

Review

# Life Cycle Assessment of Electric Vehicle Batteries: An Overview of Recent Literature

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Received: 30 March 2020; Accepted: 28 May 2020; Published: 4 June 2020



**Abstract:** In electric and hybrid vehicles Life Cycle Assessments (LCAs), batteries play a central role and are in the spotlight of scientific community and public opinion. Automotive batteries constitute, together with the powertrain, the main differences between electric vehicles and internal combustion engine vehicles. For this reason, many decision makers and researchers wondered whether energy and environmental impacts from batteries production, can exceed the benefits generated during the vehicle's use phase. In this framework, the purpose of the present literature review is to understand how large and variable the main impacts are due to automotive batteries' life cycle, with particular attention to climate change impacts, and to support researchers with some methodological suggestions in the field of automotive batteries' LCA. The results show that there is high variability in environmental impact assessment; CO<sub>2</sub>eq emissions per kWh of battery capacity range from 50 to 313 g CO<sub>2</sub>eq/kWh. Nevertheless, either using the lower or upper bounds of this range, electric vehicles result less carbon-intensive in their life cycle than corresponding diesel or petrol vehicles.

**Keywords:** battery electric vehicles; environmental impacts; life cycle assessment; review

## 1. Introduction

In recent years, the introduction of electric vehicles, and in particular electric passenger cars, has been seen as a great opportunity to reduce both urban air pollution and greenhouse gas emissions from the transport sector [1]. In particular, for what concerns urban air quality, the absence of tailpipe emissions from electric vehicles (EVs) justify this idea, confirmed by a recent study that estimates 500,000 premature deaths every year due to pollutants in the European Union, where transportation represents the main air pollutants source, especially in urban areas [2]. Regarding the reduction of greenhouse gases, EVs can rely on an overall higher efficiency [3] and, in countries where it is relevant, on the penetration of renewable energy sources in the national electric generation mix [4]. However, these considerations do not allow us to state that electric vehicles are better than Internal Combustion Engine Vehicles (ICE Vehicles), since it is not possible to compare EVs and ICE Vehicles considering only emissions that occur during vehicles use phase. In order to properly compare ICE vehicles and EVs, researchers should consider impacts related to electric energy production, fossil fuels production, vehicle and battery production and end of life phases in the LCA of EVs. In other words, an LCA approach, which allows analyzing of the environmental impacts occurring during vehicles entire life cycle, should be adopted [5]. Of course, many comparative LCAs of EVs vs. ICE Vehicles and also some literature reviews on the topics have been published in the last decade [3], but in this paper, we want to focus our attention on a particular component of the EVs: the battery. Batteries in fact are a central element in electric vehicles, and one of the most relevant distinctive elements (together with the powertrain) between EVs and ICE Vehicles. Moreover, batteries' production generates energy

consumption and environmental impacts which have the potential to negatively affect the electric vehicles' benefits due to the use phase, with particular reference to climate change emissions. In order to investigate this issue and also to support researchers that are going to perform new LCA studies on EVs batteries with methodological suggestions, a review of recent LCA studies is presented in this paper. Far from being comprehensive and exhaustive, our study focuses its attention on studies performed in the last decade, since the traction battery sector is characterized by a continuous and rapid technological evolution [6]. The analysis of the selected studies has been carried out following the scheme of an ISO 14040 compliant LCA study: Goal and Scope, Inventory (Life Cycle Inventory—LCI), Life Cycle Impact Assessment (LCIA), Conclusions as summarized in Table 1, where the description of each section is reported in *italic*. In the following paragraphs, besides a brief description of the selected studies, for each of the LCA steps recommended in ISO 14040 standard, we analyze the main methodological differences among the studies, trying to draw useful conclusions for future traction batteries LCA studies.

**Table 1.** Analysis scheme considered to evaluate literature review documents.

		Title
	Bibliographic reference	Bibliographic reference following the APA style (American Psychological Association).
Goal and Scope	Target of the study	Specify the target of the study; specify if the LCA is attributional or consequential (if possible).
	Functional unit	Specify the functional unit considered and evaluate whether it is suitable to represent the service analyzed.
	System boundaries	Specify the system boundaries and the phases of the analysis considered. Possibly, state the omitted phases and the reason for their exclusion.
	Allocation system	Indicate any allocation system used (mass, economic, etc.) and how the end of life is managed (cut-off, default, system expansion).
	Cut-off rules	Specify any cut-off rules and the parameters considered.
	Impact categories and methods	Indicate impact categories and methods used in the study.
Inventory—LCI	Data source	Report data source, specifying if primary or secondary data are considered.
LCIA	Results	Summarize the results of the study.
Sensitivity and uncertainty analysis	Considered parameters and techniques	Specify parameters and techniques considered to realize sensitivity and uncertainty analysis (if present).
Conclusions	Main conclusions of the study	Summarize the main conclusions of the document.

## 2. The Assessed Documents

The literature review was realized by searching in Google Scholar for the following keywords: Automotive batteries life cycle assessment, Automotive batteries life cycle, Battery life cycle, Electric vehicle batteries environmental impacts.

From the search results, we selected only the works that presented the following features:

- LCA of batteries used in automotive applications, rejecting all the papers that analyze batteries in other contexts (e.g., for stationary use).
- Documents assessing a specific battery life cycle phase, for example, production or end of life and recycling phase, and identifying materials and operations with relevant environmental impacts.
- Studies comparing different battery models, characterized by different chemistry, power, energy density and storage capacity.
- Automotive batteries literature reviews.
- Studies assessing a single battery model and identifying the major impacts due to materials and operations, suggesting sustainable alternatives.

According to these criteria, seventeen documents were suitable for the current literature review (Table 2).

**Table 2.** Documents analyzed within this bibliographic review.

Authors	Title	Year	Type of Document
Cusenza, M, A; Bobba, S; Ardente, F; Cellura, M; Di Persio, F	Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles [7]	2019	Journal paper
Helmers, E; Weiss, M	Advances and critical aspects in the life-cycle assessment of battery electric cars [8]	2017	Journal paper
Ioakimidis, C, S; Murillo-Marrodan, A; Bagheri, A; Thomas, D; Genikomaskis, K	Life Cycle Assessment of a Lithium Iron Phosphate (LFP) Electric Vehicle Battery in Second Life Application Scenarios [9]	2019	Journal paper
Ellingsen, L, A, W; Majeau-Bettez, G; Singh, B; Srivastava, A, K; Valøen, L, O; Strømman, A, H	Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack [10]	2014	Journal paper
Notter, D, A; Gauch, M; Widmer, R; Wager, P; Stamp, A; Zah, R; Althaus, H, J	Contribution of Li-ion batteries to the environmental impact of electric vehicles [11]	2010	Journal paper
Romare, M; Dahllöf, L	The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries [12]	2017	Technical report
Dunn, J, B; Gaines, L; Barnes, M; Sullivan, J	Material and Energy Flows in the Materials Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle [13]	2014	Technical report
Amarakoon, S; Smith, J; Segal, B	Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles [14]	2013	Technical report
ReCharge	PEFCR - Product Environmental Footprint Category Rules For High Specific Energy Rechargeable Batteries for Mobile Applications [15]	2018	Technical guide
Nordelöf, A; Messagie, M; Tillman, A, M; Söderman, M, L; Van Mierlo, J	Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? [4]	2014	Journal paper
Richa, K; Babbitt, C, W; Nenadic, N, G; Gaustad, G	Environmental trade-offs across cascading lithium-ion battery life cycles [16]	2017	Journal paper
Faria, R; Marques, P; Garcia, R; Moura, P; Freire, F; Delgado, J; de Almeida, A, T	Primary and secondary use of electric mobility batteries from a life cycle perspective [17]	2014	Journal paper
Oliveira, L; Messagie, M; Rangaraju, S; Sanfelix, J; Rivas, M, H; Van Mierlo, J	Key issues of lithium-ion batteries—from resource depletion to environmental performance indicators [18]	2015	Journal paper
Liu, C; Lin, J; Cao, H; Zhang, Y; Sun, Z	Recycling of spent lithium-ion batteries in view of lithium recovery: A critical review [19]	2019	Journal paper
Peters, J, F; Baumann, M; Zimmermann, B; Braun, J; Weil, M	The environmental impact of Li-Ion batteries and the role of key parameters—A review [20]	2017	Journal paper
Majeau-Bettez, G; Hawkins, T, R; Strømman, A, H	Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles [21]	2011	Journal paper
Dai, Q; Kelly, J, C; Gaines, L.; Wang, M	Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications [22]	2019	Journal paper

Most of these documents were published between 2014 and 2019, and only three of them between 2009 and 2013. Thirteen documents are papers published in scientific journals, three documents are research centers' technical reports and one work is a technical guide.

### 3. Goal and Scope

The goal and scope phase describes and defines the LCA study and the processes involved in the life cycle: targets, functional unit, system boundaries, impact categories, possible allocation procedures and cut-off rules. In the present paragraph, we analyze the main methodological choices made by different authors for this relevant part of an LCA study and we make some recommendations for future LCAs application on traction batteries.

### 3.1. Functional Unit

ISO14040 [23] and ISO14044 [24] standards define the LCA functional unit as the quantified performance of a product system, to be used as a reference unit. The functional unit has to be consistent with the goal and scope of the study and must provide a reference for normalizing the input and the output data. It is important to remind that thanks to the choice of a proper functional unit, it is possible to compare different systems and products offering similar services. In our analysis, despite the relatively limited number of analyzed papers, we found several different functional units. In three studies, [7,9,16] the functional unit is the battery pack. This kind of functional unit does not seem to be particularly appropriate, since it does not refer to the service offered by the systems (as requested by the ISO 14040 norm) and does not allow us to easily compare the environmental performances of different batteries. Although in reference [15], the suggested functional unit is 1 kWh of delivered energy over the service life of batteries, in five works [10,12,18,21,22], the functional unit is the battery unit storage capacity (e.g., 1 kWh, except for [21] where it is 50 MJ). As the assessed batteries are housed in electric vehicles, the authors in [11] and [4] decided to choose 1 km traveled as the functional unit, whereas in references [14] and [17], the distance traveled by the vehicle during its entire lifetime is considered. The functional unit is not clearly defined only in references [8,13,19] due to the nature and contents of these documents. As discussed, 1 kWh of battery capacity is the most used functional unit as it allows the comparison of different batteries' systems in an easy way [7]. Nevertheless, this functional unit seems more suitable for cradle to grave studies, and other functional units relating to the distance travelled, such as 1 km or the distance travelled in the battery life time, can be used, as far as transport is the service provided by the system. However, assumptions concerning the life of the battery itself must be well clarified. Although sometimes it is useful to express results also per unit of mass (kg of battery) [10], mass-based functional units are not related to the performance of the analyzed systems and we do not recommend to use them in traction batteries LCA studies.

### 3.2. System Boundaries

In the LCA methodology, the system boundaries definition is a way to identify which processes within the entire life cycle of the involved systems need to be analyzed or, for the sake of simplification, can be neglected. The system should be modelled to have only input and output elementary flows. System boundaries define process phases that need to be included within the LCA and their choice has to be consistent with the target of the study. Except for [8,13,19], which do not define clearly the system boundaries of their work, all the other documents explain their LCAs system boundaries in a clear way. Eight studies out of seventeen [7,9,11,14,16–18,20] analyze all batteries phases (cradle to grave): raw materials extraction and manufacturing, batteries production, transportation, use phase, end of life with material recycling. Three studies [10,12,22] analyze only batteries production, by a cradle to gate assessment, due to the lack of reliable information for modelling the use and the end of life phases. In reference [21], system boundaries include the production and the use phases, not considering the end of life impacts. Whenever possible, as suggested in references [15] and [4], we recommend to go through cradle to grave analysis, considering all phases of a battery during its life cycle.

### 3.3. Allocation System

The allocation process splits the input and output flows of a multiple product process between the analyzed system product and one or more other system products. The inputs and outputs have to be allocated to the different products following clear rules, defined at the beginning of the analysis. Most of the assessed documents do not specify any allocation rules, whereas only two studies mention the allocation: [11] and [15]. The first document [11] declares that there is no allocation regarding recycled products in the end of life. As a consequence, all the charges that may arise from material production are assigned to the first life of the product, even if the same can be reused, for example in a stationary domestic storage system. The second document [15] states that no accurate indication

for a possible allocation is provided, as there are no co-product cases identified during batteries' production phase. However, if it is necessary to allocate impacts of any co-products linked to the battery manufacturing process, to solve multi-functionality problems, authors recommend to apply a predefined hierarchic approach: division or system expansion; allocation based on a relevant physical relationship; allocation based on some other relationships. In batteries' LCAs, allocation seems relevant only when considering recycling and second life scenarios.

#### 3.4. Cut-Off Rules

Cut-off rules define material or energy flows, associated with the process unit, which are excluded from the study. Eight studies use a cut-off system, whereas nine studies do not use it or it is not possible to deduce the following criteria [4,7,8,13,14,16,18,19,21]. In five studies [9,10,12,20,22], authors do not include in their analyses impacts and benefits linked to material recycled during end of life phase. This choice is due to a high uncertainty of data and information about recycling, reuse and substitution of primary raw material with secondary material. In reference [11], materials and processes are excluded when their potential contribution is negligible. This choice is based on a mass, energy demand and expected impacts per unit of mass or energy. Of course, given the growing importance of recycling materials in the framework of the circular economy and the use of critical materials in battery production, we encourage the inclusion of end of life and recycling in future LCA studies. As in reference [15], which uses a 1% cut-off rule, neglecting all phases which have impacts lower than this threshold, we suggest that negligible phases are: batteries distribution during the end of life, infrastructure and equipment for batteries assembly and recycling.

#### 3.5. Impact Categories and Methods

As described in the European Commission ILCD Handbook recommendations [25], impact categories selection must be consistent with the goal of the study. Furthermore, impact categories choice has to be complete, and should cover all the main environmental issues related to the system. In order to compare the results from different studies, it is certainly needed that studies use the same metrics: i.e., the same impact categories and the same impact method for their quantification. In our analysis, only eight studies [7,9,10,17,18,20–22] clearly explain the impact method used for quantifying midpoint impact categories [25], while six studies [4,11,12,14–16] declare the impact categories used but they do not specify the impact method followed. Finally, three studies [8,13,19] do not report any results evaluable with usual LCA impact categories or methods proposed by the ILCD Handbook [25]. In Figure 1, the impact categories used in the assessed studies are resumed.

The most used impact category is global warming (fourteen studies out of seventeen), followed by acidification (ten out of seventeen) and eutrophication (nine out of seventeen). Seven works use the impact categories ozone depletion and particulate matter, whereas six documents use the impact categories CED—cumulated energy demand, abiotic depletion, human toxicity and ecotoxicity. Other categories considered less frequently are: photo oxidant formation and resource depletion (five studies), fossils depletion (four studies), ionizing radiation (three studies), land use and water use (two studies). On the basis of these results, considering the impact categories used in almost 40% of the assessed studies, and taking into account the lesson learnt from reference [20], in an automotive battery LCA, it is suggested to use the following impact categories: global warming, acidification, eutrophication, ozone depletion, particulate matter, abiotic depletion, human toxicity, ecotoxicity and CED (Cumulated Energy Demand).

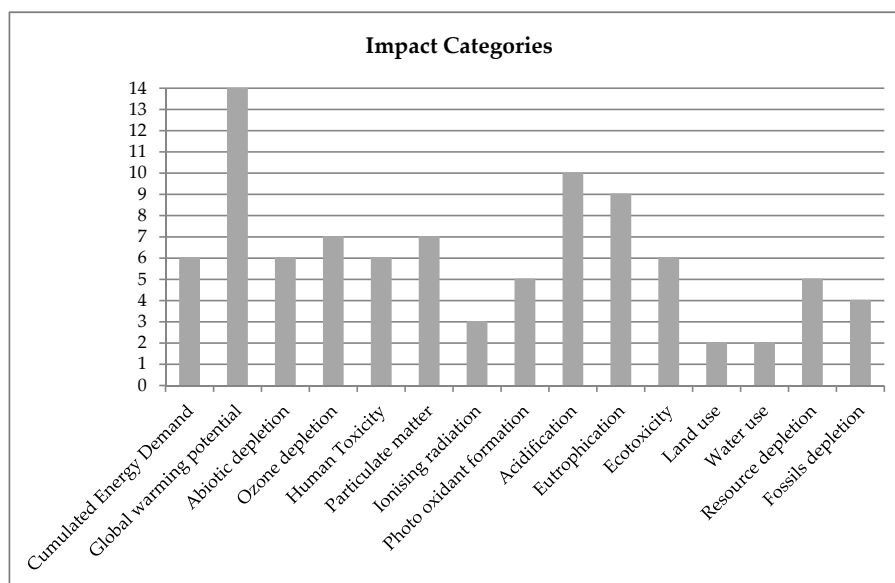


Figure 1. Impact categories used in the assessed studies.

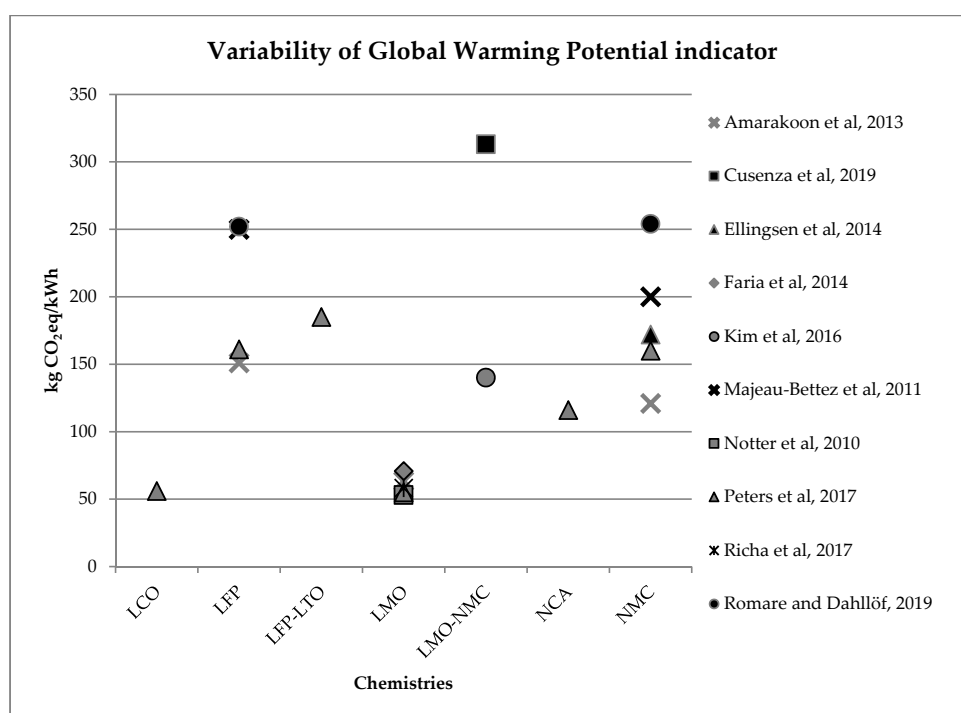
#### 4. Life Cycle Inventory—LCI

Inventory includes data collection and calculation procedures to quantify relevant inputs and outputs in the assessed system. Data collection includes their validation, data and process units' relationship, the relationship between data and reference flow and functional unit. In our work, we focus our attention on data quality. Data for the analysis can be divided in two categories: primary data, directly collected from producers and users of the systems, and secondary data, derived from the existing literature (including databases). Although technical guidelines in reference [15] and two literature reviews realized by the authors in [12] and [20] strongly recommend using primary data, most of the existing studies use secondary information. Only six of the analyzed works [7,10,11,14,18,22] use primary data obtained thanks to direct collaboration with batteries manufacturers, which provided information about the amount of material for each component, energy consumption for battery production, waste, percentage of recycled material used and battery maintenance operations. One study, reference [17], uses primary data only to evaluate battery energy consumption during the use phase, while [9,16,21] consider only secondary data, obtained from the available literature and from the Ecoinvent database. In general, it is possible to observe a lack of primary data that either are absent or cannot be presented in the studies due to industrial confidentiality reasons. Although this critical issue is justified by the high rate of competition and innovation of the sector, the lack of information related to primary data affects the transparency and replicability of many studies. Furthermore, it is difficult to update studies based on outdated databases (for example, reference [10]) or to check the results against different energy mixes.

#### 5. Life Cycle Impact Assessment—LCIA

In an LCA, the impacts evaluation phase (Life Cycle Impact Assessment—LCIA) allows the assessment of potential impacts extent using data collected in the LCI. This operation links inventory data with specific impact categories and indicators, in order to better evaluate these impacts. The LCIA phase gives important information for life cycle results interpretation. Since different studies rely on different hypotheses, make use of different databases for background data and, above all, use different Life Cycle Impact Assessment Methods with their own unit, results cannot be compared easily with each other [20]. Nevertheless, some general conclusions may be drawn. First of all, for almost all impact categories, results show that the environmental major impacts of batteries life cycle occur during the production phase [7] and are due to energy consumption during materials and component

production [11,16]. In particular, anode production process is responsible for the greatest impacts for impact categories such as eutrophication and acidification, whereas the cathode has major impacts for global warming and abiotic depletion [17]. Coming to the amount of the environmental impacts, results show great variability. Variability is due to, as mentioned, the use of different hypotheses and databases, but it is also linked to the different batteries' chemistry. As discussed, global warming is the most investigated impact category, since EV market penetration is mainly driven by transport sector decarbonization. Figure 2 summarizes results variability linked to greenhouse gas emissions per kWh of batteries capacity, relating to batteries production phase. These values are extracted or inferred by the assessed studies in this literature review. Depending on the different technologies and on the age of the studies, greenhouse gas emissions per kWh batteries capacity can range from 53 kg CO<sub>2</sub>eq/kWh to more than 300 kg CO<sub>2</sub>eq/kWh.



**Figure 2.** Variability of the global warming potential indicator (kg CO<sub>2</sub>eq/kWh) for batteries production phase (LCO: Lithium Cobalt Oxide; LFP: Lithium iron phosphate; LFP-LTO: Lithium iron phosphate-Lithium Titanate; LMO: Lithium Manganese Oxide; LMO-NMC: Lithium Manganese Oxide-Lithium Nickel Cobalt Manganese; NCA: Lithium Nickel Cobalt Aluminum Oxide; NCM: Lithium Nickel Cobalt Manganese Oxide).

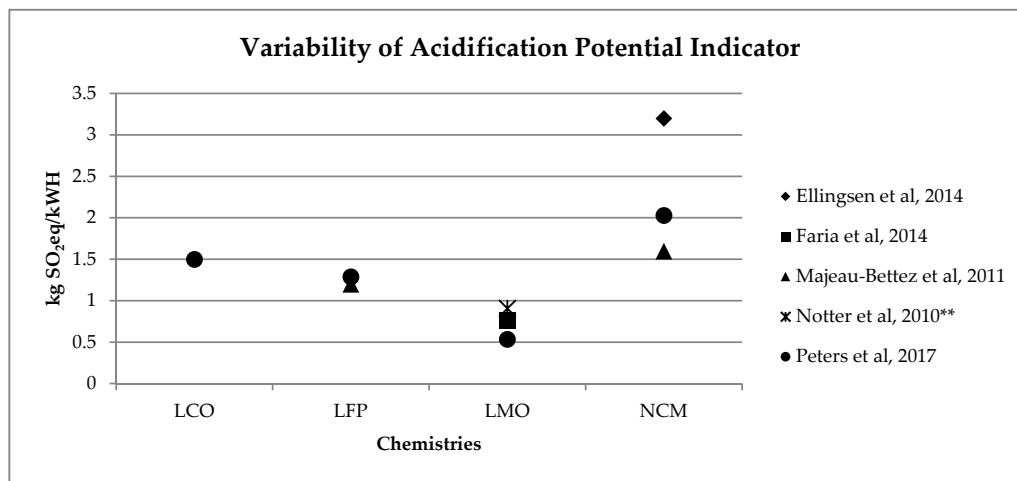
Considering a modern EV equipped with a 40 kWh battery lasting for 210,000 km [3], the lower and the upper values in Figure 2 correspond to an emission per km ranging from less than 10 g CO<sub>2</sub>eq/km to almost 60 g CO<sub>2</sub>eq/km. Nevertheless, despite this high variability, if we consider for the other vehicles life cycle phases, the CO<sub>2</sub>eq/km reported in reference [3], the total CO<sub>2</sub>eq/km life cycle emissions of an average middle size EV equipped with a 40 kWh battery, are lower than those of similar diesel or petrol cars, no matter if we consider the upper or the lower bound of battery CO<sub>2</sub>eq emission variability (see Table 3).

A similar range of variability can be found for other, less investigated, environmental impact categories (see Figures 3–6). Again, if we consider a 40 kWh battery lasting for 210,000 km, and we consider the results from reference [1] for the other life stages, we can see that while for some impact categories for which EV perform worst, like eutrophication [1], the variability of the impacts associated with battery production does not affect the environmental ranking among EV and the corresponding ICE Vehicle. For categories like acidification, the use of the lower bound value implies that EV performs

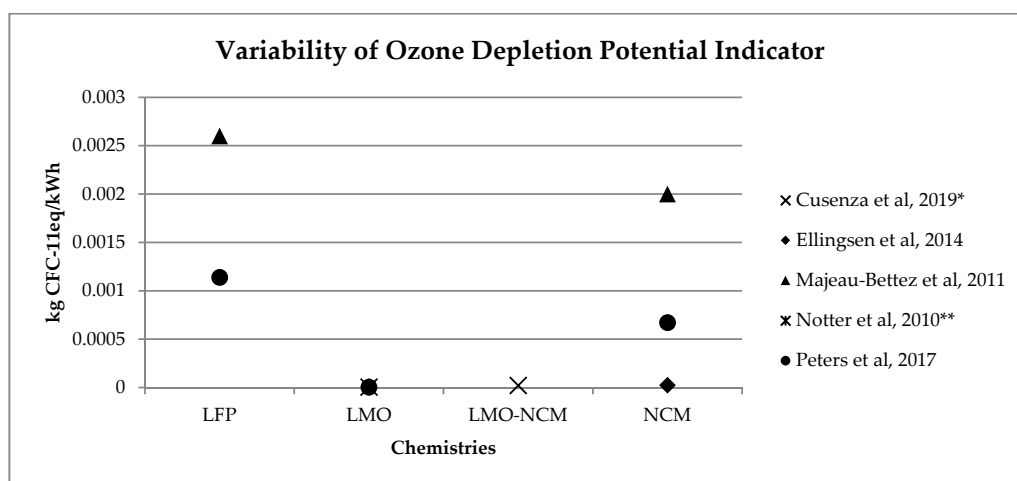
better than ICE Vehicle, while the use of the upper bound value implies that the ICE Vehicle is the best performer (see Table 4).

**Table 3.** Effects of the variability of CO<sub>2</sub>eq emission per kWh of battery on the life cycle comparison among a middle size electric, diesel and petrol car. Battery CO<sub>2</sub>eq emission per km derives from Figure 2, considering 40 kWh of capacity and 210,000 km of life. CO<sub>2</sub>eq emission per km of remaining life cycle phases are taken from reference [1].

g CO <sub>2</sub> eq/km	Vehicle Production	Battery Production		Maintenance	Road	Fuel/Electricity Production	Use	Total	
	(w/out battery)	Min	Max			IT marg. Mix		Urban Cycle	Min
Diesel	38.2	0.0	0.0	7.7	0.6	41.1	198.5	286.1	286.1
Electric	37.7	9.5	59.6	6.2	0.6	92.5	0.0	146.6	196.7
Petrol	41.5	0.0	0.0	7.4	0.5	59.1	221.6	330.0	330.0

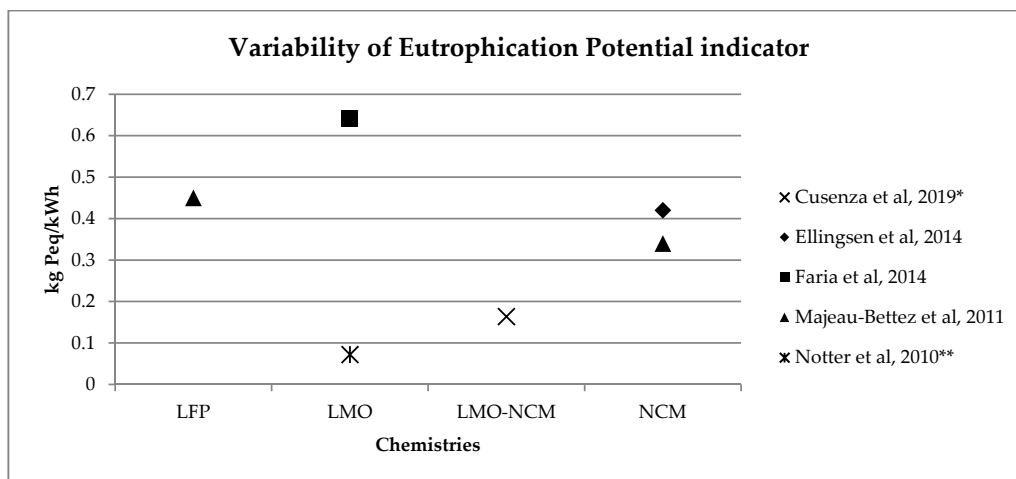


**Figure 3.** Variability of acidification potential (kg SO<sub>2</sub>eq/kWh) for batteries production phase (LCO: Lithium Cobalt Oxide; LFP: Lithium iron phosphate; LMO: Lithium Manganese Oxide; NCM: Lithium Nickel Cobalt Manganese Oxide); \*\* data from reference [11] have been updated using Ecoinvent v 3.5.

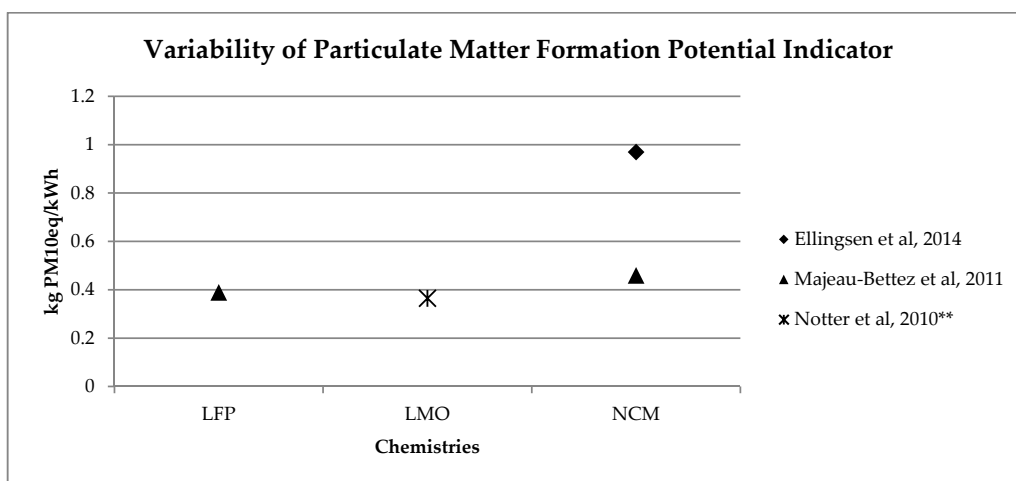


**Figure 4.** Variability of ozone depletion potential (kg CFC<sub>11</sub>eq/kWh) for batteries production phase (LFP: Lithium iron phosphate; LMO: Lithium Manganese Oxide; LMO-NCM: Lithium Manganese Oxide-Lithium Nickel Cobalt Manganese; NCM: Lithium Nickel Cobalt Manganese Oxide); \* data from reference [7] are calculated on the basis of the total amount and the percentage for battery production, \*\* data from reference [11] have been updated using Ecoinvent v. 3.5.





**Figure 5.** Variability of eutrophication potential (kg Peq/kWh) for batteries production phase (LFP: Lithium iron phosphate; LMO: Lithium Manganese Oxide; LMO-NCM: Lithium Manganese Oxide-Lithium Nickel Cobalt Manganese; NCM: Lithium Nickel Cobalt Manganese Oxide); \* data from reference [7] are calculated on the basis of the total amount and the percentage for battery production, \*\* data from reference [11] have been updated using Ecoinvent v 3.5.



**Figure 6.** Variability of particulate matter formation potential (kg PM10eq/kWh) for batteries production phase (LFP: Lithium iron phosphate; LMO: Lithium Manganese Oxide; NCM: Lithium Nickel Cobalt Manganese Oxide); \*\* data from reference [11] have been updated using Ecoinvent v 3.5.

**Table 4.** Effects of the variability of acidification potential (g SO<sub>2</sub>eq) and eutrophication potential (g PO<sub>4</sub>eq) per kWh of battery on the life cycle comparison among a middle size electric, diesel and petrol car. Battery Emissions per km derives from Figures 3 and 5, considering 40 kWh of capacity and 210,000 km of life. Emissions per km of remaining life cycle phases are taken from reference [1].

Impacts/km	Vehicle Type	Vehicle Production & Disposal	Battery Production & Disposal		Fuel/Electricity Production & Supply	Use & Maintenance	Total	
			Min	Max			Min	Max
Acidification Potential	EV	0.10	0.10	0.70	0.23	0.02	0.46	1.00
g SO <sub>2</sub> eq	ICE	0.14	-	-	0.55	0.11	0.79	0.79
Eutrophication Potential	EV	0.06	0.01	0.12	0.06	0.01	0.27	0.25
g PO <sub>4</sub> eq	ICE	0.06	-	-	0.07	0.03	0.16	0.16

Of course, many of the impacts associated with battery production could be lowered by recycling battery components and using recycled materials for battery production. Recycling may reduce material production energy demand up to 50% and can help to decrease environmental impacts for all the impact categories assessed [4]. Although there are a number of technologies and combinations of technologies being developed for batteries recycling (hydrometallurgy is close at hand, and can potentially extract more materials than pyrometallurgy) [12], battery recycling options are not always included in the analysis, due to the lack of relevant and reliable information [20]. Recently, a very careful recycle phase analysis has been realized in reference [7]. This work states that the environmental credits associated with materials recovered through battery recycling processes exceed the environmental impacts associated with recycling processes in all the impact categories examined, with the exception of ozone depletion, ionizing radiation and freshwater ecotoxicity. The environmental credits are particularly relevant for some impact categories such as: marine eutrophication (−27%), human toxicity (about −20% for human toxicity no cancer effect and −40% for human toxicity cancer effect), particulate matter (−17%) and abiotic depletion (−16.4%). In particular, the environmental credits related to cobalt, nickel and manganese sulphates, copper and steel are really significant and rise up to almost 80% for an important category such as abiotic depletion. Moreover, the environmental benefits linked to recycling could be increased if other cell components/materials, such as graphite, electrolyte and aluminum, are recovered, i.e., by designing battery cells to make disassembling and separating the cell components easier and more secure [7]. Additionally, for climate change impact, recycling can gain relevant positive effects, and the saved emission can be in a range of 16–32 kg CO<sub>2</sub>eq/kWh [26]. For what concerns lithium recycling, instead, further research is still needed [19].

## 6. Sensitivity and Uncertainty Analysis

In general, because of the lack of primary and reliable data from industry, several assumptions have to be made in LCA studies. For this reason, sensitivity analysis has an important role, especially in a traction battery LCA, where some data and information are difficult to be found or cannot be declared by battery manufacturers due to their confidentiality. Moreover, in comparative LCAs, sensitivity analysis is requested by the ISO 14040 standard. However, sensitivity analysis is realized only in eight studies out of seventeen, and the related parameters can be organized in three categories: energy, distance driven, battery components materials and their recycling rate. The first category refers mainly to the energy mix consumed during the use phase and in the battery manufacturing phase [4,7,10,11,14,21]. The energy mixes consumed can considerably affect the final results, especially if these mixes are characterized by a high rate of non-renewable energy sources. For this reason, it is important to consider an appropriate energy mix [1] or simulate different mixes or different daily charging period. Sensitivity analysis should also be applied to the amount of energy used for battery production and to the composition of the energy mix used in this life cycle stage, given its relevance in traction battery LCA [7,10]. The second category is linked with the total distance driven, during their entire lives, by the e-cars where batteries are deployed [7,10,11,14,17]. This parameter can influence the final results of the studies and for this reason, different distances can be considered in order to verify the robustness of the results. Finally, the third category refers to battery components' materials and their recycling rate during the end of life phase [7,11,14,16,21], which could represent a relevant parameter in an LCA study. The sensitivity analysis related to this parameter could help to identify the materials with higher environmental impacts and if material recovery can help to reduce environmental impacts or if recycling operations generate more impacts than components disposal.

## 7. Conclusions

The review analyzed seventeen recent studies on automotive batteries LCA. This analysis is realized to give useful information to carry out new LCAs of automotive batteries and to provide a more complete picture of electric vehicle batteries LCAs. Almost all the assessed works have a good degree of compliance with the indications given by ISO 14040 [23] and ISO 14044 [24] international standards,

but some documents do not fully comply with these two standards when they analyze batteries' impacts. We found that the functional unit definition is very heterogeneous and not always appropriate, and many studies consider different functional units, basing their choice on the analysis they have to realize. Consequently, the assessed works suggest many functional units: the whole battery pack, 1 kWh of storage capacity, 1 kg of battery, the distance travelled by the electric vehicle (equipped with the batteries) during its lifetime or 1 km. In view of the foregoing, the most suitable functional units for LCA of traction batteries seem to be 1 km of travel distance along the entire battery life cycle or, for sake of comparability with the existing literature, 1 kWh of battery storage capacity (specifying the battery's number of charging cycles during its lifetime). Many studies, except for [8,13,19], clearly define the system boundaries of their analysis. Only eight out of seventeen studies consider all impacts generated by the batteries during their life, realizing a cradle to grave assessment. The evaluated phases are: raw materials extraction and manufacturing, batteries production, transportation, use phase, and end of life with material recycling. Only few studies rely on primary data, while many of the assessed studies use secondary data, obtained from available literature documents or from the Ecoinvent LCA database. In general, we register a lack of primary data and of transparency both on bills of material and on energy consumption during the battery production phases. It seems important to encourage new automotive battery LCA using updated and reliable primary data, since using old data in a sector where technologies are evolving rapidly can lead to wrong conclusions and wrong decisions. For what concerns impact categories, there is a very heterogeneous situation, even if some impact categories are more frequently used (global warming, acidification, eutrophication) whereas others are used only in few studies (e.g., water use, land use, ionizing radiation). Basing on this literature review, to realize an automotive battery LCA authors suggest to consider the following: global warming, acidification, eutrophication, ozone depletion, particulate matter, abiotic depletion, human toxicity, ecotoxicity and CED (Cumulated Energy Demand). The review also underlines the importance of carrying out sensitivity analysis on some key parameters such as: battery lifetime, recycling/second life scenarios, energy mixes in production and use phase, percentage of recycled material used during the production phase.

As regards LCIA results, there is a great variability in all the impact categories that were comparable among different studies (global warming, ozone depletion, acidification, eutrophication and particulate matter formation). For global warming, one of the main impact categories under the spotlight, this variability ranges from 53 to 313 g CO<sub>2</sub>eq/kWh of battery capacity. Our analysis shows that no matter the value considered within this range, the EVs show lower impact in their life cycle when compared to diesel or petrol cars. For other analyzed impact categories we found similar variability but if for eutrophication EVs perform worse than ICE Vehicles for any value within the variability range, for impact categories such as acidification and particulate matter formation, the use of the lower or upper bound of the variability range completely change the comparison among EVs and ICE Vehicles. This confirms that other impact categories than global warming should be investigated in LCA of traction batteries. Moreover, our review shows that batteries components which generate the greatest impacts during the production phase are the cathode active material and the anode copper and aluminum. Key aspects that could be improved to reduce these impacts are: battery lifetime extension, increase in battery efficiency and energy density. In addition, energy mix considered during the battery different life phases could be very important to decrease impacts: an energy mix with an important contribution of renewable energy sources can reduce dramatically battery overall impacts. Many studies underline that battery second life, that is battery use in stationary storage systems after their use in the automotive field, can help to reduce storage systems overall impacts. Finally, although investigated by a relatively small number of studies, it appears that material recycling, especially cobalt and nickel, could represent another useful solution to further reduce batteries' overall impacts, avoiding virgin material use during storage devices' production.

**Author Contributions:** Conceptualization, A.T. and P.G.; Methodology, A.T. and P.G.; Software; Validation, M.L.C. and P.G.; Formal Analysis A.T. and M.L.C.; Investigation, A.T., M.L.C. and P.G.; Resources; Data Curation, A.T.

and M.L.C.; Writing—Original Draft Preparation, A.T.; Writing—Review and Editing, A.T., M.L.C. and P.G.; Visualization, A.T. and M.L.C.; Supervision, P.G.; Project Administration, P.G.; Funding Acquisition. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work has been financed by the Research Fund for the Italian Electrical System in compliance with the Decree of 16 April 2018.

**Conflicts of Interest:** The authors declare no conflict of interest.

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