Global warming potential of batteries for vehicle applications, from production to recycling

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ABSTRACT

This study provides a structured review and synthesis of existing Life Cycle Assessment (LCA) studies on six battery chemistries—PbA, NMC, LFP, NCA, LTO, and LMO—commonly used in transportation applications. Rather than conducting a new LCA, this work compiles and analyzes data from multiple sources to establish a comparative framework for assessing the global warming potential (GWP) of these technologies.

The analysis focuses on emissions generated across key life cycle stages, including material extraction, battery production, transportation, recycling, and end-of-life, while integrating uncertainty through a data quality indicator. Results indicate that the average GWP for lithium-based batteries is 110.3 $kgCO_2eq/kWh$, with recycling processes reducing emissions by approximately 39.7%. Lead-acid batteries exhibit a lower GWP (67.7 $kgCO_2eq/kWh$) but are technically outperformed by lithium-based chemistries in energy density and cycle life.

The findings highlight the need for a holistic approach in battery selection, emphasizing the importance of integrating technical performance indicators such as energy density, charge/discharge cycles, and recyclability when assessing environmental impact. This study supports the development of eco-efficient energy storage solutions and informed decision-making for sustainable transportation applications.

KEYWORDS

Battery; Global warming potential; Lithium battery; Lead battery; Life cycle Analysis; CO_2 equivalent

1. Introduction

In the current context of energy transition, lithium-ion batteries have become essential for all electric vehicles. In response to the increasing demand for electric vehicles, the production of lithium-ion batteries experiences a spectacular growth: their usage has gone from 20 GWh in 2010 to 160 GWh in 2018, with an estimated 4 TWh in 2040 considering the continuous increase in their production [1]. Due to this increase, the environmental impact of lithium-ion batteries must be evaluated to determine their true contribution to reducing greenhouse gas emissions.

Evaluating the global warming potential (GWP) of battery chemistries is crucial in aligning with the United Nations Sustainable Development Goal (SDG) for affordable and clean energy. As electric vehicles play a key role in the transition to sustainable energy, it is essential to ensure that the batteries used contribute meaningfully to reducing emissions throughout their lifecycle. By understanding the GWP, we can make more informed decisions that support SDG 7 and the broader sustainability goals.

The environmental impact of batteries is evaluated based on their GWP, expressed in CO_2 equivalent (CO_2eq), using a Life Cycle Assessment (LCA) approach. This method quantifies emissions associated with each stage of the battery life cycle.

LCA can be performed from cradle-to-grave, including all stages from raw material extraction to end-of-life. In this study, the system boundaries are defined as material extraction, battery manufacturing, transportation from the production site to the vehicle assembly site, end-of-life, and recycling (Fig. 1). The use phase is omitted to ensure broad applicability of the results, as battery performance and energy consumption vary depending on the application and external factors. This boundary selection aligns with previous LCA studies that focus on the manufacturing and end-of-life impacts of batteries [2].

The battery manufacturing stage encompasses all processes related to the assembly of battery components, while the end-of-life stage includes dismantling, destruction, or landfill disposal. Battery recycling is also considered a crucial stage, as it offsets emissions from raw material extraction and manufacturing, thereby reducing reliance on virgin materials. Although recycling processes remain costly and energy-intensive, they contribute significantly to minimizing the environmental footprint of battery technologies [3].

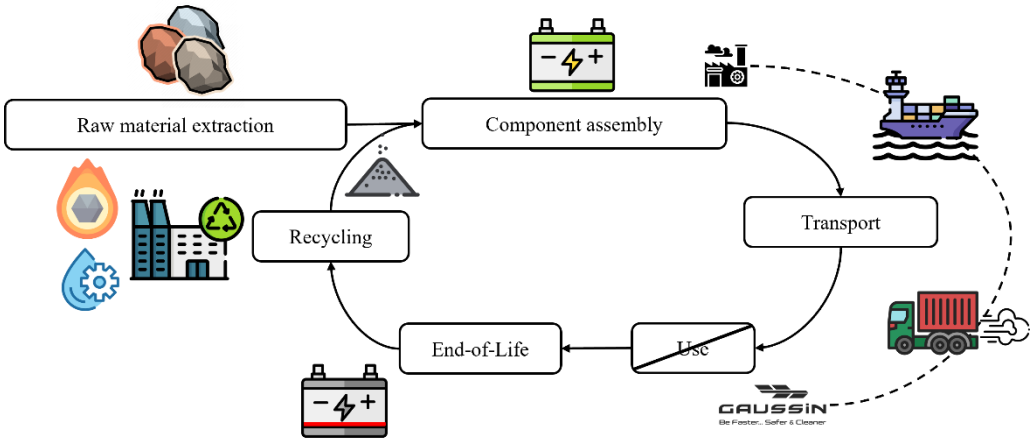

Fig. 1. Stages considered in life cycle analysis.

In this article, a comparison of the global warming potential of six commonly used battery technologies in the transportation sector is carried out [4]. The battery technologies are as follows: lead-acid (PbA, PbO_2/Pb with H_2SO_4 electrolyte), lithium iron phosphate (LFP, $LiFePO_4$), lithium nickel cobalt aluminum (NCA, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$), lithium nickel manganese cobalt (NMC, $LiNi_xMn_\gamma Co_{(1-x-\gamma)}O_2$), lithium manganese oxide (LMO, $LiMn_2O_4$), and lithium titanate oxide (LTO, $Li_4Ti_5O_{12}$).

Although PbA batteries are not used as the primary propulsion system for electric vehicles, they serve as a relevant benchmark in this study due to their well-established recycling process and long-standing use in transportation for auxiliary applications [5]. Their mature supply chain, from production to recycling, offers a valuable reference point when evaluating the sustainability of emerging lithium-based battery chemistries.

To conduct a meaningful comparative analysis of these chemistries, this study compiles and evaluates existing life cycle assessment data rather than introducing new values. The objective is to provide a standardized comparative framework for the global warming potential of various battery chemistries while integrating uncertainty considerations to support informed decision-making in eco-design.

The functional unit used is the energy capacity of the battery in kWh.

The aim of this work is to establish a reference global warming potential for batteries widely used in the transportation industry and enable industry professionals and researchers to have an initial comprehensive yet fair approach in making an environmental choice for a specific battery chemistry. In a first time, the global warming potential for the production stages of batteries, with and without recycled materials, is identified for each battery chemistry through a literature review. Due to the diversity of references, a data quality indicator is assigned to each of them to deduce an uncertainty in the presented results. Finally, we compare the global warming potential found for each battery with their technical characteristics.

2. Background analysis

The growing demand for electric vehicles sparks an increase in the production of lithium-ion batteries, which are central to this technological shift. However, the environmental impact of these batteries, especially their GWP, must be carefully analyzed across their entire lifecycle. This section provides an overview of the literature and key findings on the GWP of various battery chemistries, focusing on material extraction, battery production, end-of-life, and recycling processes. By synthesizing data from multiple sources, the analysis aims to inform the selection of more sustainable battery technologies for electric vehicle applications.

2.1. Literature review

The literature review includes around 60 references published over the last 15 years, including scientific articles as well as some research reports conducted by public organizations [6], [7], [8], [9], [10]. The references come from different countries to cover a wide range of perspectives such as the location of battery manufacturing as well as the recycling method used. They are listed in the Table A. 1. in chronological order, according to battery chemistries, year and countries of publication.

The information's collected relates to the global warming potential at the stages of material extraction, battery production, end-of-life, and recycling, as well as the distribution of emissions within the battery manufacturing process, between material extraction and production stages. The functional unit of the references corresponds to the one used in the article, which is the energy capacity of the battery in kWh. In general, the references covered in this article deal with life cycle assessment in the field of energy storage and transportation, with results expressed in $kgCO_{2eq}$/kWh, and with publication years after 2010.

By selecting references based on the desired criteria, this review includes 62 articles. The publication year of the articles range from 2010 to 2024. Starting from 2016, an increase in publications about the environmental impact of batteries is observed (Fig. 2): nearly 80% of the studied articles are published in or after 2016.

This interest in environmental impact is not visible across all chemistries. PbA, LMO and LTO batteries remain a minority in these studies, while significant interest has emerged since 2020 for NMC and LFP batteries (Fig. 2). This perceived trend in publications is largely explained by the market share held by these batteries. In 2020, the battery market in China is dominated by NMC batteries at over 80%,

while in 2011, 75% of the Chinese battery market is dominated by LFP batteries. Interest in the global warming potential of LFP batteries has increased since 2020, possibly due to Tesla's announcements regarding the use of LFP batteries in their vehicles [11].

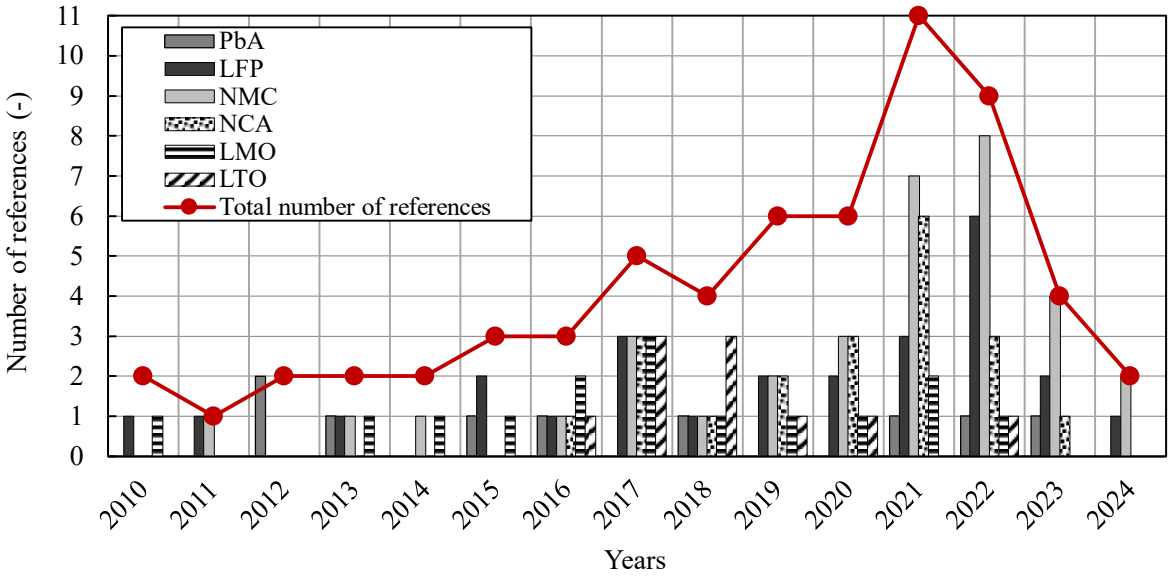

Fig. 2. Evolution of the total number of references meeting the search criteria over the years, according to the studied battery chemistry or chemistries.

Of all the references studied, less a quarter of them come from China and just under 20% from Germany (Table A. 1). More broadly, nearly 52% of the references come from Europe, 30% from the Asian continent, and 11% from America. These contrasts are largely explained by the differences between the environmental policies pursued on these continents.

Generally, in Europe, these policies are stricter than in other parts of the world. Many European countries implement a series of directives that impose high environmental standards, such as the European Union Emissions Trading System which aims to reduce greenhouse gas emissions on the continent [12]. In Asia, although the situation varies greatly from one country to another, some countries like China initiate the “Energy Revolution Strategy” [13] to reduce air and water pollution. Finally, in America, and more specifically in the United States, environmental policy is influenced by the political party in power. For example, under the Obama administration, measures are taken to reduce greenhouse gas emissions and promote electric vehicle [14], but under the Trump administration, these measures are largely abandoned [15].

In addition to regional environmental policies, battery chemistry also plays a significant role in sustainability considerations. Although lead-acid (PbA) batteries are not typically used for propulsion in electric vehicles, they remain relevant for comparison in this study due to their extensive use in auxiliary applications within the transport sector. PbA batteries also represent the most mature battery technology, with a long history dating back to the industrial revolution [16]. Their high recyclability—accounting for over 85% of secondary lead production [17]—serves as a benchmark for evaluating the sustainability of newer battery chemistries. Including PbA batteries allows for a comprehensive life cycle analysis and highlights best practices for future improvements in lithium-ion battery recycling.

2.2. Qualification of the references studied

The references cited in Table A.1 exhibit varying levels of reliability and quality, which necessitates a rigorous evaluation process to avoid overemphasizing low-quality data. To achieve this, a data quality indicator (DQI) is applied, providing a quantitative measure of uncertainty in the collected data.

The DQI framework, based on [18], is specifically designed for references related to Life Cycle Assessment studies. This methodology introduces uncertainty by assessing six key factors that influence the reliability of reported environmental impact values:

- Baseline Uncertainty (U_1) - Represents the fundamental variability of environmental impact indicators in the dataset.
- Reliability (U_2) - Verifies whether the data has been experimentally validated or derived from literature reviews.
- Completeness (U_3) - Assesses whether the dataset is representative of the studied system.
- Temporal Correlation (U_4) - Evaluates the alignment between the reference's publication year and the study's timeframe.
- Geographical Correlation (U_5) - Examines whether the reference data aligns with the geographical scope of this study.
- Technological Correlation (U_6) - Assesses whether the reference data comes from relevant sources, such as industrial applications or laboratory studies.

Table 1
Uncertainty factors

Indicator score	1	2	3	4	5
Reliability (U_2)	0.000	0.0006	0.002	0.008	0.04
Completeness (U_3)	0.000	0.0001	0.0006	0.002	0.008
Temporal Correlation (U_4)	0.000	0.0002	0.002	0.008	0.04
Geographical Correlation (U_5)	0.000	$2.5.10^{-5}$	0.0001	0.0006	0.002
Technological Correlation (U_6)	0.000	0.0006	0.008	0.04	0.12

Each factor is scored on a scale of 1 to 5, where 1 represents high-quality data and 5 represents lower reliability. These scores are weighted based on their importance, with values ranging from 0 to 0.12 (see Table 1). The baseline uncertainty factor (U_1) is directly tied to the unit of environmental impact in the reference. In this study, U_1 is set to 0.0006 for all references, as they all focus on global warming potential (GWP) expressed in CO_{2eq}.

Once the DQI factors are determined for each reference, the variance associated with a single reference, $\sigma_{DQI}{}^2$, is calculated as:

$$\sigma_{DQI}{}^2 = \sum_{i=1}^{n=6} \sigma_n \quad \text{(Eq.1)}$$

Where n represents the number of uncertainty factors considered (six in this study).

The total variance for a set of references corresponding to a battery chemistry (e.g., LFP, NMC, NCA, etc.) is then computed using the quadratic sum of individual variances:

$$\sigma_{DQI\,X}{}^2 = \sum_{i=1}^{m} \sigma_{DQI\,i}{}^2 \text{ with } X = \text{LFP, NMC, NCA, LMO, LTO} \quad \text{(Eq.2)}$$

Where m is the number of references used for each battery chemistry. This variance calculation is crucial for quantifying data dispersion and uncertainty, particularly in the evaluation of GWP for material extraction and battery manufacturing stages.

An example is provided with reference [19]. Based on the uncertainty values defined in Table 1, the quality indicators are estimated as follows:

- Baseline uncertainty: 0.0006 (related to the study of CO_{2eq})
- Reliability: 0 (score 1 in the pedigree matrix)
- Completeness: 0.0001 (score 2 in the pedigree matrix)
- Temporal correlation: 0.008 (score 3 in the pedigree matrix)
- Geographical correlation: 0.00005 (score 2 in the pedigree matrix)
- Technological correlation: 0.12 (score 5 in the pedigree matrix)

The total uncertainty for this reference is 0.36, according to Eq.1. The uncertainty for the set of references on LFP batteries is calculated as 1.17, following Eq.2. Taking into account both this uncertainty and the observed variance among references, the total GWP uncertainty for LFP batteries is estimated at: ± 58.60 $kgCO_{2eq}.kWh^{-1}$.

2.2.1. Technical characteristics

Before discussing the technical characteristics of each battery chemistry, Fig. 3 presents the chemical structures and active materials of the studied battery types. These elements are common to various battery chemistries discussed in this study, with differences primarily arising from the active materials used in the electrodes.

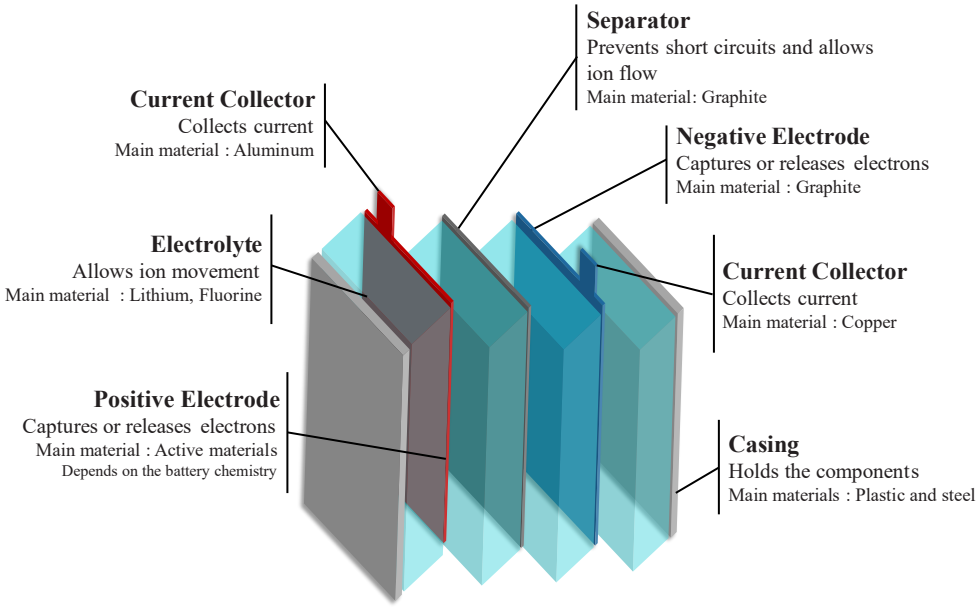

Fig. 3. Schematic representation of a lithium-ion battery cell, showing the main components and their primary materials. These materials vary depending on the specific battery chemistry.

In Table 2, the technical characteristics of batteries are presented, including their specific energy. These values are derived from manufacturer datasheets, where standard discharge conditions are specified. For Li-ion batteries, the characteristics are taken for a discharge cycle performed at 1C, with an ambient temperature of 25°C. However, for PbA batteries, the data were taken for a discharge rate of 0.01C at 25°C. This differentiation is crucial as energy density varies based on operating conditions, emphasizing the importance of specifying these conditions when assessing battery performance. While these values may not fully represent real-world applications, they are provided as informative benchmarks, in line with industry practices, where laboratory test conditions are used for reference purposes. The specific energies listed in this table are calculated as averages from the values sourced from the references cited within.

In addition to these considerations, the choice of battery chemistry depends on its intended application. While LTO batteries are not widely adopted in passenger electric vehicles due to their cost and energy density constraints, they have demonstrated significant potential in heavy-duty mobility applications, particularly in port and industrial transport [20], [21]. Their high cycle life, rapid charge capability, and enhanced safety make them a relevant alternative for specific use cases where energy density is less critical than durability and operational reliability.

Table 2

General batteries specifications

Battery Chemistry	Specific Energy (Wh/kg)		Life Cycle		Cost (€/kWh)		Nominal voltage (V)		Safety
PbA	40.00	[22][23] [24][25]	1000	[26][27] [28]	116	[29]	2.0	[24]	unknown
LTO	80.00	[24][30] [31][32]	5000	[33][34]	900	[35]	2.4	[24][34]	3
LMO	128.60	[36]	750	[24][28] [33][34]	288		3.7 - 3.75	[34][31]	4
LFP	151.30	[23][32] [37][38]	2400	[28][33] [34]	235	Internal data	3.2	[34]	5
NCA	200.00	[30][39] [40]	875	[33][34]	700	[41]	3.65	[31][17]	1
NMC	207.40	[32][42]	1571	[24][28] [33][34]	294	Internal data	3.6	[23][34]	2

Regarding the life cycle of batteries, it represents the number of discharges cycles a battery can undergo. This number also depends on the specified depth of discharge in the test. Typically, with a depth of discharge of 80%, more cycles are achieved compared to a depth of discharge of 100% [36] . The results presented in the Table 2 are calculated as averages of the values found in the references cited in the table.

Battery cost is a critical factor in selecting the appropriate chemistry for electric vehicle applications. As shown in Table 2, the cost per kilowatt-hour (€/kWh) varies significantly across different battery chemistries. PbA batteries remain the most affordable option, with an estimated cost of 116 €/kWh, though their lower specific energy and shorter lifespan limit their use primarily to auxiliary applications [43].

Among lithium-ion batteries, LFP offers one of the lowest costs at 235 €/kWh, making it a cost-effective solution with high safety and cycle life. In contrast, NCA has higher costs, reaching 700 €/kWh, respectively, due to their higher energy density and superior performance in high-power applications. LTO stands out as the most expensive chemistry at 900 €/kWh, primarily because of its extended cycle life and exceptional charge/discharge capabilities.

Concerning the nominal voltage of batteries, in the case of 100% electric vehicles and electric-hydrogen vehicles, batteries are often directly connected to the DC/DC bus. This configuration is simpler to implement than other hybridization topologies because does not require a DC/DC converter between the batteries and the DC/DC bus, thus having a simpler energy management strategy [44]. Nowadays, in heavy mobility, DC/DC bus voltages tend to increase from 400V to 800V. The lower the nominal voltage of the batteries, the more batteries need to be connected in series [35].

Battery stability stands as a critical aspect, especially concerning safety. The reference [46] compares the combustion processes of LFP and LMO batteries, revealing that the LMO battery generates more heat than the LFP battery. Determining the best chemical stability among the five chemical compositions is essential. This information holds particular importance in the transportation sector, where minimizing risks is necessary. Additionally, in the case of hybridization with a fuel cell, prioritizing the most stable technology is paramount. [47] compares LFP, LTO, NCA, and NMC chemistries, also measuring the amount of energy released during thermal runaway. Findings indicate that the LFP battery emits the least energy during this phase, while the NCA battery emits the most. By

associating these two references, one can deduce, on a scale of 1 to 5 (1 being the least stable and 5 the most stable), which of these chemical compositions offers the greatest stability.

The technical specifications of the batteries discussed in this paragraph are compared with batteries currently available on the market. The PbA battery is compared with the RS Pro Lead Acid Battery 12V, 65Ah. The LFP battery is compared with the Eve LF280K Prismatic 3.2V battery. For the NMC battery, the comparison is made with the 3.7V 50 Ah CATL 811. As for the NCA battery, it is compared with the NCA103450 from Panasonic. Regarding the LTO battery, the comparison is made with the LECLANCHE M2 LT34 LTO module of 34Ah. The characteristics found in commercial datasheets correspond to the references used. Unfortunately, no LMO batteries are found for comparison.

2.2.2. Analysis of batteries production location

Production regions for batteries are examined by consulting the manufacturing sites of battery manufacturers for the studied chemistry. The regions under investigation include Asia, the United States, Europe and Africa. The distribution of global battery production for PbA, LFP, NMC, NCA, LMO, and LTO across the previously mentioned six regions is depicted in Fig. 4. These data are updated in March 2024. The detailed findings of this study are available in *Battery production location* file in supplementary materials.

Out of 27 PbA battery manufacturers, 48% are produced in Asia, with more than half in China. The productions are then divided between Europe and the United States, with 22% and 26% of production respectively. The remaining 4% of production comes from Africa.

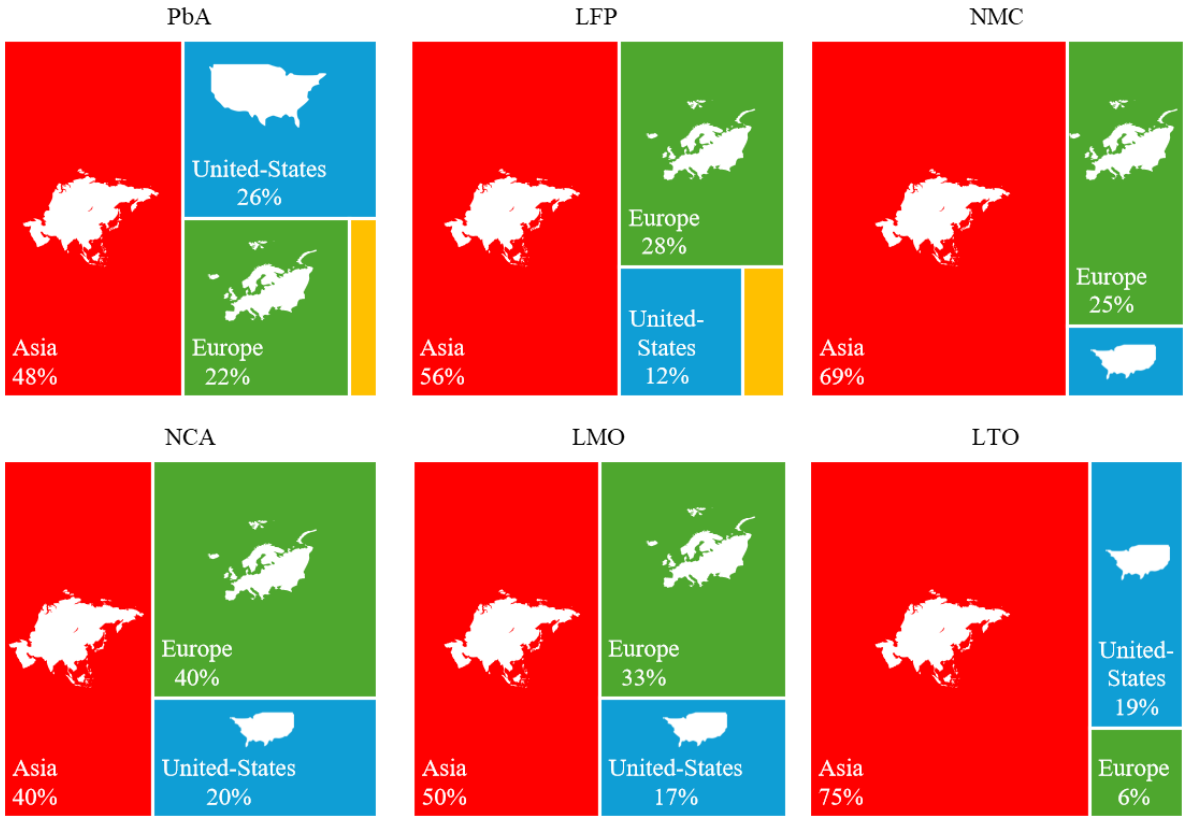

Fig. 4. Distribution of worldwide battery production. Red areas represent the Asian continent, blue areas the United-States, green areas Europe and yellow areas North Africa.

The production of lithium batteries, across all chemistries, is mainly located on the Asian continent, apart from NCA batteries where the market is dominated by Europe. The market is then shared between Europe and the United States [48]. The lithium battery market is dominated by Asia for several

reasons that are explained hereafter. The first relates to the lithium resources in this continent: even though most of the world's lithium reserves are found in Latin America and Australia, China has the world's largest reserve of lithium. The second reason is their manufacturing expertise: Asian countries have developed cutting-edge manufacturing skills for lithium-ion batteries and master all stages, from cell design to battery packs. These skills have enabled them to quickly respond to the significantly increased demand for lithium batteries in recent years. Finally, production costs remain lower in China and other Asian countries due to cheaper labor, more flexible environmental regulations, and government subsidies. However, Europe and the United States are also starting to invest in lithium battery production to reduce their dependence on Asian imports [49].

3. Determination of global warming potential by sector

The influence of each life cycle stage on the total Global Warming Potential varies depending on the study boundaries. Some studies decompose battery production into two sub-stages: raw material extraction and battery manufacturing [7], [38], [50], [51], while others consider it as a whole [37], [52]. Similarly, end-of-life can either be treated as a single process [6], [10], [53] or divided into end-of-life treatment and recycling [50], [52], [54].

In this study, the total Global Warming Potential is calculated as follows:

$$GWP_{total} = GWP_{extraction} + GWP_{manufacturing} + GWP_{transport} + GWP_{EoL} + GWP_{recycling} \quad \text{(Eq.3)}$$

GWP_{total} represents the total global warming potential, $GWP_{extraction}$ the global warming potential of materials extraction, $GWP_{manufacturing}$ the global warming potential of battery manufacturing, $GWP_{transport}$ the global warming potential of transporting batteries from their manufacturing site to the vehicle assembly site, GWP_{EoL} the global warming potential of battery end-of-life and $GWP_{recycling}$ the global warming potential of battery recycling.

Based on this framework, we categorize references into four groups:

- $GWP_{production}$: considers emissions from both material extraction and battery manufacturing.
- $GWP_{gross\ production}$: integrates the effect of recycling on total emissions from battery production.
- Distribution of emissions between extraction and production.
- Distribution of emissions between production and end-of-life.

3.1. Global warming potential for battery production

The global warming potential of battery production, encompassing both material extraction and battery manufacturing, is established through an extensive review of literature references. The details of the referenced studies are available in the supplementary materials file titled *GWP values for each chemistry_details*.

To quantify these emissions, the GWP of battery production (without considering recycling) is defined as:

$$GWP_{production} = GWP_{extraction} + GWP_{manufacturing} \quad \text{(Eq.4)}$$

Fig. 5 illustrates the dispersion of GWP values reported in the literature for battery production without recycling. The dataset includes studies that either consider the full production cycle or focus solely on raw material extraction or battery manufacturing. To ensure consistency and comparability in the following analyses, the mean values from these distributions are retained as representative figures in the subsequent sections.

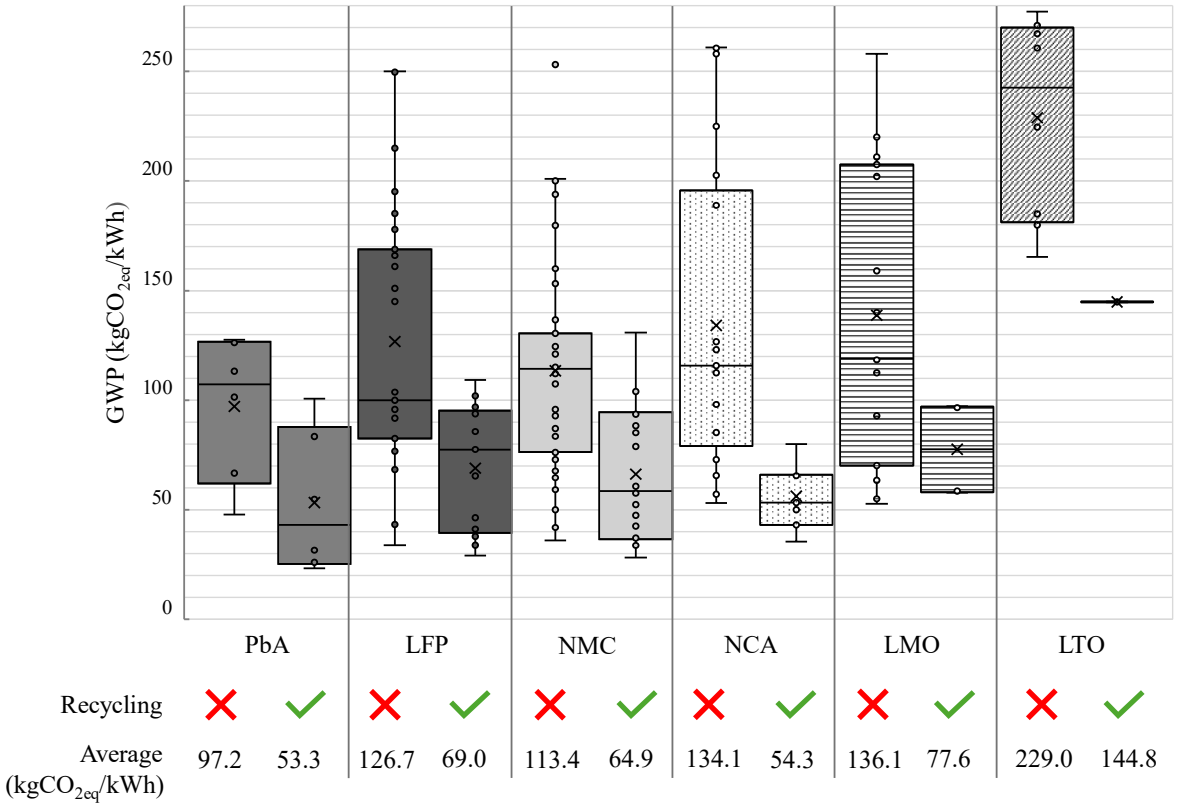

Fig. 5. Overview of Global Warming Potential associated with battery production: Comparison of emissions data with and without consideration of recycling.

The global warming potential for battery production, including material extraction and battery manufacturing, is established through the reference study. The details of this study are available in the supplementary materials file titled *GWP values for each chemistry_details*.

For emissions related to PbA battery production, only 5 references are found [28], [53], [54], [55], [56]. This low number is explained by the combination of two factors: the interest in these batteries and the interest in life cycle analysis. During the 2010s, there is significant interest in PbA batteries, while interest in life cycle analysis remains comparatively low. After 2015, this trend reverses. These two factors lead to a low publication rate for life cycle analysis of PbA batteries in the last ten years. Of the five references presented, four are selected. References [53], [56] indicate a lower global warming potential for battery production without recycled materials compared to values calculated when recycling effects are considered: theses references are therefore excluded from this study. The initial standard deviation for emissions from PbA battery production is 29.8 $kgCO_{2eq}$/kWh. By adding the uncertainty due to the data quality indicator, the final standard deviation increases to 30.5 $kgCO_{2eq}$/kWh, with an average of 97.2 $kgCO_{2eq}$/kWh (see Fig. 5).

Among NMC, LFP, LMO and NCA batteries, the largest number of references is found for NMC batteries, while the smallest number is found for LTO batteries. The standard deviation for global warming potential to produce NMC, LFP, LMO and NCA batteries is 45.5 $kgCO_{2eq}$/kWh, 58.4 $kgCO_{2eq}$/kWh, 65.0 $kgCO_{2eq}$/kWh and 67.5 $kgCO_{2eq}$/kWh, respectively. This standard deviation only considers the data and not the uncertainty due to the data quality indicator. When the data quality indicator is added, the standard deviation for NMC increases to 46.6 $kgCO_{2eq}$/kWh, for LFP is 59.4 $kgCO_{2eq}$/kWh, for LMO is 65.9 $kgCO_{2eq}$/kWh and for NCA is 68.5 $kgCO_{2eq}$/kWh.

Given the number of publications found on the life cycle analysis of NMC batteries, particularly on their global warming potential for production, and the minimal standard deviation of these data, the values reported for NMC chemistry have the highest reliability criterion.

Regarding LTO batteries, 10 references are found. Among these nine references, only one is not included in the calculation of the average [57] as the life cycle analysis is conducted for a Lithium

Titanate Oxide - Nickel Cobalt Oxide (LTO-NCO) chemistry. The standard deviation, initially without considering the data quality indicator, is 41.29 $kgCO_{2eq}$/kWh. Publications on this chemistry are more recent than 2016, which highlights an interest in these lithium batteries a little later than for other lithium chemistries, with a publication range from 2010 to today. Considering the uncertainty, the standard deviation from the average of emissions related to the production of LTO batteries is 43.08 $kgCO_{2eq}$/kWh. The LTO battery exhibits the highest GWP for battery module production, but this finding requires further consideration. It should be noted that the production methods for LTO batteries are not as mature as those for other types, potentially accounting for this elevated production value [26].

3.2. Global warming potential for battery production with recycling

The number of studies examining the global warming potential of batteries produced with recycled materials is significantly lower than those focusing on batteries made from virgin raw materials. To ensure a consistent comparison of data, this study categorizes the GWP of battery production while accounting for recycling effects. In this context, recycling reduces the demand for virgin materials, thereby lowering the associated GWP. Consequently, recycling is considered a credit in the overall production GWP, emphasizing its positive environmental impact. The potential negative effects of recycling—such as energy consumption and emissions from the recycling process—are accounted for separately in the end-of-life stage.

Two main recycling techniques are used for lithium-ion batteries:

- Hydrometallurgical Recycling: This process involves dissolving battery materials in acids to extract valuable metals such as lithium, nickel, and cobalt. It typically results in lower energy consumption and fewer emissions compared to pyrometallurgy, but generates chemical waste that requires treatment [58] .
- Pyrometallurgical Recycling: This method involves high-temperature smelting to recover metals. It is energy-intensive and produces more CO_2 emissions, but is advantageous for handling large volumes of battery waste and recovering high-purity metals [59].

Several studies have highlighted the trade-offs between these methods in terms of energy consumption, material recovery efficiency, and emissions. References [60] and [61] emphasize that hydrometallurgy is preferable for minimizing GWP, while pyrometallurgy is more scalable for large-scale recycling.

Fig. 5 illustrates the distribution of GWP values reported in the literature for battery production without recycling. However, some studies incorporate the benefits of recycling, which helps reduce emissions by decreasing the need for newly extracted raw materials. In these cases, the GWP of gross production (including the impact of recycling) is defined as:

$$GWP_{\text{gross production}} = GWP_{\text{production}} + GWP_{\text{recycling}} \quad \text{(Eq.5)}$$

Since $GWP_{recycling}$ is negative ($GWP_{recycling} < 0$), this formulation accounts for emission savings due to the reuse of secondary materials.

Among the different battery chemistries analyzed, NMC-based batteries have the highest number of references discussing emissions from recycled battery production. Out of 33 references focusing on NMC chemistry, 12 include recycling effects, representing 36% of the total references for this battery type.

The highest proportion of studies incorporating recycling is observed for PbA batteries, where 50% of the total references (4 out of 8) address the impact of recycling. In contrast, LMO batteries have the lowest representation, with only 2 references out of 12 considering net production emissions. For NCA batteries, 4 references out of 15 include recycled materials, 2 out of 6 for LTO and 8 out of 16 for LFP.

In general, the number of references found on a specific topic reflects its current trends. The highest ratios of studies on life cycle analysis using recycled versus virgin materials are found for PbA, NMC, and LFP chemistries. PbA batteries are the most recycled batteries globally, representing over 85% of the total secondary lead, which accounts for 60%-66% of the total global lead production [5]. NMC and LFP batteries remain the focus of current recycling efforts due to their growing use in vehicles.

Regarding the standard deviation of the data, its evolution follows that of the number of references found. Thus, the standard deviation for LTO batteries is close to zero, as only one reference is available. The largest standard deviation is observed for NMC batteries, which also have the highest number of references. This dispersion of data contrasts with what is observed regarding the global warming potential for the net production of batteries. It is explained by the diversity of recycling methods used in life cycle analysis, as well as by the types of chemistry of this type of battery. For example, in the case of reference [62], recycling by hydrometallurgy is studied, while references [63], [64] address recycling by both hydrometallurgy and pyrometallurgy. Regarding the studied chemistries, references [64], [65], [66] provide the global warming potential for NMC622 chemistry; references [66], [67] cover NMC 111 chemistry; NMC811, NMC424 chemistries in reference [66] and NMC532 in reference [65]. In general, very small samples are studied for references dealing with recycling, making statistical analysis unsuitable. However, it nevertheless allows for accounting for uncertainty in the results presented.

Regarding the NCA battery, 4 references dealing with the global warming potential are found, providing a total of 6 values to produce a battery with recycled materials. By averaging these values, the global warming potential to produce an NCA battery with recycled materials amounts to 54.3 $kgCO_{2eq}$/kWh. The same method is used for other battery chemistries.

Among all the studied chemical compositions, a reduction in global warming potential, ranging from 27.3% to 59.5%, is observed between emissions related to production and gross production. The lowest reduction is obtained for the LTO chemistry, while the highest reduction is found for the NCA chemistry. For the other chemistries, the decrease in recycling-related emissions ranges from 42.8% to 45.5%. These findings are corroborated by references [37], [51], [63], [68], [69].

3.3. Breakdown of production emissions between material extraction, battery manufacturing and end-of-life

The production of batteries is divided into two stages: material extraction and battery manufacturing. The transportation of materials from extraction sites to manufacturing facilities is included in the battery manufacturing stage. In terms of global warming potential, it is crucial to differentiate between these two stages, as this allows us to identify the primary emission sources. This distribution is evaluated for batteries made from virgin materials. In general, material extraction contributes more to total emissions than battery manufacturing (see Fig. 6).

To account for both battery production and end-of-life emissions, we define the net GWP as follows:

$$GWP_{net} = GWP_{production} + GWP_{EoL} \quad \text{(Eq.6)}$$

Where GWP_{net} represents the total net emissions from both production and end-of-life processes.

Each life cycle stage contributes a fraction of the total global warming potential, which we define as the impact rate (τ_i). The sum of these impact rates equals one, ensuring that all phases are accounted for:

$$1 = \tau_{extraction} + \tau_{manufacturing} + \tau_{transport} + \tau_{EoL} + \tau_{recycling} \quad \text{(Eq.7)}$$

Since recycling contributes to emission reductions, it is treated as a negative factor ($\tau_{recycling} < 0$).
The impact rate for each stage is calculated as the ratio of its emissions to the total emissions:

$$\tau_i = \frac{GWP_i}{GWP_{total}} \quad \text{(Eq.8)}$$

Where i represents the life cycle stage being analyzed. These impact rates vary depending on the battery chemistry and the specific life cycle stage under consideration.

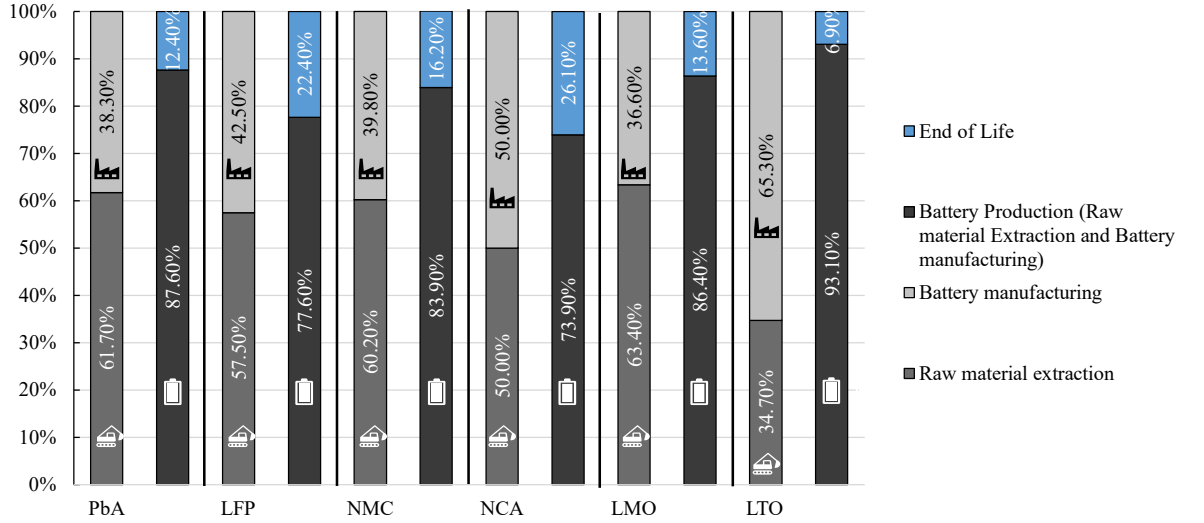

Fig. 6. Breakdown of battery production between raw materials extraction and battery manufacturing, and the impact of end-of-life versus battery production

For PbA batteries, approximately 62% of the total GWP of production comes from material extraction [28], [56]. Lead extraction alone accounts for nearly two-thirds of these emissions.

For LFP batteries, material extraction represents 57% of total production emissions when the battery manufacturing occurs in the United States [6], [70].

A larger number of references detail NMC battery emissions. On average, 60% of total emissions come from material extraction, a higher share than for LFP batteries but with a similar order of magnitude.

- References [10], [62] report that 81–85% of emissions originate from material extraction when NMC batteries are manufactured in Europe or China (NMC622 chemistry).
- References [7], [70] estimate that 59–63% of emissions come from raw material extraction.
- For NMC111 chemistry, references [52], [71] report 35–45% of total emissions linked to material extraction.

Regarding NCA batteries, reference [72] estimates that 50% of total emissions in battery manufacturing come from raw material extraction, but the location of production is not specified.

LMO batteries have a high material extraction footprint, with 86–87% of production emissions attributed to material extraction [10], [73], both assuming a European electricity mix.

Finally, LTO batteries lack precise data on the extraction-production breakdown. Using [74], emissions from material extraction were estimated based on battery composition and energy density.

The net GWP includes both battery production and end-of-life emissions. The end-of-life stage consists of burial, dismantling, and internal transportation during disposal.

- For PbA batteries, only one reference provides a breakdown: end-of-life contributes 12% of net emissions, including waste management (incineration, landfill) [38].
- For LFP batteries, reference [64] reports an end-of-life share of 9–11%, accounting for dismantling and recycling. However, [69] estimates this impact at 48% due to differences in recycling processes (hydrometallurgy-based methods).
- For NMC batteries, references [52], [68] estimate end-of-life impacts between 11–18%.

- For NCA batteries, reference [59] estimates end-of-life emissions at 5.42 $kgCO_{2eq}$/kWh, while In [75] reports a much higher value of 26.7 $kgCO_{2eq}$/kWh, depending on the recycling and disposal scenario considered.
- LMO batteries have end-of-life contributions of 13–17% [10], [73] assuming European-based dismantling and recycling processes.
- LTO batteries have an estimated end-of-life impact of 7% in Europe [76].

3.4. Battery transport emissions

The methodology for calculating the global warming potential of battery transport involves several key steps. Initially, the specific energy of batteries and their primary production sites are determined (see 2.2.1 Technical characteristics). Next, distances between battery production sites and vehicle assembly sites are estimated using various transport modes, with an emission factor specific to each mode applied to these distances. This comprehensive approach allows for the calculation of total emissions associated with battery transport.

Battery transportation primarily occurs via three main modes: ship, truck, and train, with further distinctions within each category. Shipping methods include container ships or ferries, while truck transportation varies based on the predominant transport category. Similarly, three types of trains are differentiated, with emission factors varying accordingly. Supplementary data provide distances based on production sites and primary transport modes, obtained from the Ministry of Ecological Transition. These distances are calculated from battery production sites to vehicle assembly sites, chosen to align with eco-design requirements for electric powertrain manufacturing. The chosen assembly site, located in Héricourt, France, serves as a case study reflecting collaboration with GAUSSIN company. Battery production sites vary by specified chemistry and may be located across Asia, the United States, Europe, Africa, or the United Kingdom.

For each region, a representative country is selected, simplifying the study and standardizing transport emission calculations. The global warming potential $GWP_{transport}$ is then determined by summing the product of the emission factors Fe and the distances D and dividing the result by the specific energy E_s (see Equation 9). In the following equation, i represents the transport type, and n the number of transport type used in the battery transportation.

$$GWP_{transport} = 10^{-3}.\frac{1}{E_s}\sum_{i=1}^{n} Fe_i.D_i \quad \text{(Eq.9)}$$

Transportation emissions vary depending on the battery's production site, the mode of transportation, and the specific energy involved. Notably, PbA batteries transported from Asia by truck exhibit the highest global warming potential at 37.4 $kgCO_{2eq}$/kWh, whereas the lowest emissions occur when transported by train from Europe. NMC and NCA batteries have the highest energy density, at 207.40 Wh/kg and 200.00 Wh/kg, respectively, and are the ones with the lowest emissions value. For transport by train from a production site located in Germany to the vehicle assembly site, the global warming potential is 0.04 $kgCO_{2eq}$/kWh. Generally, European-produced batteries, regardless of transport mode or chemistry, have a global warming potential below 1.5 $kgCO_{2eq}$/kWh. In this article, GAUSSIN company's system-sizing batteries are sourced from Europe, hence, the global warming potential associated with battery transportation from Europe is chosen.

4. Results and Discussions

The total global warming potential is determined by combining the data presented in the previous sections. Initially, the analysis concentrates on interpreting the average data. Subsequently, the second section discusses the uncertainties considered in these results and compares these environmental criteria with the technical characteristics of the batteries.

4.1. *Results: Total global warming potential*

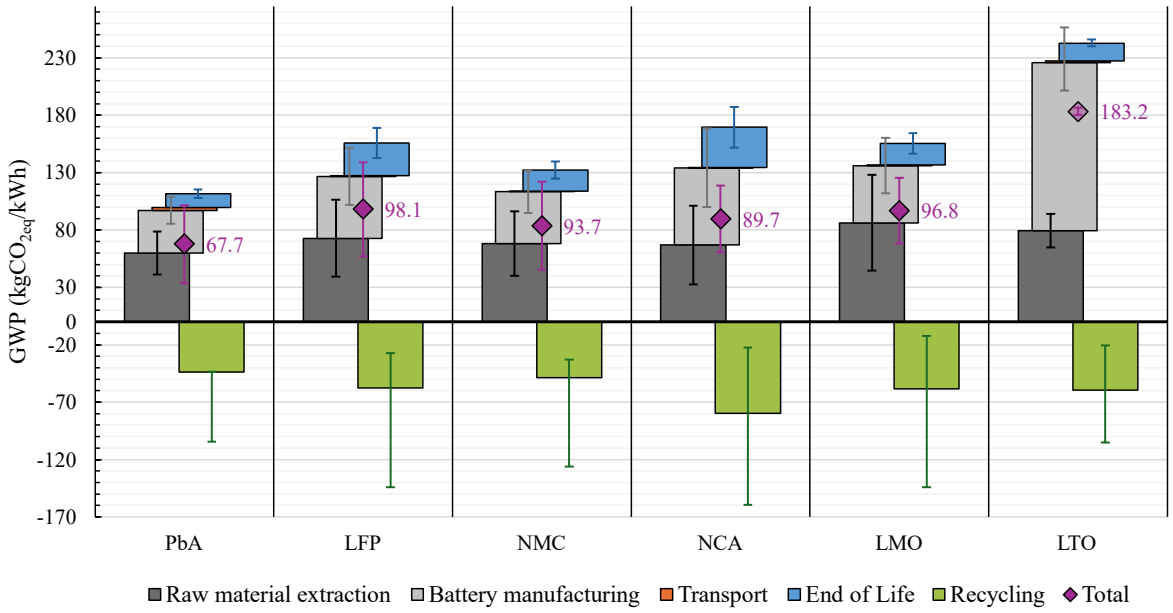

Fig. 7. Total global warming potential for each lifecycle stage, incorporating uncertainties

The PbA battery exhibits the lowest total global warming potential, measuring 67.7 $kgCO_{2eq}$/kWh, while the LTO battery shows the highest, reaching 183.2 $kgCO_{2eq}$/kWh. This notable disparity can be attributed to the LTO battery's technology immaturity. Excluding the LTO battery, the lithium batteries examined in this study have an average total global warming potential of 92.1 $kgCO_{2eq}$/kWh (see Fig. 7).

Generally, for lithium batteries (excluding the LTO battery), material extraction contributes to 48.8% of the total global warming potential associated with production and end-of-life. Recent studies emphasize the importance of optimizing recycling techniques to mitigate this impact. Notably, advanced strategies such as pollutant-free pyrolysis have demonstrated significant potential in reducing fluorinated gas emissions during battery recycling, thereby improving the environmental footprint of end-of-life processes [77].

Recycling yields a reduction of -39.7% across the entire global warming potential, with the NCA battery exhibiting the most significant impact, showing emissions decrease by -47.1%. This observation aligns with recent literature emphasizing the role of effective recycling strategies in minimizing emissions from high-energy batteries [78].

End-of-life represents just over a quarter of the average total global warming potential, with the highest value observed for the NCA battery.

In this study, transportation's impact is deemed negligible. Opting for European-made batteries results in almost zero global warming potential. However, if batteries are sourced from China and transported to the vehicle assembly site in France, the average total global warming potential for lithium batteries, including the LTO battery, would increase by an average of 2.9 $kgCO_{2eq}$/kWh.

4.2. *Discussion of uncertainties and selection criteria*

Total uncertainties are calculated by associating the extreme values of global warming potential for the net and gross production of each chemistry. The uncertainty present in net production is proportionally reflected in the distribution of the global warming potential of the end-of-life batteries. Emissions due to transportation remain unchanged for all battery chemistries.

In terms of the total global warming potential, the values may fluctuate from approximately 28.7 $kgCO_{2eq}$/kWh to 40.9 $kgCO_{2eq}$/kWh, except for the LTO battery, where the total global warming

potential ranges from 3.0 to 3.40 $kgCO_{2eq}$/kWh. This minor variance can be attributed to the limited availability of references regarding the life cycle analysis of LTO batteries.

The field of life cycle analysis applied to batteries in the transportation sector is continuously evolving, with improved accuracy and diversification, considering various recycling methods, manufacturing locations, and battery chemistries. This diversity enhances precision but also complicates standardization when attempting to provide general recommendations.

To provide a more practical approach to battery selection, three Pareto front analyses are conducted, allowing for the identification of the most suitable battery chemistry based on specific application needs. The battery chemistry that best fits a given requirement is the one closest to the origin (zero), which represents the optimal solution.

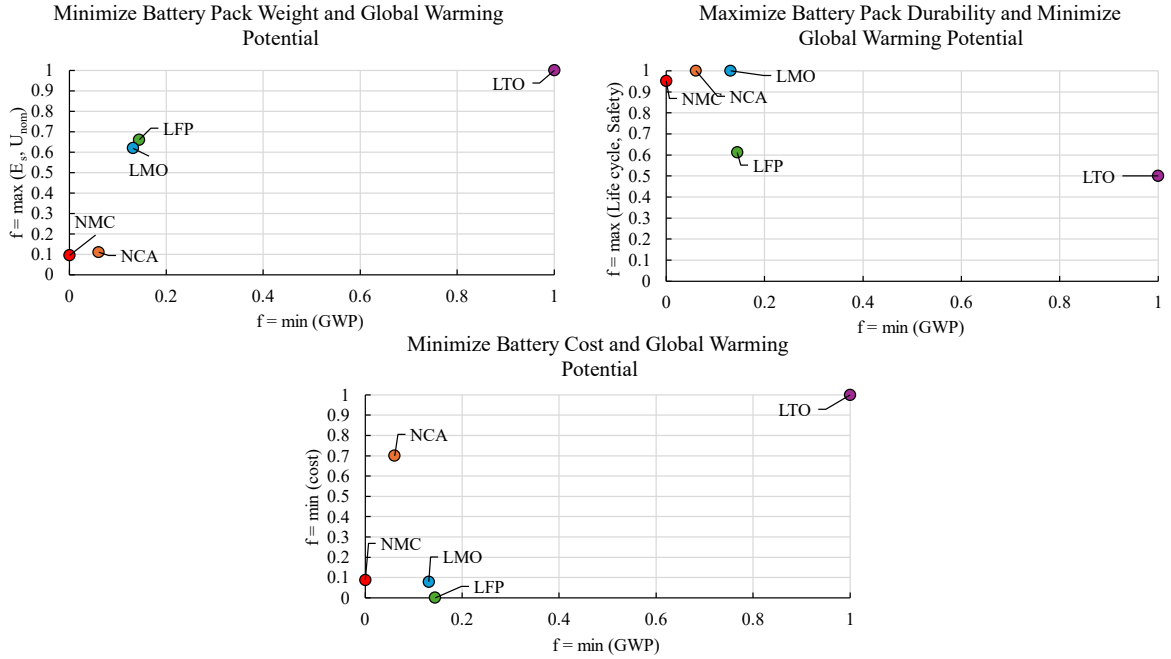

Fig. 8. Multi-criteria battery selection based on global warming potential and key performance metrics

If the objective is to minimize battery pack weight and global warming potential, the first graph in Fig. 8 provides relevant insights. In lightweight electric mobility applications (e.g., urban transport, electric bicycles, scooters), reducing battery pack weight is essential for improving efficiency and vehicle performance. In such cases, battery chemistries with high energy density and high nominal voltage are preferred, as they reduce the number of cells needed in series to achieve the required DC bus voltage. The analysis highlights NMC chemistry as the most suitable option for achieving both weight reduction and lower GWP.

If the objective is to maximize durability while reducing GWP, the second graph in Fig. 8 illustrates the most suitable option. In fleet-based applications, such as electric buses, battery longevity is crucial, as operators seek to minimize replacement frequency, thereby lowering both long-term costs and environmental impact. In this scenario, LFP batteries offer the best trade-off, providing a high cycle life while maintaining a relatively low GWP.

If the objective is to minimize battery pack cost while reducing GWP, cost-sensitive applications—such as affordable electric vehicles—require a careful balance between price and environmental impact. The analysis highlights NMC batteries as the most optimal choice, offering a competitive cost alongside a lower GWP.

Beyond these cases, additional factors can refine battery selection, such as power density, charging speed, and operational constraints. For instance, LTO batteries, while exhibiting a higher GWP, are

designed for high-power applications where fast charging and long cycle life are critical, making them suitable for heavy-duty transport and industrial applications.

These findings demonstrate that battery selection cannot be based solely on GWP values. Instead, technical trade-offs must be carefully considered to ensure optimal battery sizing for each specific use case. The graphs presented here are just examples, and they can be adapted according to the reader's specific needs and the technical characteristics obtained.

5. Conclusion

Through an in-depth bibliographic analysis, this article presents the global warming potential of PbA, LFP, NMC, NCA, LMO, and LTO batteries, which are commonly used in the transportation sector. The results highlight the diversity of parameters considered in life cycle assessments and the challenges associated with standardizing available data. To quantify uncertainties, a data quality indicator was applied to each reference, providing a more rigorous evaluation of environmental impacts. The study covers the entire battery life cycle, including material extraction, manufacturing, transportation, end-of-life, and recycling.

Beyond assessing global warming potential, this study introduces a more practical approach to guiding battery selection based on specific applications. The integration of Pareto fronts illustrates how different technical criteria (durability, cost, weight) can be balanced against environmental impact. These decision-making tools emphasize that battery selection cannot be based solely on GWP but must consider a comprehensive set of technical and economic trade-offs.

The results further reinforce the importance of an eco-design approach in defining powertrain systems for mobility applications. By simultaneously integrating environmental, technical, and economic criteria, it becomes possible to guide battery chemistry selection toward more sustainable solutions tailored to user needs.

Acknowledgement

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Appendix A

Table A. 1.
Presentation in chronological order of the references used in this article as well as the battery chemistries covered.

Reference	Battery chemistry	Country of publication
[80]	LMO	Switzerland
[81]	LFP	Sweden
[19]	LFP, NMC	Norway
[53]	PbA	United-Kingdom
[82]	PbA	United-States
[56]	PbA	Thailand
[6]	LFP, NMC, LMO	United-States
[83]	NMC	Norway
[8]	LMO	Norway
[28]	PbA	China
[73]	LFP, LMO	Belgium
[84]	LFP	Belgium
[85]	LFP, NMC, NCA, LMO, LTO	United-States

[86]	LMO	Korea
[38]	PbA	Germany
[35]	NMC, LTO, NCA	Germany
[87]	NCA, LMO	Germany
[88]	LFP, NMC, LMO	China
[2]	LFP, NMC, NCA, LMO, LTO	Germany
[89]	LFP	Canada
[50]	LFP, NMC, NCA, LMO, LTO	Germany
[10]	LTO	United-Kingdom
[90]	PbA	China
[76]	LTO	Germany
[70]	LFP, NMC, NCA	United-States
[91]	LMO	Italy
[7]	NMC	Sweden
[92]	LFP	Belgium
[93]	NCA	Belgium
[74]	LTO	China
[57]	LFP, NMC, NCA, LMO, LTO	United-Kingdom
[63]	LFP, NMC, NCA	Germany
[72]	NCA	Austria
[94]	NMC	China
[95]	NCA	Germany
[62]	NMC	China
[96]	NMC, LMO	Europe
[97]	NCA	Australia
[52]	NMC	Italy
[98]	LFP, NMC	Germany
[65]	NMC	Italy
[67]	NMC, NCA	United-States
[9]	LFP	United-Kingdom
[37]	LFP, NMC, LMO	China
[99]	PbA	Sweden
[64]	NMC	China
[100]	NMC, NCA	Sweden
[101]	LFP	China
[68]	LFP, NMC	China
[66]	LFP, NMC, NCA	China
[102]	NCA	China
[69]	LFP, NMC	China
[103]	NMC	United-States
[104]	LFP, NMC, LMO, LTO	China
[54]	PbA, LFP, NMC	Sweden
[105]	NMC, NCA	Germany
[106]	NMC	Germany
[55]	LFP, NMC, PbA	China
[75]	NMC, NCA, LFP	Taiwain
[107]	NMC	India
[108]	NMC	Germany
[109]	NMC, LFP	Italy

Appendix B.

Supplementary information is available for this paper.

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