Environmental impacts of batteries for transportation application according to different life cycle steps

Clotilde ROBERT
GAUSSIN GROUP, Héricourt
FEMTO-ST, CNRS, Univ. Bourgogne Franche-Comté,
France
c.robert@gaussin.com

Alexandre RAVEY
FEMTO-ST, FCLAB, UTBM, CNRS, Univ. Bourgogne Franche-Comté
France
alexandre.ravey@utbm.fr

Raphaël PEREY
GAUSSIN GROUP, Héricourt
France
r.perey@gaussin.com

Daniel HISSEL
FEMTO-ST, FCLAB, CNRS, Univ. Bourgogne Franche-Comté
France
daniel.hissel@univ-fcomte.fr

***Abstract*—Knowledge of the environmental impact at different steps of the battery life cycle is essential due to the environmental and geopolitical tensions surrounding the electric vehicles. Because of the diversity of data on this subject, it is difficult to deduce which battery chemistry has the least impact on the environment. In this paper, a method to determine the environmental impact of batteries for raw material extraction, batteries production, transport, end-of-life, and recycling is proposed. The analysis shows that the lead-acid battery has a lower global warming potential than lithium batteries for the same energy.**

Keywords—battery, environmental impact, global warming potential

I. Introduction

To reduce the share of greenhouse gas emissions from transportation, the electrification of vehicles has increased considerably over the past 10 years, leading to a 33% increase in Lithium-ion battery production between 2019 and 2020 ([1], [2]).

The interest of the vehicles electrification on the climate is often questioned in public debates with the justification of the batteries environmental impact. Indeed, the battery production and the raw materials extraction represent a drastic part of greenhouse gas emissions in the battery life. Moreover, the emissions linked to the battery transportation from their production place to their assembly place are added to these last. What is the greenhouse gas emissions value of a battery during its different life step? Does this value vary depending on the battery chemistry used?

For a given battery chemistry, different values of greenhouse gas emissions are found in the literature. These differences are mainly due to the steps considered in the battery life cycle and the functional unit chosen. Taking all these parameters into consideration, it becomes difficult to establish a greenhouse gas emission value for a battery chemistry in order to deduce which one has the least impact on the environment.

To solve the data discrepancy problem, a statistical study is performed on the data collected in several publications. This study focuses on battery's chemistry used in transportation application i.e., Lead and Lithium technologies. The selected chemistry used in this paper are: Lead-Acid (PbA) Lithium-iron Phosphate (LFP), Nickel Manganese Cobalt (NMC), Nickel Manganese Aluminum (NCA), Lithium Manganese Oxide (LMO) and Lithium Titanate Oxide (LTO).

A first analysis is performed on the battery raw materials extraction and production emissions. Then a second analysis is, on one hand, to determine the distribution between battery raw materials extraction and production and, on the other hand, battery raw materials extraction, production, and end-of-life (EoL). The next step is to calculate the recycling impact on the emissions related to raw materials extraction and production. Finally, the battery transportation emissions from their production site to the vehicle assembly site are calculated.

Although the disparity of greenhouse gas emission values is noted in several publications ([3], [4]), no explicit choice is made among all proposed values. This article proposes an informed choice between all the proposed emission values as well as a comparison between the batteries used in embedded applications.

II. Background

To know the batteries environmental impact, the Global Warming Potential (GWP) is generally used. It measures the effect of all greenhouse gases on the climate, based on CO_{2eq} unit. In the energy storage field, GWP is expressed in terms of weight, energy capacity or energy delivered. The GWP is calculated according to different life cycle steps: it can cover the steps from raw material extraction to production ([4]–[8]) or be extended to the end of life of the battery ([5]). In addition, the production location, and the use of recycled materials in the battery design have a strong impact on GWP. For example, if the batteries are designed in a country where electricity production is heavily dependent on the use of coal, the GWP is higher compared to a battery design located in a country where electricity is produced using nuclear power ([6], [9]). The GWP is also higher if the battery is built from virgin materials rather than recycled materials ([5], [6]).

The influence of each life cycle steps on the total GWP varies depending on the steps included within the studies. Generally, the production is either decomposed into 2 sub-steps, which are the raw materials extraction and the battery production ([9]–[12]), or considered as a whole ([13], [14]). The same phenomenon is present for the end-of-life: it can be thought in its entirety or decomposed into 2 steps, which are recycling and end-of-life. The use phase includes the electricity used for the operation of the battery, maintenance, and replacement of the battery ([8], [13], [14]). Between these steps, different paths of transport are studied: the first one is the transport between the manufacturing steps ([9], [14]), the second one is the transport between the production site and the vehicle assembly site ([5], [15]).

Following this definition of GWP, 5 life cycle steps are chosen: raw materials extraction, battery production, transportation, end-of-life, and recycling (see Figure 1). The transportation stage illustrates the transportation from the battery production site to the vehicle assembly site. The end-of-life step includes landfill, battery dismantling, the transportation associated with this step and the transportation to recycling site. Recycling reduces the emissions associated with the extraction of materials and the production of the battery.

For each step, a percentage allocation is given following statistical studies of several references for each battery category.

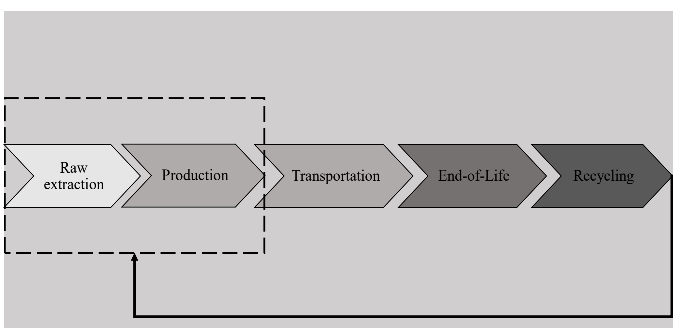

Figure 1 : Life cycle steps

III. Determination of the Global Warming Potential related to the differents sectors

A. Equations definition

The total greenhouse gas emissions is the sum of the emissions related to the steps: raw materials extraction, battery production, transportation, end-of-life and recycling (see Equation 1).

$$GWP_{total} = \left| \begin{array}{l} GWP_{extraction} + GWP_{production} + \\ GWP_{transport} + GWP_{EoL} + GWP_{recycling} \end{array} \right. \quad (1)$$

Each sector has an impact rate τ. The impact rate is different for each sector and each battery chemistry studied (Equation 2). It is defined as the ratio of sector emissions to total emissions (Equation 3).

$$1 = \left| \begin{array}{l} \tau_{extraction} + \tau_{production} + \tau_{transport} + \tau_{EoL} + \tau_{recycling} \\ \text{With } \tau_{recycling} < 0 \end{array} \right. \quad (2)$$

$$\tau_i = \frac{GWP_i}{GWP_{total}} \text{ with } i = \begin{cases} extraction \\ production \\ transport \\ EoL \\ recycling \end{cases} \quad (3)$$

Recycling has a positive impact on the GWP of a battery's life because it reduces the proportion of virgin materials in batteries, and therefore has a direct impact on the raw materials extraction and production step (Equation 4).

$$GWP_{\substack{extraction \\ production \\ recycling}} = GWP_{\substack{extraction \\ production}} - GWP_{recycling} \quad (4)$$

Greenhouse gas emissions without transportation are presented in Equation 5. Raw emissions are defined as the sum of the emissions from the raw materials extraction, battery production and battery end-of-life steps (Equation 6).

$$\begin{cases} GWP_{\substack{total \\ without\ transport}} = GWP_{total} - GWP_{transport} \\ 1 = \tau'_{extraction} + \tau'_{production} + \tau'_{EoL} + \tau'_{recycling} \end{cases} \quad (5)$$

$$\begin{cases} GWP_{raw} = GWP_{\substack{extraction \\ production}} + GWP_{EoL} \\ 1 = \tau''_{extraction} + \tau''_{production} + \tau''_{EoL} \end{cases} \quad (6)$$

B. *Method for the calculation of total greenhouse gas emissions*

Figure 2 describes the method used to calculate the total GWP for each battery category.

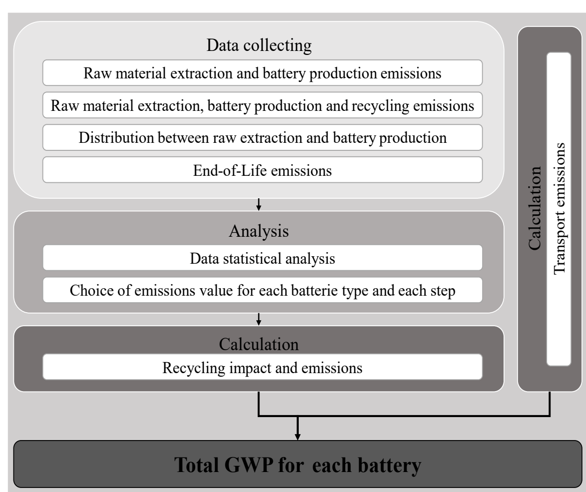

Figure 2 : GWP Determination Method

First, the greenhouse gas emissions from the raw materials extraction step are combined with the emissions from the battery production. Indeed, in many publications, the emissions are given for both steps together ([5], [6], [9], [16], [17]). Secondly, the distribution of emissions between the raw materials extraction step and the battery production is defined thanks to the study of references ([10], [17]).

Once this distribution is known, studies are done on the greenhouse gas emitted at the end of the battery's life and on the greenhouse gas sum of raw material extraction, battery production and recycling.

The same statistical analysis is carried out for these 3 steps. This analysis consists of listing all the data found and comparing them by calculating the average, the median and looking for the extremes. The selected value is chosen according to 3 criteria: the quality of the data provided, its validity and its concordance with the analysis performed.

At this level, the first result obtained gives the raw greenhouse gas emissions for each type of battery studied, i.e., GWP for the raw materials extraction, production, and end-of-life steps.

The impact of recycling is then found using Equation 4 and the data from the statistical study led.

C. *Presentation and treatment of collected data*

a) Raw emissions

The first table shows the distribution of emissions between raw material extraction and production for each battery type.

TABLE 1: GWP REPARTITION FROM RAW MATERIAL EXTRACTION AND PRODUCTION

Battery type	Raw material extraction [%]	Production [%]	References
PbA	68.14	31.86	[7], [12], [18]
LFP	60.26	39.74	[10], [17]
NMC	65.88	34.12	[10], [17]
NCA	18.00	82.00	[19]
LMO	90.97	9.03	[6], [17]
LTO	15.00	85.00	[19]

Emissions for virgin material extraction and production are given in Table 2. These emissions do not consider the impacts of recycling. For the NMC, NCA and LMO batteries, the value given represents the average of the emissions found in the cited references. For the LFP battery, the median is calculated to keep a better representation of the values found. For the LTO battery, only one value is found. Finally, for the PbA battery, the emission distribution given in Table 1 is applied to the value from reference [5] to calculate the emissions related to extraction and production.

To find the share of emissions due to the end-of-life of batteries, two methodologies are implemented.

The first one is to remove the share of emissions due to operation and recycling and to keep only the share of emissions for extraction, production, and End-of-Life. It applies in the case where the share of emissions related to recycling is differentiated from that related to End-of-Life ([5], [10], [13]).

The second method applies in the case where End-of-Life and recycling are combined ([15], [17], [20]). First, the share of emissions related to operation and/or transport is subtracted. Then the share of emissions due to recycling (see Table 5) is subtracted from the share of emissions from end-of-life and recycling. The results are presented in Table 3.

By combining the emissions distributions presented in Table 1 and Table 3 with the emissions values in Table 2, Figure 3 illustrating the raw emissions for each battery category is obtained.

TABLE 2: GWP FROM RAW MATERIAL EXTRACTION AND PRODUCTION WITHOUT RECYCLING

Battery type	GWP [$kgCO_{2eq}$/kWh]	References
PbA	146.76	[5]
LFP	164.78	[5], [17], [21]
NMC	154.89	[4], [5], [19]
NCA	142.75	[4]
LMO	116.32	[4], [19]
LTO	185.00	[4]

TABLE 3: BREAKDOWN OF GWP BETWEEN RAW MATERIAL EXTRACTION AND PRODUCTION AND END-OF-LIFE

Battery type	Raw material extraction & production [%]	EoL [%]	References
PbA	87.61	12.39	[12]
LFP	72.36	27.64	[5], [10], [17], [20]
NMC	96.30	3.70	[13]
NCA	55.22	32.66	[5]
LMO	54.79	45.21	[15]
LTO	91.58	8.42	[22]

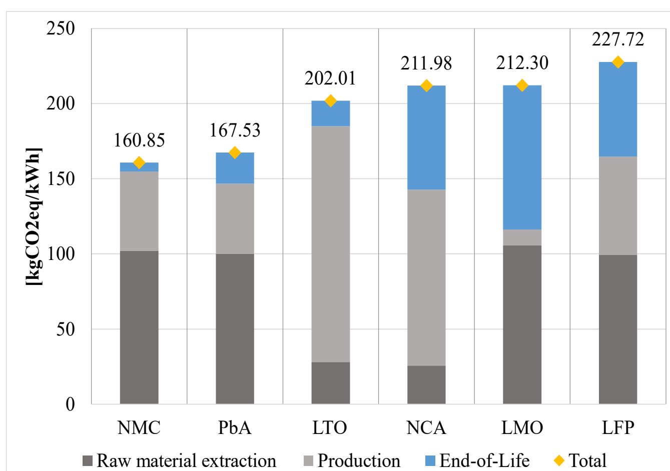

Figure 3 : Raw GWP

b) Addition of the recycling impact : total emissions without transport

Table 4 is like Table 2 except that the emissions provided for extraction and production consider the recycling of materials. For PbA, LFP and NMC batteries, the emission value represents the average of the data found in the cited references. For NCA and LMO batteries, only one value is found. For the LTO battery, no data is available in the literature.

Using equations 4 and 5, the gain and share of recycling emissions are known (see Table 5). Since recycling emissions data for LTO batteries are not available in the literature, they were estimated using reference [22] and the following equation:

$$GWP_{recycling} = \tau'_{recycling} . GWP_{\substack{total \\ without\ transport}} \quad (7)$$

Combining the data from paragraph a) with the emissions from the recycling part, Figure 4 is obtained.

TABLE 4: GWP FROM RAW MATERIAL EXTRACTION AND PRODUCTION WITH RECYCLING

Battery type	GWP [$kgCO_{2eq}/kWh$]	References
PbA	47.77	[7], [23], [24]
LFP	64.50	[6], [14]
NMC	122.52	[9], [13]
NCA	55.85	[5]
LMO	60.5	[14]
LTO	Data unavailable	No reference

TABLE 5: GWP GAIN FROM RECYCLING AND IMPACT ON THE DISTRIBUTION OF EMISSIONS

Battery type	GWP [$kgCO_{2eq}/kWh$]	Impact [%]
PbA	-98.99	-144.44
LFP	-100.28	-78.68
NMC	-32.37	-25.20
NCA	-86.90	-60.87
LMO	-55.82	-35.67
LTO	-35.23	-17.44

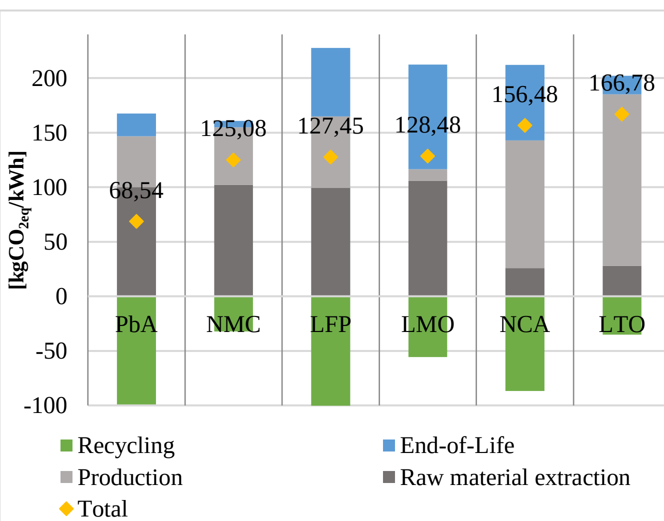

Figure 4: GWP total without transport

D. Calculation of transport greenhouse gas emissions

First, the location of the suppliers is studied. Lithium batteries are mainly manufactured in China, Europe, and the United States. Acid batteries are mostly made in China or Germany.

The transport is carried out according to 3 major modes which are: ship, truck, and train. Each mode of transportation has its own emission factor (F_e) (see Table 6) ([25]). This factor expresses the equivalent CO_2 emissions released according to the ton transported and the kilometer traveled. Thus, for a transport by ship, the container ship is differentiated from the ferry. In the same way as the diesel train is differentiated from the electric train used in Europe and the electric train used in France. For the transport by truck, two container weights are considered: 26 and 40 tons.

TABLE 6: EMISSION FACTOR DEPENDING ON TRANSPORTATION MODE

Transportation mode	F_e [$gCO_{2éq}/(t.km)$]
Container ship (CS)	10.70
Ferry (F)	73.45
Truck 26 tons (T_{26})	161.00
Truck 40 tons (T_{40})	94.00
Electric train in Europe (ET_{EU})	13.50
Electric train in France (ET_F)	1.55
Diesel train (DT)	28.10

The distances are obtained from the site referenced in [25] and depend on the mode of transportation chosen. They are calculated from the battery production site to the vehicle assembly site. In this study, the vehicle assembly site is in Héricourt, France. The battery production sites considered are China, Germany, Morocco, the United Kingdom (UK) and the United States (US), with their capital cities as reference points. The tables below show the distance travelled depending on the battery production site and the main mode of transport chosen. Emissions are calculated for each trip by multiplying the distance traveled by the transportation mode by the emissions factor:

$$GES_{transport} = M_{transported} \sum_i Fe_i . D_i \ \text{ with } i = \begin{cases} CS \\ F \\ \dots \\ DT \end{cases} \quad (8)$$

With:

- F_e = emission factor [$gCO_{2eq}/(t.km)$]
- D = distance travelled [km]
- $M_{transported}$ = transported mass [t]

If the majority mode of transportation is by container ship, the weight transported is 40 tons, otherwise 26 tons (see Table 7, Table 8, Table 9).

The GWP due to transportation is obtained by dividing the sum of the emission factors by the battery energy density of the batteries (E_s) multiply by the transported mass:

$$GWP_{transport} = \frac{GES_{transport}}{M_{transported} . E_s} \quad (9)$$

With:

- E_s = specific energy [Wh/kg]

Finally, by combining equations 8 and 9, the transportation emissions for each battery type are independent of the mass transported:

$$GWP_{transport} = \frac{1}{E_s}\sum_i Fe_i.D_i \quad (10)$$

The GWPs are calculated for each chemistry. Then, the GWP used for transportation is the maximum GWP obtained for all presented parameters. shows the maximum GWP found for each battery type. For each battery type, the GWP is maximum for a production site in China and most of the transport made by truck. The transport emissions of PbA batteries are higher than for Lithium batteries due to their low energy density.

TABLE 7 : DISTANCE TRAVELLED FROM THE BATTERY PRODUCTION SITE TO THE VEHICLE LOADING SITE FOR TRANSPORT BY TRUCK

Production site	**Travelled distance [km]**		**Emissions [tCO_{2eq}]**
	(T_{26})	(F)	
China	9301.80	0.00	38.94
Germany	573.89	0.00	2.40
Morocco	2690.48	31.43	5.66
UK	1336.64	40.16	5.67

TABLE 8 : DISTANCE TRAVELLED FROM THE BATTERY PRODUCTION SITE TO THE VEHICLE LOADING SITE FOR TRANSPORT BY CONTAINER SHIP

Production site	**Travelled distance [km]**		**Emissions [tCO_{2eq}]**
	(CS)	(T_{40})	
China	17143.13	2241.26	15.76
US	10442.81	1274.09	9.26
Morocco	1954.89	859.61	4.07

TABLE 9 : DISTANCE TRAVELLED FROM THE BATTERY PRODUCTION SITE TO THE VEHICLE LOADING SITE FOR TRANSPORT BY TRAIN

Production site	**Travelled distance [km]**			**Emissions [tCO_{2eq}]**
	(ET_{EU})	(ET_F)	(DT)	
China	1477.08	169.44	303.15	3.35
Germany	452.73	169.44	34.43	0.19
UK	667.61	724.21	0.00	0.26

TABLE 10: GWP FROM TRANSPORTATION

Battery type	**E_s [Wh/kg]** (1C@25°C)	**$GWP_{transport}$ [$kgCO_{2eq}$/kWh]**
PbA	40.00	37.40
LFP	151.30	9.90
NMC	207.40	7.20
NCA	200.00	2.00
LTO	80.00	18.70
LMO	128.60	11.60

IV. RESULTS AND DISCUSSIONS

Based on the presented results in Figure 5, three notable points can be observed:

- Recycling allows a reduction of 51% on average of the GWP total;
- Transportation has small impact on the total GWP of the battery life cycle, since it represents only 12% of the total GWP;
- The extraction of materials is, on average, the stage that emits the most greenhouse gases (about 56% of the total GWP).

The impact of recycling is dependent on the development of recycling channels. Thus, for a high degree of maturity of the battery, the recycling impact is more important. Nevertheless, this impact should be considered with care because not all batteries are recycled.

Among the batteries for transport, the PbA battery has the least impact on the environment and the LTO the most one.

Finally, even if at first glance the PbA battery turns out to be less impactful for the environment than the Lithium batteries, the energy density also needs to be considered in the choice of a more environmentally friendly battery. Indeed, the the PbA battery energy density being 3 to 4 times lower than that of Lithium batteries. So, to design a system with the same energy capacity of battery, it is necessary to have 3 to 4 times more PbA battery than Lithium batteries.

Following this article and as a perspective, the social impact of batteries will be determined. The knowledge of the social impact of batteries will allow to make an informed choice for the dimensioning of an electric drive train.

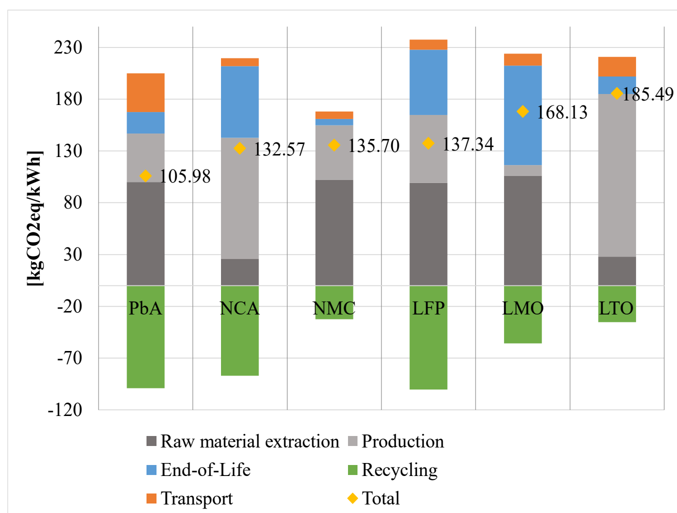

Figure 5 : GWP total

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