Life cycle inventories for modelling the production of battery electric vehicles in the European life cycle assessment studies

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Abstract

Battery electric vehicles are expected to reduce greenhouse gas emissions of road transport. Along with the development of the electric mobility, life cycle assessments are increasingly carried out and published with the aim to evaluate the environmental impacts of battery electric vehicles. This review analysed 15 European life cycle assessments to investigate which data referring to the production stage are most commonly used in the literature and which data are the most recent. Data sources focusing on battery manufacturing are many and regularly revised. In contrast, data sources focusing on the rest of the vehicle are fewer and often based on data from traditional internal combustion engine vehicles integrated with data on the electric components.

1. Introduction

In 2017, road transport was responsible for 72% of GHG emissions from transport in the European Union (EU), with passenger cars contributing to 44% (EEA, 2019). Among the different measures put in place by the EU to contrast climate change, the Regulation 2019/631 set an ambitious target: to limit the average CO_2 emissions of new passenger cars to a maximum of 95 gCO_2/km by 2021, intended as the fleet average for each car company (European Parliament and Council of the European Union, 2019). Additionally, the EU already set the 2025 and the 2030 targets, i.e. a reduction of 15% and 37.5%, respectively, of the 2021 fleet CO_2 emissions. For manufacturer groups, the most common strategy to lower the average emissions of their fleet is its electrification, although collaborative efforts with oil & gas companies are taking place in order to develop new-generation fuels. The current typologies of electric vehicles (EVs) are: hybrid EVs (HEVs), plug-in hybrid EVs (PHEVs), range-extended EVs (REEVs), battery EVs (BEVs), and fuel-cell EVs (FCEVs). Almost all manufacturer groups have been announcing new EVs models or electrified versions of older models. In 2021, the EU carmakers are expected to offer 92 BEV and 118 PHEV models (T & E, 2019). Regarding the last data about new passenger car registrations in the EU in 2018, the market share of HEVs was 3.8%, whereas the market share of electrically-chargeable vehicles was 2.0% (ACEA, 2019a). Besides their potentially huge contribution in decreasing GHG emissions compared to conventional powertrains, BEVs and FCEVs also improve the local air quality (more than HEVs, PHEVs, and REEVs, which are not zero-emissions vehicles). This review is focused on passenger BEVs only, because BEVs are the natural evolution of hybrid EVs and a relatively mature technology, not like FCEVs which are still a niche (ACEA, 2019b).;,

Due to the development of electric mobility, several life cycle assessments (LCA) have been recently carried out and published. Their main aim is to evaluate the environmental impacts of BEVs and to compare them with those of ICEVs (internal combustion engine vehicles). The majority of LCAs suggests that BEVs emit lower life-cycle GHG emissions with respect to conventional ICEVs, except where electric energy is produced from coal or energy mixes largely based on fossil sources (EEA, 2018; Hawkins et al., 2012; Nordelöf et al., 2014). On the other hand, recent studies showed that even a BEV driven in Poland, a country with a high share of coal-derived electricity, causes a lower impact on the climate change than an ICEV (Burchart-Korol et al., 2018; Messagie, 2017). Although this conclusion is becoming consolidated in the literature, it is necessary to continuously evaluate and compare the electric mobility with any other propulsion technology (biofuels, e-fuels, hydrogen, etc.) without preconceptions. To be sure to choose the best route towards the decarbonisation of transport, high-quality data for LCAs of BEVs are desirable. The main stages of the life cycle of a BEV are: production of the vehicle and the battery; production of electricity; use phase; end-of-life. It is already recognised that the use phase is the main responsible for the GHG emissions (Hawkins et al., 2012). However, the manufacturing phase of a BEV can be the main responsible for impacts on human health and can make a great contribution to the impact categories regarding the ecosystem (EEA, 2018; Nordelöf et al., 2014). Compared to an ICEV, in fact, the sum of battery, electric motor and power electronics increases the use of copper, nickel, aluminium, iron and some critical raw materials. Other components are not necessary in a BEV, such as the clutch, the gearbox, the transmission system, the exhaust gas cleaning devices, including the catalyst. In any case, the manufacturing phase of a BEV generally causes more GHG and air pollutant emissions than that of an ICEV, mostly due to the battery (EEA, 2018). Furthermore, to increase the vehicle range of BEVs, lighter materials could be gradually used for the vehicle's body. In light of the above considerations, it is suggested to pay an adequate attention to the production stage when performing the LCA of a BEV.

2. Method

This review investigates which data referring to the production stage of BEVs are commonly used in the LCAs and which data are the most recent. The analysis covers 15 publications issued in the last five years (2015-2020), reported in Table 1. The starting source was a list from a recent review about EVs (Marmiroli et al., 2018), with additional studies identified from the references listed by recent publications. To be eligible for the review, a study had to comply with four requisites:

- to be located in Europe;

- to assess a light-duty vehicle (LDV, in other words passenger cars and light commercial vehicles);
- to include at least one assessment regarding a BEV;
- to include the manufacturing of the vehicle within the system boundary of the LCA.

Table 1: list of reviewed LCAs and their system boundary (CtG: Cradle-to-Grave, EoL: End-of-Life), reference vehicle, functional unit (F.U.), and vehicle lifetime (expressed as total mileage)

Authors	**System boundary**	**Reference vehicle**	**F.U.**	**Lifetime**
Helmers et al., 2020	CtG	Smart Fortwo (first gen.), VW Caddy	1 km	150,000 km
Marmiroli et al., 2020	CtG w/o EoL	Light commercial vehicle	One delivery mission	240,000 km
Almeida et al., 2019	CtG	Small city car, medium-sized family cars, large full-size cars, large SUV	1 km	Not reported
Girardi et al., 2019	CtG	VW Golf	1000 km	230,000 km
Burchart-Korol et al., 2018	CtG	Nissan Leaf	150,000 Km	150,000 km
Giordano et al., 2018	CtG w/o EoL	5-ton Iveco Daily 50C van, model year 2014	1km	20,000 km/y 8 or 12 y
Raugei et al., 2018	CtG w/o EoL	Compact passenger vehicle	150,000 km	150,000 km
Helmers et al., 2017	CtG	Smart Fortwo (first gen.)	100,000 km	100,000 km

Authors	System boundary	Reference vehicle	F.U.	Lifetime
Lombardi et al., 2017	CtG w/o construction and EoL of glider	GM Chevrolet Malibu (repowered)	200,000 km	200,000 km
Van Mierlo et al., 2017	CtG	Small passenger car	1 km	209,597 km
Ellingsen et al., 2016	CtG	Mini car, medium car, large car, luxury car	180,000 km	180,000 km
Girardi & Brambilla, 2016	CtG	Smart Fortwo, Chevrolet Spark, Fiat 500, VW Golf, Ford Focus, Kia Soul	1 pkm	Smart: 175,000 km; Chevrolet, Fiat: 200,000 km; VW, Ford, Kia: 230,000 km
Tagliaferri et al., 2016	CtG	Nissan Leaf	1 km	150,000 km
Bauer et al., 2015	CtG	VW Passat	1 km	240,000 km
Girardi et al., 2015	CtG	VW Golf	150,000 km	150,000 km

3. Results

a. Structure of a BEV

Proper modelling of a BEV requires to know exactly how the vehicle is composed. The lack of a detailed LCI often leads to model the vehicle body of an EV by adapting the LCI of an ICEV's body. In fact, car body and auxiliary systems of many BEVs do not necessarily differ from those of ICEVs, except for some models incorporating lightweight materials (EEA, 2018). The original LCI of an ICEV is usually enriched with the electric powertrain and deprived of the components that, instead, are not present. The vehicle components that do not generate propulsive energy are called together 'glider'. The glider is often assumed to be identical in electric and conventional vehicles. The glider comprises chassis/body, axle, brakes, tyres and wheels, seats, doors, bumpers, cockpit, belts, windshield and windows, lights, suspension systems, A/C system, etc. (Del Duce et al., 2016; Notter et al., 2010). As mentioned before, several conventional components of the powertrain of an ICEV are not present in a BEV. Table 2 summarises the main differences between ICEVs and BEVs (Del Duce et al., 2016; Ellingsen et al., 2014; Giordano et al., 2018; Hawkins et al., 2012; Marmiroli et al., 2020; Notter et al., 2010).

Table 2: main differences between BEVs (Battery Electric Vehicle) and ICEVs (Internal Combustion Engine Vehicle), regarding the components

Components that are present in an ICEV and not in a BEV	**Components that are present in a BEV and not in an ICEV**
● Air filter ● Alternator ● Clutch ● Engine oil and oil filter ● Fuel tank, distribution systems and fuel filter ● Gearbox ● Internal Combustion Engine (ICE) ● Radiator ● Starting system ● Torque converter (with automatic transmission) ● Treatment line for exhaust gases	● Battery pack: - Battery cells - Battery Management system (BMS) - Cooling system - Packaging ● Cables (high power) ● Capacitor ● Charger ● Converter ● Electric motor(s) ● Inverter ● Power Distribution Unit (PDU) ● Regenerative braking system ● Single-ratio gearbox

b. Methodological choices

System boundaries, reference vehicles and functional units chosen by authors are already shown in Table 1. Total mileage is rather variable, with a rough average of 180,000 km. Results expressed per km significantly depend on the lifetime. In fact, the production, maintenance and end-of-life impacts of a BEV are distributed over the lifetime. Therefore, the longer the lifetime, the lower the impacts per km.

Climate change was the most studied impact category (13/15 studies), followed by human toxicity (9/15), photochemical oxidant formation (9/15), acidification (9/15), particulate matter formation (9/15) and fossil resource depletion (7/15).

The batteries considered in the studies were Li-ion batteries, except for two cases where NaNiCl batteries were analysed. The reported types of Li-ion batteries were LMO (6/15 studies), LFP (4/15), NMC (4/15), NCA (2/15), LMR-NMC (1/15), while 5/15 studies did not specify the battery type. Giordano *et al.* (2018) examined both NaNiCl and Li-ion batteries. The Li-ion batteries were assumed to last for the entire vehicle lifetime in 9/15 LCAs (up to 240,000 km), to be replaced in 3/15 LCAs (at 150,000-160,000 km), while 4/15 LCAs did not specify this aspect.

c. LCI data sources for the battery

Based on the work by Peters *et al.* (2017), relations between studies were traced seeking the interconnections of LCI data sources used in the reviewed studies. This was useful to understand, ultimately, which are the LCI data sources, which studies provide original data, and which are based upon previous LCIs. Only 4/15 LCAs added original data to already existing ones. In their two studies, Helmers *et al.* (2017, 2020) based the battery composition on the work of Majeau-Bettez *et al.* (2011) but developed own data from the electrification in a laboratory of a Smart and a VW Caddy. Giordano *et al.* (2018) gathered new inventory data for the NaNiCl battery using primary data from the manufacturer, while for Li-ion batteries they utilized the BatPaC modelling tool (ANL, 2020b). To model their light-commercial vehicle, Marmiroli *et al.* (2020) used confidential primary data from the manufacturer. The LCI by Ellingsen *et al.* (2016) was based on their previous work, in which they had acquired data from several sources, including a battery producer (Ellingsen et al., 2014). Tagliaferri *et al.* (2016) and Burchart-Korol *et al.* (2018) relied on the previously mentioned work by Majeau-Bettez *et al.* (2011), who had combined several secondary data in a detailed way. Almeida *et al.* (2019) used GREET_2018, a model estimating weight and material of each vehicle’s component based on user-defined settings (Wang et al., 2018; ANL, 2020a), Bauer *et al.* (2015) used data from Notter *et al.* (2010), while Lombardi *et al.* (2017) used data by Zackrisson *et al.* (2010). Van Mierlo *et al.* (2017) ultimately relied on confidential data from SUBAT project (Matheys et al., 2007; Van den Bossche et al., 2006). The three studies by Girardi *et al* (2015, 2016, 2019), as well as Raugei *et al.* (2018), relied on the ecoinvent database (Del Duce et al., 2016; Leuenberger & Frischknecht, 2010; ecoinvent, 2020).

d. LCI data sources for gliders and powertrains

The same approach presented above was applied to glider and powertrain inventories. Like for batteries, only Giordano et al. (2018), Helmers et al. (2017, 2020) and Marmiroli et al. (2020) provided new original data. Giordano et al. (2018) acquired primary data from Iveco (vehicle manufacturer) and various OEMs. Helmers et al. (2017, 2020), in addition to their own data, received data about motor and lead battery from two OEMs. To model their light-commercial vehicle, Marmiroli et al. (2020) used confidential primary data. Almeida et al. (2019) relied on GREET_2018 (Burnham et al., 2006; Das, 2004). The remaining LCAs used ecoinvent (Del Duce et al., 2016; Leuenberger & Frischknecht, 2010).

For the glider, ecoinvent relies on an old, albeit updated over the years, LCI of a VW Golf (Schweimer and Levin, 2000). Primary data from BRUSA (company) were used to model the powertrain (Del Duce et al., 2016).

4. Conclusions

15 LCAs on European BEVs were reviewed, with a special focus on LCI data sources regarding the production stage. Several methodological choices differ among the studies, with reference to lifetime mileage, impact categories and type of battery. To reduce the variability among LCAs, it is recommended to continue the process of standardisation, without sacrificing the evolutionary and dynamic nature of LCA. In this sense, it is worth citing the “Guidelines for the LCA of electric vehicles”, whose aim was to «create a common framework concerning methodological choices and assumptions for LCAs of electric vehicles» (Del Duce et al., 2013). For what concerns the battery’s LCI, the analysis points out that, every two or three years, original or partially original databases are published and made available to LCA practitioners. For what concerns the powertrain and the glider, there is a chronic lack of primary data, likely due to the confidentiality of the bill-of-material of vehicles, which is not generally made available by manufacturers (Messagie, 2017). The reviewed literature suggests that no BEV manufacturer has made a complete LCI publicly available so far. To give credibility to LCA studies in the automotive sector, data should always be updated and consistent with the evolution of automotive engineering. We recommend that EV manufacturers consider data sharing as an opportunity to better understand their products and, also, to advertise themselves. Finally, it is worth saying that this was a partial literature analysis. Therefore, it could be useful to expand the analysis to LCAs on a global scale and with a more systematic approach.

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