Analysis of the carbon footprint of electric vehicles in relation to their life cycle

Análisis de la huella de carbono de los vehículos eléctricos con relación a su ciclo de vida

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ABSTRACT

In order to determine the environmental impact of electric vehicles (EVs), a comparative analysis was made between the CO2 emissions of internal combustion vehicles (ICEs) during their entire life cycle and the emissions of electric vehicles. This study sought to have a more realistic perspective. For this purpose, the life cycle of both types of vehicles was divided into three phases, calculating the kg of CO2 emitted during each of them. The results showed the significant difference in CO2 emissions generated by both types of vehicles, with ICVs generating 32,492 kg of CO2 more than EVs with NCM lithium-ion batteries and 32,403.7 kg of CO2 for those with LFP batteries. Once the analysis was done, it was determined that EVs are an appropriate response to the environmental crisis that the world is currently facing.

Key words: Electric vehicles, emissions, internal combustion vehicles, kg CO2, lithium-ion battery, environmental crisis.

RESUMEN

Con el fin de determinar el impacto ambiental de los vehículos eléctricos (VEs), se realizó un análisis comparativo entre las emisiones de CO2 de los vehículos de combustión interna (VCIs) durante todo su ciclo de vida y las emisiones de los vehículos eléctricos. Este estudio buscó tener una perspectiva más realista. Para esto, se

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dividió al ciclo de vida de ambos tipos de vehículos en tres fases, calculando los kg de CO2 emitidos durante cada una de ellas. Los resultados evidenciaron la significativa diferencia de emisiones de CO2 generadas por ambos tipos de vehículos, siendo los VCIs los que generaron 32,492 kg de CO2 más que los VEs con batería de ion-litio NCM y 32,403.7 kg de CO2 para los que tienen batería LFP. Una vez realizado el análisis se determinó que los VEs son una respuesta apropiada para enfrentar la crisis ambiental que enfrenta el mundo actualmente.

Palabras clave: Vehículos eléctricos, emisiones, vehículos de combustión interna, kg de CO2, batería ion-litio, crisis ambiental.

INTRODUCTION

The Electric Vehicle (EV) has re-emerged as a suitable candidate to respond to the environmental crisis, resulting from greenhouse gas (GHG) emissions, that the planet is currently facing. This has resulted in a growing incidence of these in the global market, accounting for 5.6% of all vehicles sold worldwide in 2022, compared to 0.5% in 2018 (Kwok et al., 2023). Faced with such a prospect, an increasingly growing automotive industry, with a 6% increase in total vehicle production by 2022, according to the Organisation Internationale des Constructeurs d'Automobiles (OICA, 2023), has sought to encourage the implementation of such vehicles in the global market. Ecuador has joined this electrification campaign, with a 56% growth in sales of electrified vehicles in 2022 compared to the previous year (Asociación de Empresas Automotrices del Ecuador [AEADE], 2023).

EVs offer advantages such as reduced maintenance and spare parts usage, zero emissions from the exhaust system and higher efficiency of the power generated by the powertrain (Wang & Santini, 1993). While this may lead to the interpretation that EVs are completely environmentally benign, this is not entirely accurate. The reality is more complex, so a Life Cycle Assessment (LCA) becomes imperative to give a holistic view of the true environmental impact of EVs.

In this study, a comparative investigation of the impact of EVs in relation to their counterpart, Internal Combustion Vehicles (ICEs) in relation to their lifecycle was carried out in order to determine whether the electric alternative satisfactorily meets the global need to reach zero emissions by 2050. In comparison to other related studies, which have focused exclusively on one of the phases that make up the car lifecycle, such as Qiao et al. (2017), who only focus on the Production Phase, this one addresses all aspects involved in the life of both types of vehicles, dividing the research into three parts: Production Phase, Operation Phase and End-of-Life Phase. Unlike other studies that address the entire life cycle, but treat each phase superficially, such as Kawamoto et al, this one focuses on each phase in detail.

In order to determine the emissions produced during the production phase of both types of vehicles (EVs and LCVs) within the analysis, data were extracted from the work of Qiao et al. in order to establish the basis and limits of the study. The data of this research were selected based on the following criteria: they are focused on the Chinese industry, the country of origin of the vehicles with the highest incidence in the Ecuadorian market; the specifications of the vehicle selected as the object of study correspond to the type of vehicle most marketed in Ecuador, being the SUV, in addition to being able to compare the data obtained by Qiao et al. (2019) and Lai et al. (2022); the analysis carried out by Qiao et al. is more extensive and precise, focusing on all the emissions generated during the Production Phase, detailing the CO2 emitted in the manufacture of all the components belonging to the vehicle, as well as taking into consideration their assembly.

To calculate the amount of CO2 produced, the components that make up the car were divided into three families: Basic Components, Special Components and Battery Components and Accessories. Finally, a section is established detailing the emissions emitted during the assembly process. In this way, the difference in emissions produced during the production of EVs and ICVs can be accurately compared. The data is as follows:

Table 1. *Emissions produced during the Production Phase per kilogram of CO2*

Family	Component	Emissions from vcis (kg-CO2)	Emissions from Ves with battery NCM (kg-CO2)	Emissions from Evs with LFP battery (kg-CO2)
Basic Components	Body: including body only, interior, exterior, and glazing	2767,9	4393,5	4393,5
		1684,7	2665,5	2665,5
	Chassis (excluding battery)	2092,5	145,6	145,6
Special Components	Powertrain System	617,4	455,2	455,2
	Transmission System	X	1179,1	1179,1
	Drive Motor	X	1010,2	1010,2
	Electronic Controller	24,5	15,1	15,1
Battery Components and Accessories	Lead-Acid Battery	X	2788,8	2892,4
		230,2	98,3	98,3
	Lithium-ion Battery	677,1	677,1	677,1

Assembly	Fluids	X	141.5	141.5
	Rims	1064,1	1064,1	1064,1
	Total	**9172,5**	**14642,5**	**14746,1**

It can be seen that in both types of EVs, those with NCM battery and those with LFP, the production of LFP accounts for 19% to 20% of the total amount of emissions.

Within the analysis of the Operation Phase there are two fundamental parts to take into account, the first is the calculation of the Carbon Footprint emitted during the operation of the vehicle and the second is the Replacement and Maintenance.

Calculation of the Carbon Footprint emitted during the operation of the vehicle

The calculation of the carbon footprint generated during the operation of both types of vehicles requires combining two methodologies, the GHG Protocol (2003) and ISO 14069 (2013), using actual data from the region studied, Ecuador. In order to perform the calculation, it is necessary to determine the period of time over which the analysis is to be carried out, the recommended period being one year, because the necessary data must be quantified in a cyclical manner.

The method to be used is the so-called "Energy Method" and it is used to calculate the energy production during the established period of time. For this purpose, the amount of energy produced by the country's non-renewable energy sources during the year 2022, the last year for which the information issued by the Agency for Regulation and Control of Energy and Non-Renewable Natural Resources (ARCERNNR) in the publication "Annual and Multiannual Statistics 2022" (2023) is available, where it is determined that the total energy produced by these sources, which in 2022 corresponded to 23.89% of the total number of producing sources, gives a sum of 7884.37 GWh. In turn, it is necessary to use the value of the Emission Factor, which is given by the National Interconnected System and not incorporated in the "2022 Report" (2023), which is 0.5015 Tn CO2/MWh. Finally, the value of the Global Warming Potential (GWP), extracted from the Kyoto Protocol (SEARCH AND PUT), is required. This is equal to 1 Tn CO2-eq/Tn GHG. The calculations are as follows:

HC= Energy Produced ×FE ×GWP Eq. [2.2.1.1].

Where:

HC: Annual Carbon Footprint (Tn CO2-eq).
Energy Produced: Total Energy Produced by non-renewable sources (MWh).
EF: Annual Emission Factor (Tn CO2-eq/MWh).
GWP: Global Warming Potential (Tn CO2-eq/Tn GHG).

This results in an Annual Carbon Footprint value of 3,954,011.555 (Tn CO2-eq/MWh).

Next, the HC emitted during the charging of electric vehicles must be determined. For this it is necessary to calculate the EF per KWh of consumption, which is done with the following formula:

FE= (Total net emissions)/(Total electricity production) Eq. [2.2.1.2].

Where:

FE: Emission factor per unit of energy available for consumption (kg CO2-eq/KWh).

Total net emissions: Annual HC (Tn CO2-eq).

Total electricity production: Total energy produced in a year (MWh).

This determines that the EF per KWh is 0.119499 kg CO2-eq/Kwh.

Then the HC of the vehicle under study has to be calculated. For this purpose, the Kia Soul model was taken as an example, extracting its consumption rates from the research by Murillo & Murillo (2019). To do so, the same formula of the Energy Method was used, modifying the units of the EF obtained to (kg CO2-eq/KWh) or (Kg CO2-eq/L) depending on the type of vehicle analysed. Finally, the variable "Energy Produced" was removed and changed to "Energy Consumed", whose units of measurement are (L/Km) or (KWh/Km) as appropriate. It should be clarified that the EF used for the calculation of the VCI was 2.2 (kg CO2-eq/L) as defined in the GHG Protocol. Thus, the following values were obtained:

$$HCVE = 0.0238 \text{ (kg CO2-eq/km) Eq. [2.2.1.3].}$$

$$HCVCI = 0.189 \text{ (kg CO2-eq/km) Eq. [2.2.1.4].}$$

Finally, from the study by Hernandez et al. (2022) the value of the amount of CO2 emitted on the fuel path from the well to the refuelling stations, to consequently be supplied to the VCI during its entire lifetime, was extracted. Its value is 7432.17 kg CO2, which should be added to the total amount of CO2 generated at the end of the life cycle.

Replacements and Maintenance.

Within the useful life of the vehicle, there are several components that need to be replaced. The periodicity with which they need to be changed will depend on the component in question. The respective information was extracted from Kawamoto et al. and Qiao et al.

Table 2. *Replacement of components during the lifetime of the vehicle.*

Componente	No.	Kg-CO2	Tipo Vehículo	Km
Batería de ion-litio NCM	1	2788,8	VE	160.000
Batería de ion-litio LFP	1	2892,4	VE	160.000
Batería de Plomo-Ácido	3	24.5/15.1	VCI/VE	50.000
Llantas	4	9,1 (unidad)	VCI/VE	40.000
Aceite de Motor	40	3,9	VCI	5.000/1.000
Refrigerante de Radiador	7	7,2	VCI	25.000
Total		**5.753,2/2.743,8**		

Source: Qiao et al. (2017, p. 11); Kawamoto et.al (2019, p. 8).

In the case of engine oil, the data extracted from the literature were modified to adjust them to the reality of the country, defining the periodicity with which it is changed in every five thousand kilometres, excluding the first oil change, which is recommended to be changed after the first thousand kilometres. The same occurred in the case of radiator coolant, defining the value at 25,000 kilometres.

End-of-Life Phase

There is considerable uncertainty concerning the exact values of kg CO2 emitted during the end-of-life stage of an electric vehicle. Values related to recycling and reuse of lithium-ion batteries still remain imprecise and/or undetermined. For this reason, the End-of-Life Cycle Phase (ELC) of this study has been divided into two parts in order to exclude imprecision in the calculation, but to keep the state-of-the-art in the analysis in perspective. Thus, the collected inventory will be presented first in the Treatment of Components, followed by the sub-theme Advances and State-of-the-art.

Treatment of Components

The CO2 emissions regarding the treatment of end-of-life vehicle components have been referenced from Kawamoto et al. where there are four processes, which are applied in the treatment of both types of vehicles, these are: Disassembly, Vehicle Shredding and Sorting, Waste Transport and Waste Disposal. The values for the four processes are shown in table 3.

Table 3. *CO2 emissions during the treatment of vehicles.*

Procesos	**Emisiones de CO2 (kg CO2)**
Desensamblado	X
Trituración y Clasificación de los vehículos	24
Transporte de los Residuos	4
Depósito de los Residuos	38
Total	**65**

Source: Kawamoto et.al (2019, p. 8).

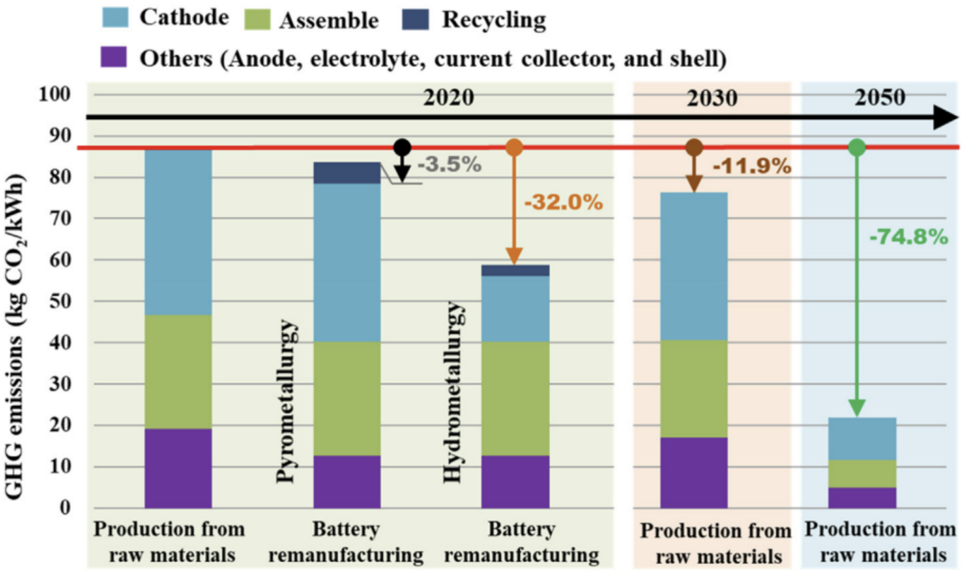
According to Kawamoto et al. the values for the Disassembly process are considerably lower than the rest, so they have not been taken into account.

Progress and future projections

"Following the European directives on the end-of-life of vehicles and waste batteries, vehicles and batteries should be collected and recycled once they have reached their end-of-life" (Koroma, M, S et al., 2022).

From the study by Lai et al. an estimate of the potential for emission reductions generated during the FCV of lithium-ion batteries was extracted. The reuse potential of the batteries was taken into consideration, which can also reduce the emissions generated during the Production Phase. This potential was calculated by combining three battery recycling and reuse methods: pyrometallurgy, hydrometallurgy and physical recycling.

Figure 1. GHG emissions during the production of batteries under recycling and reuse of materials



Source: Lai et al. (2022, p. 16).

Figure 1 shows that by 2030 the carbon footprint generated during the production of lithium-ion battery feedstock has the potential to be reduced by 11.9%. In turn, it can be determined that the hydrometallurgical method is the recommended method to be used.

MATERIALS AND METHODS

The study is focused on analysing the entire lifetime of both types of vehicles (EVs and LCVs). To do so, the amount of CO2 emissions was divided into three different phases, which are detailed below:

1. Production Phase: Extraction of raw material, production of material and its transformation, production of vehicle components, assembly.
2. Operation Phase: Production of electrical energy, combustion of gasoline, replacement of components, vehicle efficiency.
3. FCV: Disposal of components, lithium battery recycling methods.

The study has Ecuador as the study region; however, for the Production Phase and the

FCV, data from different regions were extrapolated because of the lack of the necessary processes in the Ecuadorian environment to provide information about these phases. Thus, for both phases, data was taken from various studies conducted in the United States, Europe and Asia.

Study vehicle

The subject of this study was selected in order to focus the study on the vehicle with the highest incidence and relevance in the market. This will be the one taken into account by Qiao et al. (2017), being the so-called SUV. This class was selected because, according to the information compiled in the "Yearbook 2022", developed by the AEADE (2023) at the end of September 2023, which stipulates that the Ecuadorian automotive market, in terms of light vehicles, is made up of 45.7% of SUVs marketed in the country. Within the Operation Phase, the Kia Soul model was taken as an example, in its electric and petrol version, in order to calculate the HC. This vehicle was chosen because it corresponds to the SUV category, adding that it has the advantage of having both types of vehicles studied.

Table 2. *Component weights of the study vehicle differentiated by ICV and EV (excluding batteries, fluids and tyres)*

Componente	**VCI: Material Convencional (kg)**	**VE: Material Convencional (kg)**
Sistema de Tren de Potencia	**332:** 39,5% acero, 28,6% hierro fundido, 17,1% aluminio fundido, 2,9% cobre/latón, 9,3% plástico, 2,6% caucho	**28.8:** 50% acero, 20,5% cobre/latón, 29,5% plástico
Sistema de Transmisión	**81.4:** 30% acero, 30% hierro fundido, 30% aluminio forjado, 5% plástico, 5% caucho	**55.8:** 60,5% acero, 18,9% cobre/latón, 20% aluminio forjado, 0,2% plástico, 0,4% otros
Motor de Tracción	X	**113.3:** 36,1% acero, 36,1% aluminio fundido, 27,8% cobre/latón
Controlador Electrónico	X	**99.8:** 5% acero, 46,9% aluminio fundido, 8,2% cobre/latón, 3,7% caucho, 23,8% plástico, 12,4% otros
Chasis (sin la batería)	**309:** 84,1% acero, 6,9% hierro fundido, 1% aluminio fundido, 1,2% cobre/latón, 1,8% plástico, 4,4% caucho, 0,6% otros	**488.8:** 84,1% acero, 6,9% hierro fundido, 1% aluminio fundido, 1,2% cobre/latón, 1,8% plástico, 4,4% caucho, 0.6% otros

Cuerpo: incluyendo el cuerpo únicamente, el interior, el exterior y vidrios	**570.1:** 68,3% acero, 0,7% aluminio forjado, 1,9% cobre/latón, 6,5% vidrio, 18,1% plástico, 0,5% caucho, 4% otros	**904.9:** 68,3% acero, 0,7% aluminio forjado, 1,9% cobre/latón, 6,5% vidrio, 18,1% plástico, 0,5% caucho, 4% otros

Source: Qiao el at. (2017, p. 10).

Table 2. *Weights of study vehicle components and number of component replacements taking into account the lifetime of batteries, fluids and tyres.*

Baterías, llantas y fluidos	VCI: Material Convencional (kg)	VE: Material Convencional (kg)	Remplazos
Batería de Plomo-Ácido	**16,3:** 6,1% polipropileno, 69% plomo, 7,9% agua, 0,8% otros	**10:** 6,1% polipropileno, 69% plomo, 7,9% agua, 0,8% otros	2
Batería LFP	X	**230:** 24,4% material activo, 15,2% grafito/carbón, 2,1% aglutinante, 12,4% cobre, 20,3% aluminio forjado, 18,2% hexafluorofosfato de litio. 7,8% carbonato de etileno, 7,8% carbonato de dimetilo, 1,9% polipropileno, 0,3% polietileno, 1,2% tereftalato de polietileno, 1,5% acero, 0,3% aislamiento térmico, 1% glicol, 1% partes eléctricas	0
Batería NCM	X	**170:** 28,2% material activo, 18,3% grafito/carbón, 2,4% aglutinante, 11,4% cobre, 29,7% aluminio forjado, 1,9% hexafluorofosfato de litio. 5,4% carbonato de etileno, 5,4% carbonato de dimetilo, 1,7% polipropileno, 0,3% polietileno, 1,2% tereftalato de polietileno, 1,4% acero, 0,4% aislamiento térmico, 1% glicol, 1,3% partes eléctricas	0
Llantas	**9.1 (por llanta):** 66,7% caucho, 33,3% acero	**9.1 (por llanta):** 66,7% caucho, 33,3% acero	3

Aceite de Motor	3,9	X	39
Líquido de Freno	0,9	0,9	3
Líquido de Transmisión	10,9	0,8	1
Líquido Refrigerante	10,4	7,2	3
Refrigerante de Radiador	**2,7**	**2,7**	**19**

From tables 1 and 2 it can be concluded that the net weight (taking into account battery, tyres and fluids) of the ICV is 1387.8 kg. In turn, it can be concluded that the net weight of the EV with NCM (Nickel-Cobalt-Manganese) battery is 1933 kg and with LFP (Lithium-ferrophosphate) battery is 1993 kg.

Lifetime

"In order to perform an LCA study of an automobile, it is required to define the service life based on the distance travelled as a functional unit" (Kawamoto et al., 2019). Based on the study by Kawamoto et al. (2019), this research has defined 200,000km as the useful life period of an automobile. This is because, as explained in the aforementioned study, it is the approximate average, rounded to values of multiples of 100,000, of the values extracted from the following literature:

Table 4. *Useful life values according to literature.*

Estudio	**Valor de Vida útil (km)**
BMW (2016)	150.000
Daimler (2018)	160.000
Ellingsen et al. (2016)	180.000
Messagie (2014), Audi (2012)	200.000
Amarakoon et al. (2013)	193.120
Ellingsen et al. (2016)	320.000
Toyota (2018)	100.000
Mazda (2017)	110.000
PROMEDIO	**176.640 ≈ 200.000**

Source: Kawamoto et al. (2019, p. 4).

These values were selected because the research by Kawamoto et al. carried out a study sectioned into 5 different regions, namely Australia, the United States, Europe, Japan and China, so the value they used is intended to be used universally.

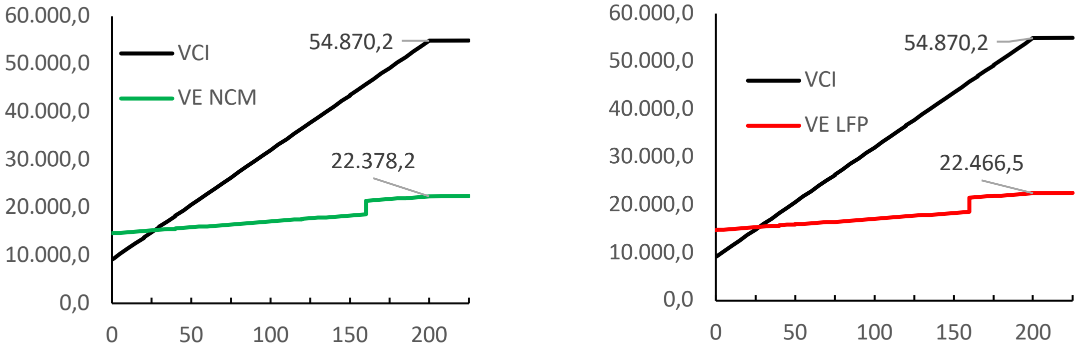
RESULTS

Life cycle environmental impact

The comparison of the calculation of the carbon footprint generated during the entire life cycle of EVs and ICVs is presented in Figure 1. It projects the sum of all the kilograms of CO2 emitted during each of the life cycle phases, starting with the base values of the total emissions generated in the Production Phase and ending with the last values generated in the FCA, whose relatively insignificant values are projected in a flat closure, concluding the relatively linear growth that is reflected during the useful life of the vehicles.

In order to project a growth as close as possible to the actual growth of the total 7432.17 kg CO2 emitted during the transport of fossil fuels over the entire lifetime of the ICV, the proportional emitted up to the mileage value of each of the necessary replacements and maintenance was used.

Figure 2. Emissions produced during life cycle



Source: Authors, 2024

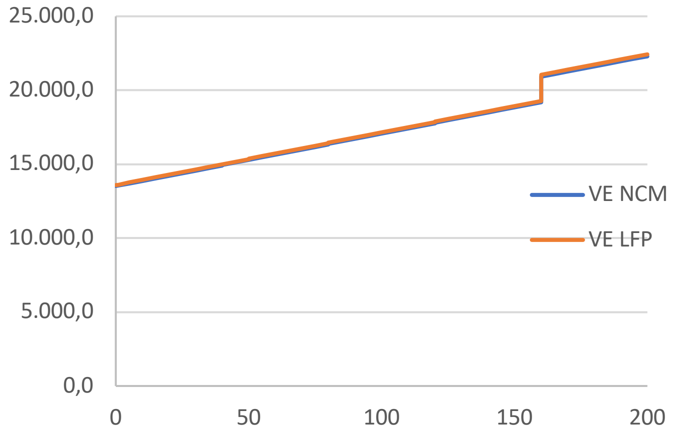
As can be seen in Figure 2, the CO2 emissions generated during the Operation Phase of both types of EVs are relatively null, mainly affected by maintenance and component replacements, with the replacement of the lithium-ion battery having the greatest impact. Finally, it can be seen that after approximately 30,000 kilometres of operation, the carbon footprint of ICVs exceeds that of EVs.

In total, the emissions generated during the lifetime of EVs are divided into 22,378.2 kg CO2 for EVs with NCM batteries and 22,466.5 kg CO2 for those with LFP batteries. In the case of ICVs, emissions total 54,870.2 kg CO2. Finally, it is necessary to add the 65 kg CO2 emitted during the End-of-Life Phase to the total of the three types of vehicles.

Estimation of the future environmental impact of the implementation of new technologies

In the studies of Lai et al. and Murillo & Murillo there is a potential to reduce the carbon footprint of EVs. Figure 3 shows an estimate of the possible emissions that will be generated in 2030 by EVs. From Lai et al. the value of electric battery production using the hydrometallurgy method was extracted. For the calculation a HC of 0.0345 (kg CO2-eq/km) was used, calculated in consideration of the projections of Murillo & Murillo. The HC of EVs is higher due to the increase in electricity production at country level. For calculation purposes, the specifications of the selected vehicle, the Kia Soul, were maintained. Similarly, the kg CO2 values of the other components involved in the Production Phase, as well as the necessary lifetime replacements, were maintained in the absence of further information in the literature, excluding the lithium-ion batteries.

Figure 3. Emissions produced during the life cycle.



Source: Authors, 2024

From Figure 3 it can be concluded that the values for EVs with NCM and LFP batteries have as final values 22,290 kg CO2 and 22,427.4 respectively. The increase of the HC of the vehicle was responsible for the minimal reduction of CO2 emissions generated by the EVs during their lifetime.

DISCUSSION

The electric vehicle, despite emitting 37% more kg of CO2 during its manufacture, is 60% less polluting than the internal combustion vehicle over its entire life cycle. This is due to its very small carbon footprint generated during its use phase, emitting 83% less kg of CO2 during its lifetime. Due to this it can be determined that the electric vehicle is currently the most environmentally friendly commercial option.

It is important to clarify that within the analysis the values of kg CO2 generated during the irresponsible disposal of lithium-ion batteries were excluded due to uncertainty and lack of accurate information. Taking into account the above, it is imperative to recognise that the calculation of the carbon footprint of electric vehicles is not accurate and that the actual CO2 emission generated by electric vehicles may be significantly higher than the one presented in this paper.

Due to the uncertainty of the current scenario, a projection into the future was included in the analysis, where it is foreseen that the treatment of vehicle waste will be more controlled and monitored, giving greater accuracy in the data obtained.

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