifecycle phase, the PHEV model exhibits a slight (3.2%) increase in energy consumption, and a corresponding rise (5.6%) in GHG emissions, compared to the HEV model. This disparity can partially be attributed to the higher vehicle mass of the PHEV, while the main contributing factors are associated with the manufacturing and recycling of a larger capacity lithium-ion battery. However, this discrepancy is modest when considering the overall environmental impact observed throughout the entire lifecycle.

(4) Despite having a higher vehicular mass, the PHEV model consumes less energy and emits fewer GHG emissions during vehicle component manufacturing (not counting fluids and batteries). This is due to the reduced usage of energy-intensive materials, such as magnesium, alumnium, rubber, and polymers.

(5) Overall, the PHEV model demonstrates a significant reduction of 29.6% in total lifecycle energy consumption and a 17.5% decrease in GHG emissions compared to the HEV model. This is mostly attributed to the higher degree of drivetrain electrification, resulting in superior fuel economy during the usage phase of the lifecycle. This reduces the demand for gasoline production within the energy-intensive upstream WTP fuel cycle phase of the lifecycle.

(6) Based on the lower overall lifecycle energy consumption and GHG emissions, it can be concluded that the PHEV displays a considerably lower environmental impact than the HEV model.

(7) The cradle-to-grave LCA methodology employed in this study has the capability to evaluate and compare the environmental implications associated with a diverse range of drivetrain electrification options, including conventional internal combustion engine vehicles (ICEVs), battery electric vehicles (BEVs), and fuel cell vehicles (FCVs). Additionally, including diesel- and bio-fuel-powered HEVs and PHEVs allows for meaningful assessments of their environmental impact in comparison to gasoline-powered HEVs/PHEVs. Future LCAs could incorporate material input inventories of both virgin and recycled materials to facilitate a comprehensive assessment of their respective environmental impacts.

The comprehensive and transparent methodology of the LCA can be easily adopted by future researchers. The contribution of the presented study has far-reaching implications within various domains. Within the realms of vehicular design, the identification of environmental impact hotspots can aid in design and material selection optimisation, aimed at improving environmental performance. Furthermore, supply chains, material selection and sourcing optimisation can be guided by these insights to minimise environmental burden.

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