# Life cycle assessment and economic analysis of the electric motorcycle in the city of Barcelona and the impact on air pollution

## Abstract

In this work, the evaluation of the life cycle of the service provided by a medium-power motorcycle in a Spanish urban environment was carried out, comparing two motorcycles, a battery electric vehicle (BEV) is compared with an internal combustion engine vehicle (ICEV). The economic study of the total costs of ownership is also carried out considering the environmental costs associated with each type of vehicle. A comprehensive inventory is compiled for both vehicles (motorcycles) that describes the most relevant components and includes two types of batteries for the BEV. A sensitivity analysis of the most impactful parameters is also considered.

The results indicate that the ICEV contributes approximately 5 times more in the global warming potential impact category mainly due to the consumption of fossil fuels. The BEV also impacts some categories in the manufacturing stage, a fact that is strongly related to the battery. Sensitivity analysis indicates that the total distance travelled plays an important role, but the electricity mix is probably the most relevant factor in terms of climate change impact category. The economic analysis reported lower environmental externality costs for the BEV, making it more affordable than the ICEV and highlighting the benefit in terms of air pollution. The BEV is presented as a suitable option vehicle from environmental and economic point of view and one of the actors to accelerate the transition towards a more sustainable urban mobility model.

Keywords: battery electric vehicle; internal combustion engine; lithium-ion battery; externality cost; air pollution

## 1. Introduction

Transportation accounts for about 25% of total global $CO_2$ emissions from fuel combustion (International Energy Agency, 2020a). A current emerging trend is electrifying mobility, and in only the last five years, the total number of electric vehicles has increased by a factor of 10 (International Energy Agency, 2020b). In part, the reason for such growth is that the electric traction vehicle is assumed to have a lower environmental impact compared to a conventional one. The literature on life cycle assessments (LCA) of electric traction vehicles is rather dense, particularly for cars. There are many studies evaluating the impact in a certain country (Petrauskienė, Skvarnavičiūtė, and Dvarionienė, 2020), for example, at the European level, in Switzerland (Bauer et al., 2015), in Poland and the Czech Republic based on heavy fuels (Burchart-Korol et al., 2018), in Norway (Hawkins et al., 2013), in Italy (Del Pero et al., 2018) and in Sweden (Nordelöf et al., 2014). The country selection is indeed relevant due to substantially diverse electricity mixes (Burchart-Korol et al., 2020). Most of these studies concluded that the impact of climate change measured in kg $CO_2$eq./km is favourable for battery electric vehicles (BEV) compared to internal combustion engine vehicles (ICEV). At the Spanish level, only the study carried out by Sánchez et al. (2013) evaluated the electricity mix to compare the greenhouse gas emissions of buses, some electric, others not, circulating in Madrid (Spain) and recently Puig-Samper Naranjo et al. (2021) reported a comparative LCA of electric, hybrid, petrol, and diesel medium passenger vehicles (European C-class) operated in Spain.

It is evident that the urban mobility model must be redefined considering the current levels of air pollution in large cities. The electrification of transport has been proposed in cities such as Barcelona and Madrid, which would represent a substantial improvement in air quality. To achieve this, all vehicle categories must be partially electrified, including motorcycles (Soret, Guevara, and Baldasano, 2014). Two-wheel vehicles are presented as an attractive option, since they require less area per vehicle and are usually the fastest urban mode of transportation (Cherry, 2007; Kopp, 2011). Furthermore, they have been experiencing promising growth and typically have lower operating costs and fuel consumption than passenger cars (Cox and Mutel, 2018). When evaluating the impact of two-wheelers, an important concept is the tank-to-wheel efficiency, which shows how much energy is reaching the wheels compared to how much energy has been delivered to the vehicle. On the other hand, the well-to-tank efficiency represents how much energy needs to be delivered to the vehicle compared to the associated primary energy. Hwang and Chang (2010) showed that electric scooters with lithium-ion batteries have a lower well-to-tank efficiency than internal combustion scooters. However, the overall well-to-wheel efficiency increases, sometimes even tripling (Weber et al., 2019). From an economic perspective, the configuration of the powertrain plays an important role. In that sense, electric two-wheelers are also a superior option, since they end up being less expensive than hybrid and conventional options (P. D. Walker and Roser, 2015).

Another technology that has been considered is hydrogen. Mellino et al. (2017) concluded that lithium-ion battery electric bikes have less impact than hydrogen bikes in the production stage, but the opposite behaviour in the use stage. In this regard, Cox and Mutel (2018) evaluated several technologies from an environmental perspective. The authors conducted a comprehensive analysis of BEV, ICEV and fuel cell motorcycles taking into account a standard urban cycle. Overall, the ICEV and fuel cell motorcycles were found to have a substantially greater climate change impact compared to the BEV. Despite the clear advantages that the BEV presents, a worrying aspect among the aforementioned works is the environmental consequences linked to the manufacturing of batteries. These are usually of the lithium-ion type due to their high energy and power density combined with high efficiencies (Nikolaidis and Poullikkas, 2017); however, there are different chemistries for lithium-ion batteries depending on the composition of the cathode. Marques et al. (2019) compared the LCA of electric cars with a service life of 200,000 km that employ either lithium iron phosphate ($LiFePO_4$) or lithium-ion manganese oxide ($LiMn_2O_4$). The $LiFePO_4$ reported better technical characteristics but the environmental impacts were higher. Zhao and You (2019) contrasted the environmental impact of a $LiMn_2O_4$ with a lithium nickel manganese cobalt oxide ($LiNi_xCo_yMn_zO_2$) battery, both installed in a midsize electric vehicle which covered a total distance of 200,000 km. The former showed a greater impact on climate change from the cradle-to-gate approach, but when considering a cradle-to-grave approach, both batteries had a similar impact. Although batteries account for a considerable part of the total cost of the electric vehicle, not many studies have performed an economic analysis. Tseng et al. (2013) compared four compact electric and hybrid family cars with a conventional one while looking for total cost. The authors concluded that with tax credits alone, electric and hybrid vehicles are a superior option from a purely economic perspective. Regarding storage technologies, few studies have focused on updated and complete life cycle cost analysis for lithium-ion batteries applied to electric vehicles, and only Simpson and G. R. Walker (2002) conducted an analysis of the ultracapacitors used as a complement to batteries.

The influence of driving patterns on the environment has been considered relevant in the analysis of electric vehicles. Karabasoglu and Michalek (2013) simulated realistic driving cycles with conventional and electric vehicles. The authors concluded that electric vehicles were less cycle-dependent, while conventional vehicles emitted more and involved higher costs on urban roads than on highways. Marques et al. (2019) evaluated three driving profiles: light, moderate and intensive. The total impact was highly variable depending on the profile. For example, the light profile's global warming potential was about half as intensive. The authors also conducted a sensitivity analysis to assess the impact of the number of batteries or the source of electricity generation, which was found to be one of the categories with the highest impact. For this purpose, the World Harmonized Test Cycle (WMTC) is a useful tool for evaluating the impact of motorcycles under a realistic riding pattern. The data can be extracted from the European Commission (2014).

Barcelona is one of the European cities with the highest population density, of the order of 16,000 inhabitants per km$^2$ (City Population, 2021). In addition, currently, Barcelona is one of the European cities with the most motorcycles and mopeds on its streets. Over half a million were registered in 2019 (UNESPA, 2019), a factor partly due to its large population, and partly because of its being home to Spain's second-largest metropolitan area, where motorcycles are more practical than cars. Urban transportation is considered to play a key role in the air quality of Barcelona (Tobias et al., 2020). Recently, it was reported that Barcelona had exceedingly high $NO_2$ values that did not comply with the European legislation (European Commission, 2019). City authorities report vehicle density at around 6,000 per km$^2$, double that of Madrid and triple that of London (Superblocks, 2019) highlighting the deleterious impact on air quality and public health. The cost of air pollution as recently valued by the World Bank in terms of total welfare losses for Spain in 2013 is estimated at 49,331 million dollars, which represents 3.4% of GDP (Baldasano, 2020).

Consequently, Barcelona and other large urban conurbations have been forced to apply action plans to improve their air quality by reducing traffic activity and emissions (Rodriguez-Rey et al., 2021). To improve the air quality, the Metropolitan Area of Barcelona has established the so-called environmental labels. These labels identify how environmentally friendly a given vehicle is. This way, certain vehicles such as old diesel cars are not allowed to access a marked zone. Other European cities such as London have relied on low emission zones as well. Despite not causing a notorious reduction on air pollution, it was observed that owners tended to switch to smaller vehicles (Ellison et al., 2013). There has been a recent increase in motorcycles demand in Europe. In the case of Spain, the registrations have grown by 8.7% in 2021 compared to the same period in 2020 (The Motorcycle Industry in Europe, 2021). The rise in electric motorcycles demand is even more significant. Grouping the markets of France, Germany, Italy, Spain and the UK, about 18620 electric motorcycles were registered in 2020, while in 2019 the registrations were 12263. Out of these five countries, Spain was where the most registrations were made, since in 2020, 6142 new electric motorcycles were registered.

In accordance with the above, a life cycle analysis focused on electric motorcycles in Barcelona allow to assess the environmental benefits of these vehicles, which show a clear upward trend both in the market and in user preference, as well as their potential contribution to reduce air pollution. Therefore, the objective of this study is to develop an exhaustive life cycle inventory and to evaluate the environmental performance of the service provided by a battery electric vehicle (BEV) using the Muvi motorcycle produced by Torrot (Barcelona, Spain) as a reference. It is compared to an internal combustion engine vehicle (ICEV) that offers the same service, the Burgman 125 (Suzuki). The analysis provides key and revealing information about the comparison between these two motorcycles, not only from an environmental point of view, but also from an economic point of view. On the other hand, the batteries for the BEV have also been analysed from the perspective of life cycle assessment. Its production is another relevant factor when considering the total impact of the vehicle. The BEV motorcycle uses lithium, nickel, manganese and cobalt oxide technology, although lithium and manganese oxide can also be an alternative for this type of vehicle. The environmental impacts of these two types of batteries are compared to determine which is the most appropriate option for urban mobility. Finally, the influence of the electric mix on the global impact of the electric motorcycle was evaluated through a sensitivity analysis.

## 2. METHODOLOGY

This section covers the aspects most strongly related to the data involved in the LCA of all the scenarios evaluated. First, a general picture of the systems is presented along with the goals and the scope of this study. Then, considerations on the life cycle analysis are presented, such as the software and the methods used, and the comments and assumptions taken into account to compile the life cycle inventory (LCI). Finally, the approach used for the economic analysis is also described.

### 2.1 Goal and scope definition

The objective of this study was to evaluate the environmental performance of a BEV and compare it with an ICEV and to evaluate the impact that the type of battery has on the electric motorcycle. The study aims to answer the following questions i) what are and where are the potential environmental impacts of BEVs, ICEVs operated in Barcelona (Spain)? ; ii) what is the impact of the type of battery used in the BEV?; iii) what is the impact of the Spanish electrical mix? and of the other parameters evaluated with the sensitivity analysis?; iv) what is the total cost of ownership for each vehicle? and what would the cost be considering the environmental externalities?. For comparing the environmental performance of both vehicles, a functional unit of 80,000 km is defined, which accounts for the distance travelled by each motorcycle across its lifetime; this falls into the range of distances considered by

Cox and Mutel (2018) and it matches the second battery replacement foreseen by the BEV manufacturer (Torrot, 2020). The scope of this analysis represents a cradle-to-grave approach and encompasses all environmentally relevant processes from resource extraction to disposal.

The analysis is based on four stages: the definition of the system along with the scope and the goal, the LCI, the impact assessment (or life cycle impact assessment (LCIA)), and finally the interpretation of the results (ISO 14040, 2006 and ISO 14044, 2006). It is assumed that the motorcycles are used in daily commutes to work in a Spanish urban environment, specifically in the city of Barcelona. As for the ICEV motorcycle, it is a more powerful motorcycle than the BEV (8.8 kW (Suzuki, 2020) against 3 kW (Torrot 2020)). However, it must be taken into account that the peak power of an electric motor occupies a wider range of speeds than an internal combustion engine. This justifies the comparison between the BEV manufactured by Torrot (Torrot, 2020) and a 125cc motorcycle (Suzuki). Regarding the impact of the battery on the BEV, two batteries are considered: a lithium nickel manganese cobalt oxide (LiNiCoMn) battery (the currently installed battery) and a lithium-ion manganese oxide (LiMnO) battery. Then, accordingly, three scenarios were compiled as follows: i) BEV with the LiNiCoMn battery, ii) BEV with the LiMnO battery, and iii) ICEV. The three scenarios are depicted in Figure 1. Emphasis is placed on the battery that powers the BEV, and therefore its associated stages are explicitly depicted.

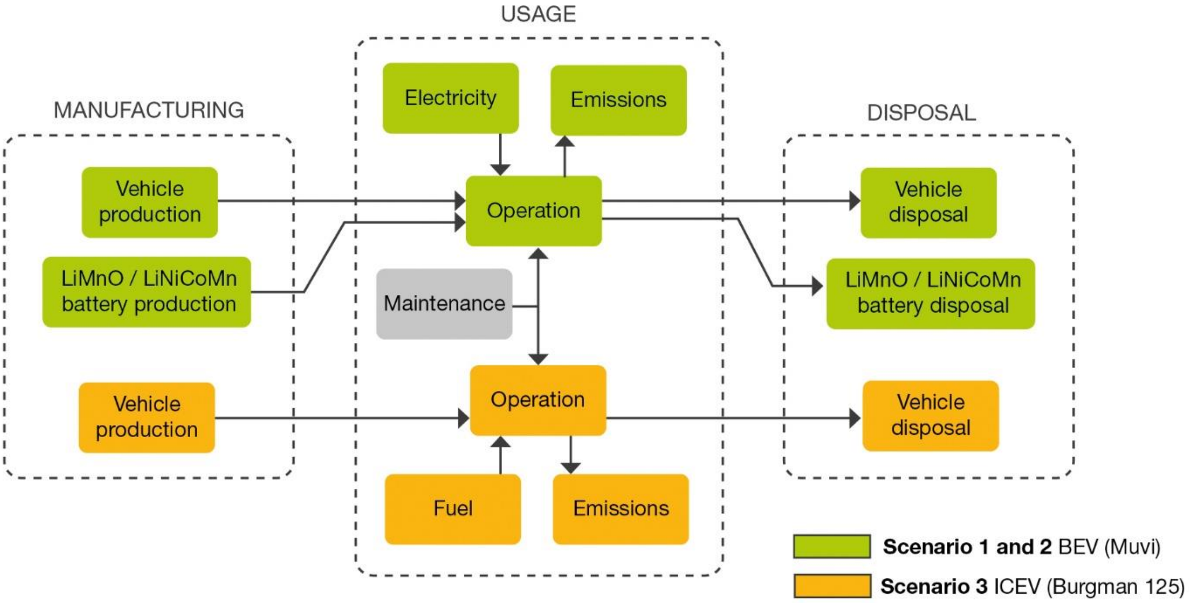


Figure 1. General scheme of the stages to be considered for the life cycle analysis of BEV and ICEV motorcycles (adapted from Petrauskienė et al. (2020) and Sophaa and Setiowatia (2017)).

The processes follow the structure defined in Figure 1, where the full service provided by the motorcycles is the combination of the manufacturing, usage (including maintenance) and disposal. These processes were conformed with the data gathered in the LCI. In the case of manufacturing, it was further divided into units (components), such as transmission, power train, etc. This nested hierarchy facilitates the attribution of the impact to each element in the motorcycle.

On the other hand, the production of the batteries and the converter for the power electronics of the BEV is carried out in China, the manufacturing of the components in Europe, and the final assembly in Spain. Thus, suppliers were specified according to their location in the world with the maximum possible accuracy. This is key, as varying the combination of electricity can translate into substantial changes in the overall results. Regarding emissions during operation, it has been assumed that they occur in an area of high population density, which is considered representative of a city like Barcelona.

The three scenarios were modelled using the open software OpenLCA and the Ecoinvent 3.6 cut-off database. It was considered that the cut-off option suited the project better than the allocation at the point of substitution (APOS) according to the boundaries of the system. To evaluate the impacts, the Ecoinvent 3.5 LCIA method database was integrated into the former one. The impacts were evaluated with the ReCiPe Midpoint (H), a hierarchical option, which is the default mode in scientific models (Golsteijn, 2012). When computing the results, the physical allocation option was chosen. Indicators such as the climate change impact, photochemical oxidant formation and human toxicity are some of the most meaningful ones for this analysis.

## 2.2 Inventory analysis

There are few studies focusing on motorcycles for this type of analysis; consequently, the inventories for both motorcycles have been gathered from specific data from the manufacturers, partially adapted from the literature and particularly prepared for this study. A realistic driving cycle was considered; that is, instead of assuming that the motorcycles travel at constant speed, a standard urban cycle such as the WMTC was used (European Commission, 2014).

The inventories of both motorbikes are compiled in Table S1 (Supplementary Material) and contain all the inputs and elements that constitute the unit processes depicted in Figure 1. A brief description of the components considered for both type of vehicles are listed in Table 1.

Table 1. Description of the main components included in the inventory for the BEV and the ICEV.

| Component | BEV | ICEV |
|---|---|---|
| Frame | The structure of the motorbike, constituted by the chassis and the central stand; it is the heaviest part as it is mainly made of steel | Formed by the components that shape the motorbike, such as the chassis, the footrest, and the gasoline tank. Covered by paint and a zinc coat |
| Transmission | A system of pulleys that transmits the power from the motor to the rear wheel | The mechanism includes the clutch, a shaft, bearings, etc. It transmits a certain speed and torque to the wheels |
| Body | Placed on top of the frame, it corresponds to the cover and the saddle; relatively light, it is generally composed of plastics | The external and most visible part of the motorbike, mainly constituted by the saddle and the windscreen |
| Electric parts | Electrically powered components such as the front and rear lights, displays, integrated circuits. It includes the power converter (modelled apart). | Includes a tiny starter battery, powered by an alternator that feeds a starter motor. There is a rectifier to adapt the voltages, and also the lights in the head and the tail of the motorbike |
| Accumulation system | Acts as an energy reservoir of about 3 kWh. The original battery is a LiNiCoMn (scenario 1), the study also considers the LiMnO technology (scenario 2) as an alternative. Both batteries are modelled in detail | The system with a radiator and a fan to lower the temperature of the internal combustion engine |
| Power train | Encompasses a permanent magnet motor whose voltage and current waveforms are adapted by the converter | With the engine as its central component (divided into the valves, the piston, the crankshaft...), it incorporates the injection system, the air filter, pumps, and the catalytic converter |
| Front/rear train | They embody secondary components such as the handlebar, the fork, the mirrors and the shock absorbers | As in the BEV, the mirrors, the belt tensor, shock absorbers, and the handlebar are under this category |
| Others | Screws, washers, accessories and small parts with low impact. They are usually placed inside the former categories | Such as screws, connectors, cables, contactors... These are auxiliary elements with a minor influence |

In terms of manufacturing, the motorcycles are generally composed of the following components: the body, the frame, the wheels, the front and rear train, the transmission, the electric parts, the battery (in the case of the BEV), and the power train. Critical components when comparing the two vehicles are mainly the engines, and in the case of the BEV, the accumulation system and the converter demand. The engines were modelled from the detailed description reported in the study by Notter et al. (2010), while the converter and the battery cathode were modelled in detail.

The BEV inventory was developed to a greater extent from the information provided directly by the manufacturer (Torrot). However, since Torrot only assembles the parts, the data did not cover all stages of the life cycle. In this regard, two local teams participating in competitive projects in the field of electric mobility, e-Ride (e-Ride, 2021) and ETSEIB Motorsport (ETSEIB Motorsport, 2021), were contacted. When this information was not enough, the data were gathered in the literature and adapted according to the characteristics of each vehicle, as has been reported in similar studies by Sophaa and Setiowatia (2017), Cox and Mutel (2018) and Strømman (2011). The most significant remarks and assumptions in the inventory are summarised in Table S2 (Supplementary Material).

### 2.3 Economic analysis and impact on air pollution

In addition to the environmental study, a preliminary cost analysis was carried out in order to compare the economic viability of the two vehicles (BEV and ICEV). On the one hand, the costs related to the phases represented in Figure 1 were considered, which have to do with the acquisition, the energy to power the motorcycles, the maintenance operations and the waste disposal. The economic cost of both motorbikes was considered by calculating the total cost of ownership (TCO) (Eq. 1) as described by Ajanovic and Haas, (2016):

$$TCO = \alpha \frac{IC}{skm} + P_f FI + \frac{C_{O\&m}}{skm} \quad (1)$$

where TCO is given in €/km and stands for a representative measure of the cost per km travelled, IC is the initial investment cost in €, skm symbolizes the yearly travelled kilometers, α is the capital recovery factor, $P_f$ is the energy price in € /MJ, FI is the specific energy consumption expressed in MJ/km, and $C_{o\&m}$ is the operation and maintenance cost per year (€/year). As described by Papavinasam, (2013), the capital recovery factor α allows to compute an equivalent annual cost; it is defined according to Eq. 2:

$$\alpha = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

where n is the assumed years of service and i represents the interest rate.

However, to establish a fair comparison framework, the externality costs of the various midpoint impact categories must also be taken into account, as suggested in the study by De Bruyn et al. (2018). This implies the conversion of each particular impact to an associated cost in monetary terms (€), which does not represent a cost of ownership but an environmental cost.

The recent COVID-19 pandemic has demonstrated the positive impact on urban air pollution, especially during the lockdown. In Barcelona, $NO_2$ concentrations decreased by approximately 50%, while PM10 decreased by approximately 30%. However, the values continue to be higher than the mentioned limit of 20 μg/m$^3$ (Tobias et al., 2020). In this regard and given that the operation stage is the most relevant stage in terms of air pollution, a sensitivity analysis was carried out focused on the variation of the input parameters most strongly related to this stage: the distance and the mix of electricity used to charge the battery.

## 3. RESULTS AND DISCUSSION

This section has the following structure: first, the results of the comparison of the BEV and ICEV in the city of Barcelona are presented in terms of LCA analysis. The BEV motorcycle is evaluated in terms of its battery by comparing LiNiCoMn and LiMnO batteries. A sensitivity analysis is carried out to validate the robustness of the inventory and also draw some conclusions about the environmental performance of each vehicle. Finally, an economic study and potential implications for EV promotion and impact on air pollution are also discussed.

### 3.1. Results of the LCA of the BEV and ICEV

The results of the midpoint impact categories for both types of motorcycles (scenario 1 (LiNiCoMn) vs scenario 3) are summarized in Table 2. The results indicate that in some categories the ICEV reported a substantially greater impact than the BEV, but in other categories the result is the opposite. For example, for the eutrophication of fresh water, which depends mainly on the manufacturing stage (Bastos et al., 2019), the BEV has a greater impact due to the manufacturing of batteries. This stage alone has practically the same impact as the total reported by the ICEV.

The particulate matter formation of the BEV is about 70% of the ICEV. In overall terms, these results agree with those reported by Cox and Mutel (2018), although the electricity mix and the age of the motorcycle are two factors that play a major role according to the authors. Although the functional units in Cox and Mutel (2018) differ from the present study, in general, the trends and differences of the related impacts between conventional and electric motorcycles are maintained.

Table 2. Results on the environmental impact categories evaluated for the BEV and ICEV.

| Category | Units | BEV | ICEV |
|---|---|---|---|
| Freshwater eutrophication (FEP) | kg P-Eq | 1.08 | 0.52 |
| Natural land transformation (NLTP) | m2 | 0.27 | 2.56 |
| Freshwater ecotoxicity (FETPinf) | kg 1,4-DCB-Eq | 359.58 | 120.22 |
| Urban land occupation (ULOP) | $m^2a$ | 12.60 | 15.24 |
| Fossil depletion (FDP) | kg oil-Eq | 453.18 | 2607.86 |
| Particulate matter formation (PMFP) | kg PM10-Eq | 4.80 | 7.09 |
| Climate change (GWP100) | kg CO2-Eq | 1439.74 | 7746.18 |
| Photochemical oxidant formation (POFP) | kg NMVOC | 7.06 | 79.84 |
| Human toxicity (HTPinf) | kg 1,4-DCB-Eq | 1791.78 | 12102.70 |
| Metal depletion (MDP) | kg Fe-Eq | 14.15 | 1.57 |
| Water depletion (WDP) | $m^3$ | 8.52 | 4.61 |
| Terrestrial acidification (TAP100) | kg SO2-Eq | 12.10 | 18.84 |
| Ionizing radiation (IRP HE) | kg U235-Eq | 570.22 | 556.83 |
| Marine eutrophication (MEP) | kg N-Eq | 2.27 | 4.99 |

| | | | |
|---|---|---|---|
| Ozone depletion (ODPinf) | kg CFC-11-Eq | 0.00131 | 0.00126 |
| Agricultural land occupation (ALOP) | $m^2a$ | 92.40 | 70.31 |
| Marine ecotoxicity (METPinf) | kg 1,4-DCB-Eq | 318.22 | 218.22 |
| Terrestrial ecotoxicity (TETPinf) | kg 1,4-DCB-Eq | 0.29 | 17.88 |

The analysis of the climate change category for the two vehicles in the manufacturing, maintenance and disposal stages is shown in Figure 2. Although the ICEV has almost double the weight of the BEV, the impact in the manufacturing stage is not strictly proportional. This can be explained mainly by the batteries and the electric motor, components that, due to the type and quantity of materials used, contribute substantially to the global warming potential.

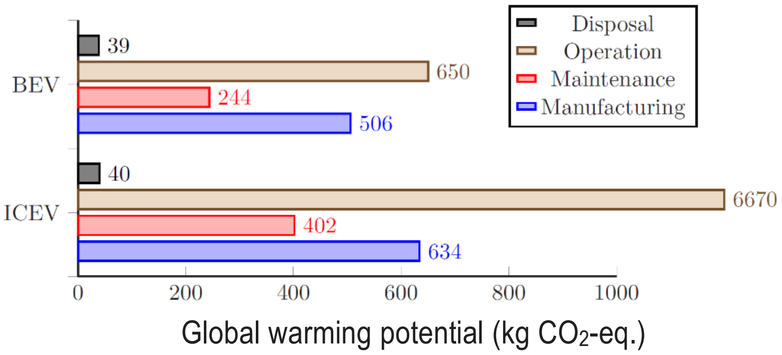


Figure 2. Global warming potential for both BEV and ICEV motorcycles.

The operation stage is where most of the impact takes place due to the direct emissions coming from the fuel throughout the life cycle of the ICEV, these being 10 times higher than for the BEV. Similar results have been reported for cars, in which the operational stage can contribute around 80% of the total global warming potential (Nordelöf et al., 2014; Hawkins et al., 2013).

It is important to note that the source of the electricity used to charge the battery plays an important role. The impact of an electric motorcycle can thus be more than double if it is powered by electricity produced only from coal plants as opposed to only from wind power plants (Cox and Mutel, 2018). Coal plants in Spain operate with an emission factor close to 1000 gCO2-eq./kWh, while the current electricity mix in Spain emits around 200 gCO2-eq./kWh as of 2019 (Grupo Red

Eléctrica, 2020). Furthermore, it is assumed that both motorcycles are designed for the same purpose; however, the ICEV weighs almost as much as two BEVs. If similar motorcycles had been chosen in terms of mass, as studied by Leuenberger et al. (2010), similar results could be achieved in the manufacturing process.

The results on the climate change category for the BEV are in agreement with those found in the literature. Cox and Mutel (2018) considered a medium power motorcycle with a total distance travelled of 46,000 km. The authors followed a cradle-to-grave approach, including the manufacturing, operating and disposal stages, with an estimated impact of around 20 g $CO_2$/km. In this study, the BEV amounts to 1450 kg $CO_2$-eq. for a total distance of 80,000 km. This translates into 18 g $CO_2$-eq./km. The ICEV results follow the same trend, causing a total impact of 7746 kg CO2-eq., which, expressed in km, represents 97 kg CO2-eq./km. Cox and Mutel (2018) studied medium-power motorcycles equipped with internal combustion engines in the power range of a 125-cc model, considering a total distance of 69,000 km, which translates into 110 g CO2-eq./km.

However, it may be convenient to study the impact of global warming potential in detail in order to find the influence of all the components of the BEV, and especially the battery. The contribution of the global warming potential from each component in the BEV is compiled in Table S3 (Supplementary Material). The frame includes the chassis, an important component in terms of weight that, according to the results obtained (Table S3), has a significant impact on the global warming potential. The power train is also relevant due to the inclusion of the brushless motor with its permanent magnets, which have a remarkable impact. The converter, considered within the electric parts, has a total impact of 9.49 kg CO2-eq., that is, around a third of the impact linked to this subcategory. The battery causes a significant impact not only in the manufacturing stage but also in the maintenance stage, which must be replaced at 40,000 km. Consequently, the LiNiCoMn battery ends up being responsible for approximately 18% of the total climate change category. The results for other midpoint categories are depicted in Figure 3.

The operation is an important stage for global warming potential, as previously discussed and observed in

Figure 2. In the case of the BEV, manufacturing and maintenance are also relevant stages for other impact categories.

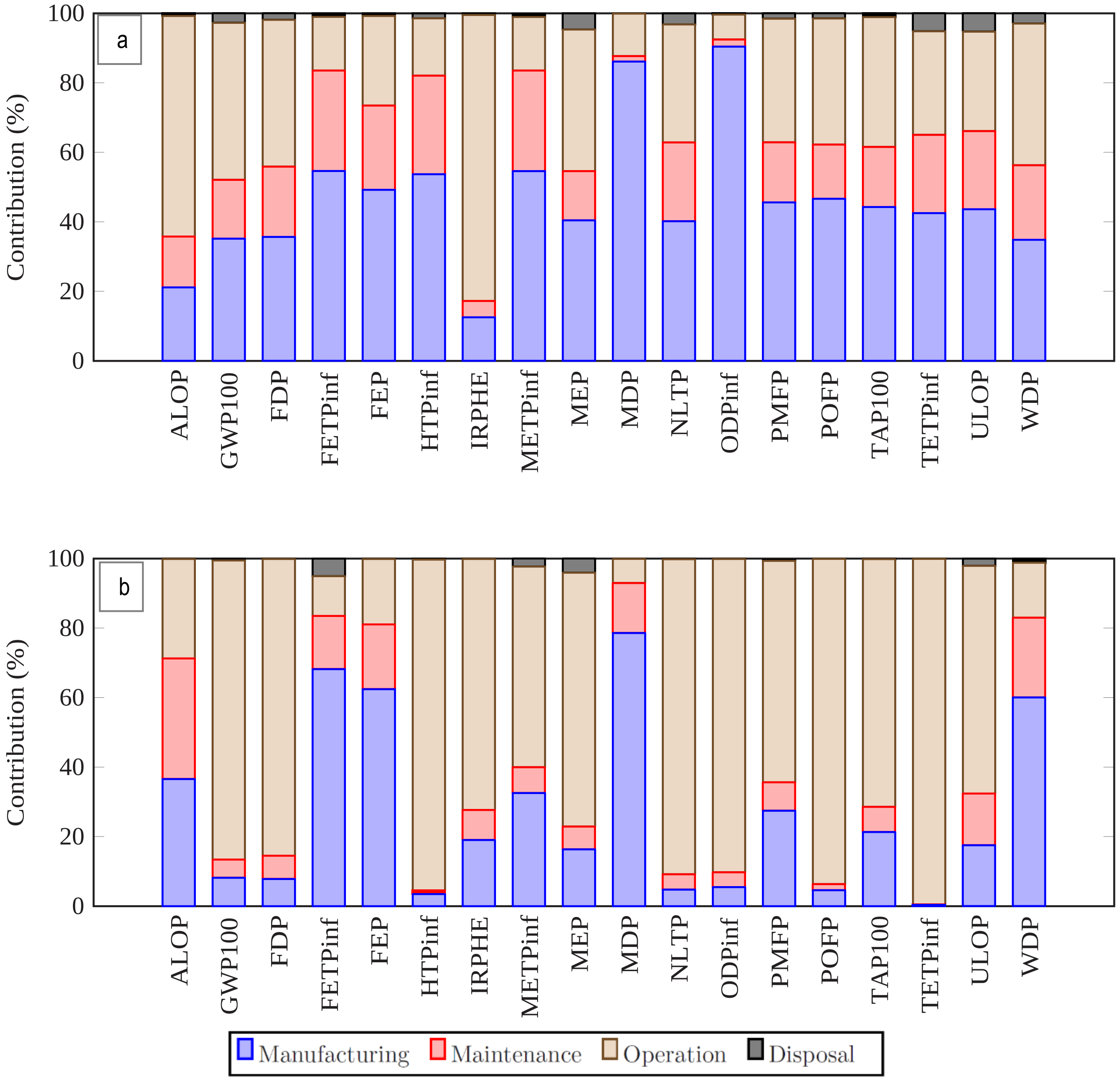


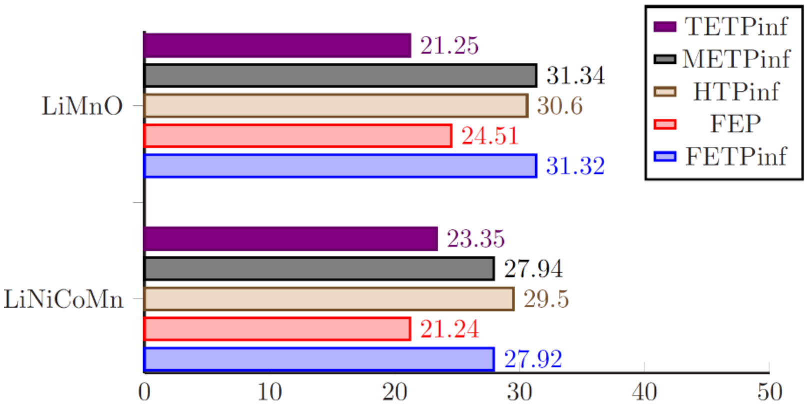
Figure 3. Midpoint impact categories (in relative terms) for both motorcycles: a) BEV (LiNiCoMn) and b) ICEV. Agricultural land occupation (ALOP); Climate change (GWP100); Fossil depletion (FDP); Freshwater ecotoxicity (FETPinf); Freshwater eutrophication (FEP); Human toxicity (HTPinf); Ionizing radiation (IRP HE); Marine ecotoxicity (METPinf); Marine eutrophication (MEP); Metal depletion (MDP); Natural land transformation (NLTP); Ozone depletion (ODPinf); Particulate matter formation (PMFP); Photochemical oxidant formation (POFP); Terrestrial acidification (TAP100); Terrestrial ecotoxicity (TETPinf); Urban land occupation (ULOP); Water depletion (WDP).

These results agree with those reported by Sanfélix et al. (2015), in which the operation stage is relevant in most of the impact categories for ICEVs and in some for BEVs. In the case of the ICEV, the most impactful stage becomes the operation, as already seen in Figure 2 for the GWP. The effect of the operation stage follows a similar trend in proportion to the gasoline cars studied by Bekel and Pauliuk (2019). In impact categories like water depletion, metal depletion, and freshwater ecotoxicity, to name a few, manufacturing was a much more relevant stage. There is not a single cause that explains this, but in the case of the BEV, the mentioned impacts are mainly due to the battery cells; in the ICEV, for the most part they are attributed to the electricity consumption and to the treatment of the metals found in the frame and the glider. Maintenance has a notable influence on these impacts, but in general, it does not play a significant role.

A relevant category worth mentioning is the formation of photochemical oxidants. These are secondary pollutants that result from the interaction between sunlight, hydrocarbons, and nitrogen oxides. They can cause serious problems in the ecosystem and in human health (Rani et al., 2011). As can be seen in Table 2, the results in this category are approximately 10 times higher for the ICEV than for the BEV due to emissions related to the consumption of fossil fuels, and this represents one of the most important benefits of the electrification of urban mobility, on which similar results were reported by Cox and Mutel (2018).

## 3.2. LCA comparison results for LiNiCoMN and LiMNo batteries of the BEV

A more detailed analysis of the batteries (scenario 1 vs scenario 2) can provide information on the contributing components in the midpoint impact categories. Tables S4 and S5 (Supplementary Material) summarize a comparison of the climate change impact category of both batteries. Figure 4 shows some of the impact categories to which the batteries become a relevant contributor.



Contribution (%) of the battery in the selected midpoint impact categories

Figure 4. Percentage contribution of both batteries in relevant midpoint impact categories: terrestrial

ecotoxicity (TETPinf), marine ecotoxicity (METPinf), human toxicity (HTPinf), freshwater eutrophication (FEP) and freshwater ecotoxicity (FETPinf).

Comparing the two BEVs, the one that incorporates the LiMnO battery has greater impacts in almost all categories. This is largely associated with its energy density, which implies the requirement for a heavier battery to provide the same autonomy. The cathode and the anode are the dominant elements in both inventories in terms of mass. Since the impacts are closely linked to each of these, the increase in mass imposed by the LiMnO battery translates directly into more significant impacts. The only exception is the terrestrial ecotoxicity midpoint impact category, where, due to the LiNiCoMn positive electrode, the contribution surpasses the LiMnO battery.

In the case of the LiNiCoM battery, the cathode is its most relevant component. Some studies in the literature addressing the impact of batteries indicate that the Battery Management System (BMS) accounted for around 10% of the impact in the battery's climate change category (Zhao and You, 2019), while around 70% of the total global warming potential of the battery is associated with the cell (Ellingsen et al., 2014). In this study, 78% of the BEV battery impact is associated with the cell and approximately 13% with the BMS. As for the LiMNo battery, the cathode has much less impact than that of the LiNiCoMn battery. Although LiMnO is a heavier battery to achieve the same amount of power, the composition of the cathode makes it less impactful. As stated above, this is the key piece of the battery. Despite using the inventory reported by Majeau-Bettez et al. (2011), the results do not differ from those obtained by Notter et al. (2010) using a different inventory. They found a relative contribution of 36.2% in the case of the cathode and 14.5% for the anode of batteries in electric cars.

The results indicate that the LiMnO battery does not produce an environmental improvement compared to the LiNiCoMn battery. Battery manufacturing has a slightly lower impact, while maintenance and disposal have a slightly higher impact. In this sense, the LiNiCoMn battery seems a good choice because it offers higher energy densities. In absolute terms, Zhao and You (2019) reached the conclusion that a complete battery pack of 250 kg causes around 2000 and 2500 kg CO2-eq. By scaling these mass values to match the BEV batteries, values around 120 and 150 kg CO2-eq. are estimated, similar to the results reported in

Tables S4 and S5.

### 3.3. Sensitivity analysis

Given that the operation stage of BEVs is affected according to the source of electricity and is also the one with the greatest impact on the environmental behaviour of ICEVs, the parameters most closely related to this stage are evaluated: the distance and the mix of electricity used to charge the battery. Table 3 presents the limits of the baseline (B), lower (L) and upper (U) levels of the analysis. Furthermore, the influence of the battery mass is also considered as it constitutes one of the sources of uncertainty in the inventory. In this case, a change of ±15% from the original mass of the battery is evaluated.

Table 3. Levels of the baseline (B), lower (L) and upper (U) limits for sensitivity analysis.

| | **BEV LiNiCoMn** | | | **BEV LiMnO** | | | **ICEV** | | |
|---|---|---|---|---|---|---|---|---|---|
| Case | L | B | U | L | B | U | L | B | U |
| Distance ($\cdot 10^3$km) | 50 | 80 | 100 | 50 | 80 | 100 | 50 | 80 | 100 |
| Electricity mix | CA | ES | CN | CA | ES | CN | - | - | - |
| Battery mass (kg) | 11.22 | 13.20 | 15.18 | 15.98 | 18.80 | 21.62 | - | - | - |

CA: Canada; ES: Spain; CH: China.

#### 3.3.1. Distance

A service life of 100,000 km for a motorcycle can be considered a rather optimistic scenario; however, it will serve as a reference to assess whether the differences observed in the operating stage are magnified. Exceeding 80,000 km implies that, according to the assumptions made in this study, a third battery will be needed in the case of the BEV. The results for this analysis are shown in Figure 5.

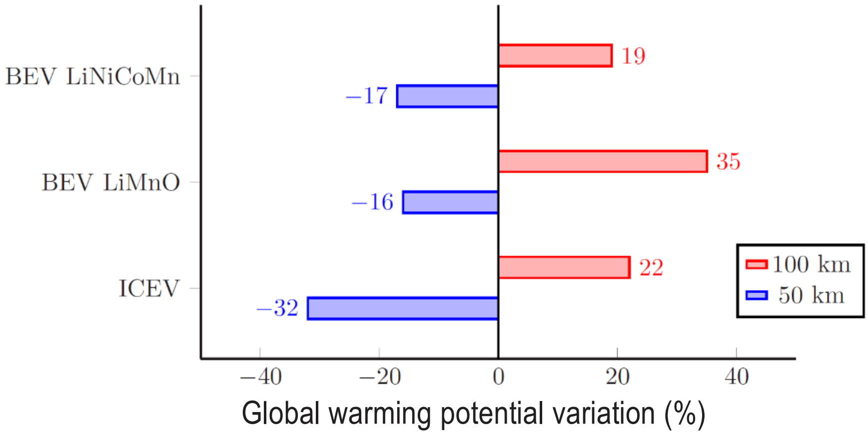


Figure 5. Influence of distance variation on the impact of global warming potential according to the baseline case (Table 3) for BEV (LiMnO and LiNiCoMn) and ICEV.

A substantial increase in the total impact of global warming potential is observed in the case of the BEV LiMnO battery for 100,000 km. This is because the maintenance and disposal stages for this type of battery increase the impact compared to that of the LiNiCoMn, as the battery has to be replaced twice (for a total of 100,000 km) and not once (as in the case of 50,000 km). The variation of the total life distance in the case of the ICEV is linear since there are no battery replacements as in the case of the BEVs.

### 3.3.2. Electricity mix

The variation of the electricity mix does not influence the ICEV; therefore, the results of the sensitivity analysis for the variation of the source of electricity generation to charge the batteries only show the results of the BEVs (Figure 6).

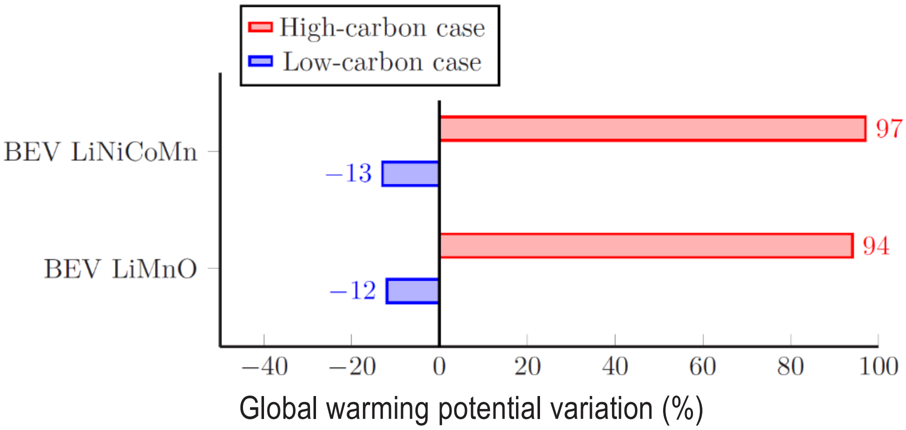


Figure 6. Influence of electricity mix variation on the impact of global warming potential according to the baseline case (Table 3) for BEVs (LiMnO and LiNiCoMn).

Three scenarios are considered: i) low-carbon case – Canada is chosen as a reference, as approximately 80% of electricity comes from low-carbon sources; ii) high-carbon case – China with 30% of electricity coming from low carbon sources is the reference in this case (Ritchie, 2021); and iii) base line case – Spain.

It is evident that the origin of the electricity plays a relevant role in view of the results shown in

Figure 6. The increase in the impact on global warming potential is greater than 90% for the two BEVs in the high-carbon case. This suggests that one way to reduce the greenhouse gases emissions in the case of Spain would be to increase the amount of renewable generation, perhaps even at the individual level as a form of distributed generation. Similar conclusions can be drawn from the literature. For example, Burchart-Korol et al. (2020) found that the impact of battery charging varies by more than a factor of ten when the vehicle is charged in France or Poland. In the case of Canada, Bicer and Dincer (2018) obtained a result of 0.160 kg CO2-eq./km, while with the Chinese electricity mix, Wu et al. (2018) reported 0.283 kg CO2-eq./km. Thus, there is a difference of around >80% taking the Canadian mix as a reference. Despite also considering a cradle-to-grave approach, the functional units in these studies were the service provided by automobiles. Thus, the results reported in this study are not directly comparable, but the results obtained confirm that the impact of the electricity mix is relevant. In fact, considering the low-carbon case, the terrestrial acidification decreases by about 18% and the particulate matter formation is reduced by 15% when compared to the Spanish mix. These two impact categories are quite significant in terms of the impact on air pollution and urban mobility.

### 3.3.3. Mass of batteries

The variation in the impact of global warming potential when their mass is reduced or increased by 15% is shown in Figure S2. As expected, no significant changes were observed when varying the mass of the battery. Taking into account that batteries contribute 15 to 20% of the total impact, by increasing the mass by 15%, their contribution to the impact of global warming potential is increased by approximately 3%. The sensitivity analysis performed is similar to that reported by Zhao and You (2019), in which the input parameters are varied by the same LiMnO and LiNiCoMn relationship. The results obtained indicate that the model appears to be robust since the variations are in the expected order of magnitude.

### 3.4. Economic analysis

This section discusses the impact of the recent paradigm shift on mobility from an economic point of view, taking as examples the two motorcycles, the Muvi (BEV) and the Burgman 125 (ICEV). The data to compute the costs, along with the final TCO according to the Eq. 1 are presented in Table S6. Assumptions considered are as follows: i) the price of the electricity, considering off-peak hours, has been considered to be 0.13 €/kWh (Bassols, 2021); ii) it is estimated that BEV consumes around 0.0247 kWh/km according to the WMTC cycle; iii) the ICEV consumes about 3 L/100km (Suzuki, 2020), and the cost of gasoline has been considered to remain constant at 1.2 €/L (Diesel Gasolina, 2021); iv) the estimated maintenance cost for the BEV is 100 €, whereas for the ICEV it is 120 € (estimations made based on Cox and Mutel, 2018); v) the cost of the battery replacement is around 500 €/kWh (Walker and Roser, 2015), which results in an approximated annualized cost of 150 €/year as the BEV includes a 3 kWh battery; and vi) the purchasing cost of the BEV and the ICEV are 4600 € and 4000 €, respectively (ElectroMotos, 2020; Suzuki, 2020).

The Suzuki Burgman 125 is a mid-power motorcycle (about 9 kW) (Suzuki, 2020), while the Muvi offers a lower nominal power of 3 kW.

The results indicate that the BEV is a competitive alternative to a traditional ICEV. Despite a higher investment cost, due to lower costs of energy, operation and maintenance, it results in a roughly 20% cheaper vehicle. In the literature, the only study that deliberately considers the cost of motorcycles is Cox and Mutel (2018). They estimated the total cost of ownership, and concluded that the lowest is linked to medium-power motorcycles, since they present a convenient balance between energy costs and acquisition costs.

Apart from the direct cost, environmental impacts can be externalised using the values from De Bruyn et al. (2018). The methodology proposes a representative factor for each midpoint impact category that transforms the impact as such into an economic cost. Externality costs have been added in the $C_{o\&m}$ term in Eq. 1. In case of the BEV, these externality costs present some variability; as a reference, the mean value has been taken. Results obtained are listed in Table 4.

Table 4. Externality costs (€) of the midpoint impact categories evaluated for BEVs and ICEV.

| **Category** | **BEV LiNiCoMn** | **BEV LiMnO** | **ICEV** |
|---|---|---|---|
| Freshwater eutrophication (FEP) | 2.01 | 2.35 | 0.97 |
| Natural land transformation (NLTP) | 0.00 | 0.00 | 0.00 |
| Freshwater ecotoxicity (FETPinf) | 12.98 | 15.83 | 4.34 |
| Urban land occupation (ULOP) | 1.07 | 1.15 | 1.29 |
| Fossil depletion (FDP) | 0.00 | 0.00 | 0.00 |
| Particulate matter formation (PMFP) | 188.18 | 198.50 | 277.98 |
| Climate change (GWP100) | 81.49 | 84.28 | 438.43 |
| Photochemical oxidant formation (POFP) | 8.12 | 8.51 | 91.82 |
| Human toxicity (HTPinf) | 177.57 | 209.33 | 1199.38 |
| Terrestrial acidification (TAP100) | 60.16 | 61.28 | 93.64 |
| Ionising radiation (IRP HE) | 26.29 | 26.52 | 25.67 |
| Marine eutrophication (MEP) | 7.05 | 7.46 | 15.52 |
| Ozone depletion (ODPinf) | 0.04 | 0.01 | 0.04 |
| Agricultural land occupation (ALOP) | 7.81 | 8.10 | 5.94 |
| Marine ecotoxicity (METPinf) | 11.49 | 14.00 | 7.88 |
| Terrestrial ecotoxicity (TETPinf) | 2.53 | 2.75 | 155.40 |
| **Total** | **586.8** | **640.0** | **2318.3** |

The overall cost analysis adds the acquisition cost, the operational one, the cost associated with the maintenance and replacement of batteries, and the total externality cost from Table 4. The externality costs of the various midpoint categories make it clear that the Burgman 125 (ICEV) costs more than the Muvi (BEV). TCO do not differ much for both vehicles (0.1166 vs 0.1447 €/km), but when considering the costs of externalities (the total in Table 4), there is no doubt that the Muvi (BEV) is the most appropriate option from the perspective of environmental costs, being approximately 25% cheaper. Moreover, having a low-carbon electricity mix would reduce the externality costs by an additional 19%.

## 3.5. Implications for EV promotion and technological development

The energy efficiency of BEVs is higher than that of other EVs (Helmers and Marx, 2012), and their battery capacity is greater, leading to potentially greater implications for electricity grids when recharged at peak hours and peak locations (Hardman et al., 2018, Moon et al., 2018, Wolbertus et al., 2018). Moreover, with rising EV demand, it will be important to understand the spatial patterns of EV adoption to minimize the risks associated with spatial accumulation of EV drivers and EV-related peak energy demand (Nicolson et al., 2017), such as transmission congestion (Hu et al., 2017), and important voltage drops (Hoogsteen et al., 2015). Increasing BEV battery capacities could have mixed impacts on the life cycle emissions rate of grid-tied BEVs and the GHG abatement from a transition away from gasoline-powered vehicles as has been reported in this tudy. Ambrose et al. (2020) concluded that larger battery systems and low utilization do not exceed expected reductions in emissions from electricity used for vehicle charging in US. These trends could be exacerbated by increasing BEV market shares for larger vehicles.

The charging of battery electric vehicles could have a big impact on the daily demand for electric power, and the peak hour of electricity consumption would become unmanageable. In particular, the Spanish grid is vulnerable due to the government's intention to achieve an increasing share of renewable energy by shutting down nuclear and fossil fuel plants. Fernández (2021) evaluated different scenarios for the Spanish electricity grid using a stochastic model, the author concluded that the most appropriate strategy lies in the development of a charging network in the workplace, which allows a slow charge of the batteries during working hours. This strategy is less commercially attractive, but represents the best option from the perspective of low emissions and electric grid reinforcement.

Globally, the adoption of electric vehicles (EV) currently relies heavily on strong EV policies (oriented on the demand side) (Münzel et al., 2019). These robust policies include a broad spectrum of road space privileges. Furthermore, these policies are clearly related to consumer preference. Brückmann et al. (2021) evaluated EV adoption in regions without strong polices, author reported that EV adoption is predicted by technology affinity, high income, green party preferences, and living in one’s own house. However, these findings represent fundamental patterns of individuals in the adoption of new mobility and energy technologies, especially when far-reaching policies are lacking. In this regard, cost of acquisition is still one of a main drivers for shifting to electro mobility, then, appropriate communication on the real cost of each technology is necessary.

### 3.6. Consequences on urban air pollution

Road transport is regarded as the main contributor to air pollution (Belis et al., 2013; Soret, Guevara, and Baldasano, 2014). In 2018 the European Environmental Agency (EEA) attributed 417,000 premature deaths to fine particulate matter in Europe as a whole. In fact, in only four countries (Estonia, Finland, Iceland, and Ireland) were the concentrations of particulate matter within the air quality guidelines proposed by the WHO (European Commission, 2020). It should be noted that some improvements have been made during these past years. For instance, annual and daily PM10 concentrations have decreased by 10–20% over the last decade (European Environmental Agency, 2020). Certainly, the effects of air pollution on the local population cannot be ignored. Spain, and in particular Barcelona, is no exception to the rule. For instance, $NO_2$ geometric mean values around 42 $\mu$g/m$^3$ were recorded, as reported by Gibergans et al. (2020). In the metropolitan area it was quantified that reducing PM10 levels to 20 $\mu$g/m$^3$ according to the WHO guidelines would mean approximately 3500 fewer deaths, 31,100 fewer cases of bronchitis in children, and a total of 54,000 fewer asthma attacks, all annually (Pérez, Sunyer, and Kunzli 2009). According to the authors, this could translate into a monetary benefit of 6400 million euros per year.

Taking into account the results of the sensitivity analysis carried out, if the low-carbon electricity mix is adopted, the impact category of photochemical oxidation formation could be reduced by about 16%. A recent study evaluated the long-term PM reduction, authors found that current electric vehicle promotion policies in South Korea have limited effectiveness in reducing PM emissions due to the weak substitution ratio between diesel vehicles and BEVs, implying that the substitution ratio between different types of vehicles must be carefully investigated when designing environmental policies for the road transport sector (Choi and Koo, 2021).

According to the results obtained in this study, BEVs represent a 30% reduction in the PM10 category. These values are positive in the sense that they can lead to a significant improvement in air quality. Furthermore, the differences in the human toxicity category suggest that the impact of the ICEV is approximately 5 times more damaging to humans than that of the BEVs. As mentioned above, BEVs have a non-zero impact. However, opting for electric mobility offers the possibility of further controlling emissions at their source. On the contrary, conventional motorcycles cause dispersed and uncontrollable emissions in the densely populated areas, which, despite the installation of catalysts, remain considerable if the air quality guidelines proposed by the WHO are considered. The solution is based not only on the promotion of electric mobility, but also on the definition of a new model of urban mobility. Therefore, combining electric mobility with promotion of freight and passenger modal split towards less polluting systems, the adoption of technical and regulatory constraints (e.g., standards and prohibitions) and appropriate financial means (e.g., taxes, charges and tolls) can significantly improve air quality (Cavallaro et al., 2018). In this sense, BEVs may be one of the alternatives with the potential to be more widely adopted in urban mobility.

The present study covers the LCA of two motorcycles, such as the Muvi and the Burgman 125, but a broader range of motorcycles could be considered. At the same time, several urban cycles could be taken into account. They could be adapted to a scenario where, for example, road congestion can be introduced, which is not uncommon in Barcelona. Varying the number of kilometers driven per year, perhaps extending 80,000 km over the course of more than a decade, can have some significant impacts on cost analysis. This situation would be unfavorable for the BEV as it would take longer to offset the investment costs and, therefore, the economic advantage over the ICEV would be diminished. It should also be noted that the cost of battery replacement will tend to drop over time, which could somehow compensate for this disadvantage.

## 4. CONCLUSIONS

In this study, a comparative analysis of the life cycle of two medium-power motorcycles in a Spanish urban environment was carried out, as well as the economic study of the total costs of ownership considering the environmental costs associated with each type of vehicle. In addition, two types of batteries were also considered to evaluate the environmental performance in terms of urban mobility and the potential deployment of BEVs in the city of Barcelona, Spain. The results indicate that the BEV is a promising option in environmental terms, since its global warming potential associated with the duration of the life cycle is approximately one fifth of that of the ICEV. The differences are mainly due to the operational stage, where the combustion of fossil fuels has a significant impact. In the other stages of the life cycle (manufacturing, maintenance and disposal) the differences are smaller. Sensitivity analysis indicates that the total distance travelled plays an important role, but the electricity mix is probably the most relevant factor in terms of climate change. This confirms the benefits of the energy transition, mainly based on renewable energy and low-carbon technologies; the environmental impact of the BEV would be further reduced with a low-carbon energy mix compared to the current one in Spain.

Air pollution continues to be an issue of concern in Spain and, more specifically, in large cities such as Barcelona and Madrid. The adoption of BEVs can be considered as one of the elements of a new mobility model to mitigate urban air pollution. It should be noted, for example, that the results of photochemical oxidation formation were 30% lower than for the ICEV.

The battery comparison shows that LiNiCoMn batteries are still a good choice for BEVs compared to LiMnOs. LiNiCoMn batteries are mainly used in electric vehicles due to their energy density; however, the results did not differ much between the two types of batteries and were in agreement with those reported in the literature. Regarding the economic analysis, the ownership costs are similar for the two motorcycles. However, by externalising environmental costs, the BEV was demonstrated to be more competitive than the ICEV, especially due to the external cost of impact categories such as particulate matter formation, climate change, and human toxicity.

Finally, it can be concluded that electric mobility must play a fundamental role in the transformation to a more sustainable urban mobility model, especially in cities like Barcelona, a fact that is based on environmental, economic and social criteria, if the impact on air pollution is taken into account, as has been discussed in this study.

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## 5. References

Ajanovic, A.,Haas, R. (2016). Dissemination of electric vehicles in urban areas: Major factors for success. Energy, 115, 1451–1458.

Ambrose, H., Kendall, A., Lozano, M., Wachche, S., Fulton, L. (2020). Trends in life cycle greenhouse gas emissions of future light duty electric vehicles. Transportation Research Part D: Transport and Environment 81, 102287

Baldasano, J.M. (2020). COVID-19 lockdown effects on air quality by NO2 in the cities of Barcelona and Madrid (Spain). Science of The Total Environment 741, 140353

Bassols, Mobility tariff, https://www.bassolsenergia.com/tarifes/llar-mobilitat-10kw/, (Accessed: 2021-09-13).

Bastos, J., Marques, P., Batterman, S. A., & Freire, F. (2019). Environmental impacts of commuting modes in Lisbon: A life-cycle assessment addressing particulate matter impacts on health. *International Journal of Sustainable Transportation*, *13*(9), 652–663. https://doi.org/10.1080/15568318.2018.1501519

Bauer, C., Hofer, J., Althaus, H. J., Del Duce, A., & Simons, A. (2015). The environmental performance of current and future passenger vehicles: Life Cycle Assessment based on a novel scenario analysis framework. *Applied Energy*, *157*, 871–883. https://doi.org/10.1016/j.apenergy.2015.01.019

Bekel, K., & Pauliuk, S. (2019). Prospective cost and environmental impact assessment of battery and fuel cell electric vehicles in Germany. *International Journal of Life Cycle Assessment*, *24*(12), 2220–2237. https://doi.org/10.1007/s11367-019-01640-8

Belis, C. A., Karagulian, F., Larsen, B. R., & Hopke, P. K. (2013). Critical review and meta-analysis of ambient particulate matter source apportionment using receptor models in Europe. *Atmospheric Environment*, *69*, 94–108. https://doi.org/10.1016/j.atmosenv.2012.11.009

Bicer, Y., & Dincer, I. (2018). Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. *Resources, Conservation and Recycling*, *132*(September 2017), 141–157. https://doi.org/10.1016/j.resconrec.2018.01.036

Bruyn, S. de, Bijleveld, M., Graaff, L. de, Schep, E., Schroten, A., Vergeer, R., & Ahdour, S. (2018). Environmental Prices Handbook. *Delft, CE Delft, October 2018 Publication*.

Brückmann, G., Willibald, F., Blanco V. (2021). Battery Electric Vehicle adoption in regions without strong policies. Transportation Research Part D 90, 102615

Burchart-Korol, D., Jursova, S., Folęga, P., Korol, J., Pustejovska, P., & Blaut, A. (2018). Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic. *Journal of Cleaner Production*, *202*, 476–487. https://doi.org/10.1016/j.jclepro.2018.08.145

Burchart-Korol, D., Jursova, S., Folęga, P., & Pustejovska, P. (2020). Life cycle impact assessment of electric vehicle battery charging in European Union countries. *Journal of Cleaner Production*, *257*. https://doi.org/10.1016/j.jclepro.2020.120476

Cavallaro, F. Danielis, R., Nocera, S., Rotaris. L. (2018). Should BEVs be subsidized or taxed? A European perspective based on the economic value of CO2 emissions. Transportation Research Part D: Transport and Environment 64, 70-89

Cherry, C. R. (2007). *Electric Two-Wheelers in China: Analysis of Environmental, Safety, and Mobility Impacts.*

City Population, Barcelona, https://www.citypopulation.de/en/spain/cataluna/barcelona/08019_ _barcelona/ (Accessed: 10.01.2022).

Choi, H., Koo, H. (2021). Effectiveness of battery electric vehicle promotion on particulate matter emissions reduction. Transportation Research Part D 93, 102758

Cox, B. L., & Mutel, C. L. (2018). The environmental and cost performance of current and future motorcycles. *Applied Energy*, *212*(December 2017), 1013–1024. https://doi.org/10.1016/j.apenergy.2017.12.100

de Assis Brasil Weber, N., da Rocha, B. P., Smith Schneider, P., Daemme, L. C., & de Arruda Penteado Neto, R. (2019). Energy and emission impacts of liquid fueled engines compared to electric motors for small size motorcycles based on the Brazilian scenario. *Energy*, *168*, 70–79. https://doi.org/10.1016/j.energy.2018.11.051

DieselGasolina, Historical price of gasoline and diesel in spain, https://www.dieselogasolina.com/Estadisticas/Historico (Accessed: 2021-12-18).

Ellison, R.B., Greaves, S.P., Hensher D.A. (2013). Five years of london's low emission zone: Effects on vehicle fleet composition and air quality. Transportation Research Part D: Transport and Environment, vol. 23, pp. 25–33.

e-Ride. (2021). *A MotoStudent Electric's competition team. Catalonia's Polytechnical University*. https://eride-etseib.upc.edu/en/welcome/(accessed 09.04.2021).

ElectroMotos. (2020). *Torrot Muvi*. https://www.electromotos.net/marcas/torrot/ muvi/ (accessed 30.12.2020).

Ellingsen, L. A. W., Majeau-Bettez, G., Singh, B., Srivastava, A. K., Valøen, L. O., & Strømman, A. H. (2014). Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. *Journal of Industrial Ecology*, *18*(1), 113–124. https://doi.org/10.1111/jiec.12072

Endesa. (2020). *Tempo Verde Supervalle*. https://www.endesa.com/es/luz-y-gas/luz/tempo/tempo-verde-supervalle (accessed 15.12.2020).

ETSEIB Motorsport. (2021). *Motorsport and Driveless-UPC*. https://etseib-motorsport.upc.edu/en/team/(accessed 09.04.2021).

European Commission. (2014). *Commission Delegated Regulation No 134/2014 of 16 December 2013 supplementing Regulation (EU) No 168/2013 of the European Parliament and of the Council with regard to environmental and propulsion unit performance requirements and amending Annex V*.

European Commission (2019). Air quality: Commission refers bulgaria and spain to the court for failing to protect citizens from poor air quality, https://ec.europa.eu/commission/presscorner/detail/ET/IP_ 19_4256, Accessed: 10.01.2022.

European Commission. (2020). *Marked improvement in Europe's air quality over past decade, fewer deaths linked to pollution*. https://ec.europa.eu/commission/presscorner/detail/en/ip 20 2168

European Environment Agency (EEA). (2020). Air quality in Europe - 2020 report. In *EEA Report* (Issue No 09/2020). https://www.eea.europa.eu//publications/air-quality-in-europe-2020-report

Fernández, R.A. (2021). Stochastic analysis of future scenarios for battery electric vehicle deployment and the upgrade of the electricity generation system in Spain. Journal of Cleaner Production 316, 128101

García Sánchez, J. A., López Martínez, J. M., Lumbreras Martín, J., Flores Holgado, M. N., & Aguilar Morales, H. (2013). Impact of Spanish electricity mix, over the period 2008-2030, on the Life Cycle energy consumption and GHG emissions of Electric, Hybrid Diesel-Electric, Fuel Cell Hybrid and Diesel Bus of the Madrid Transportation System. *Energy Conversion and Management*, *74*, 332–343. https://doi.org/10.1016/j.enconman.2013.05.023

Gibergans-Báguena, J., Hervada-Sala, C., & Jarauta-Bragulat, E. (2020). The quality of urban air in Barcelona: A new approach applying compositional data analysis methods. *Emerging Science Journal*, *4*(2), 113–121. https://doi.org/10.28991/esj-2020-01215

Golsteijn, L. (2012). *ReCiPe*. https://pre-sustainability.com/articles/recipe

Grupo Red Eléctrica. (2020). *CO2 emissions of electricity generation in Spain*. https://api.esios.ree.es/documents/591/download?locale=es (accessed 5.12.20).

Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2013). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, *17*(1), 53–64. https://doi.org/10.1111/j.1530-9290.2012.00532.x

Hwang, J. J., & Chang, W. R. (2010). Life-cycle analysis of greenhouse gas emission and energy efficiency of hydrogen fuel cell scooters. *International Journal of Hydrogen Energy*, *35*(21), 11947–11956. https://doi.org/10.1016/j.ijhydene.2010.07.148

ISO 14040. (2006). *Environmental Management Life Cycle Assessment, Principle and Framework.*

ISO 14044. (2006). *Environmental Management Life Cycle Assessment, Principle and Framework*.

Karabasoglu, O., & Michalek, J. (2013). Influence of driving patterns on life cycle cost and emissions of hybrid and plug-in electric vehicle powertrains. *Energy Policy*, *60*, 445–461. https://doi.org/10.1016/j.enpol.2013.03.047

Kopp, P. (2011). The unpredicted rise of motorcycles: A cost benefit analysis. *Transport Policy*, *18*(4), 613–622. https://doi.org/10.1016/j.tranpol.2011.03.002

Leuenberger, M., & Büsser, S. (2010). Life Cycle Assessment of Two Wheel Vehicles. *Imprint*, *2*, 1–30.

Majeau-Bettez, G., Hawkins, T. R., & Strømman, A. H. (2011). Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles. *Environmental Science & Technology*, *45*(12), 5454–5454. https://doi.org/10.1021/es2015082

Marques, P., Garcia, R., Kulay, L., & Freire, F. (2019). Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade. *Journal of Cleaner Production*, *229*, 787–794. https://doi.org/10.1016/j.jclepro.2019.05.026

Mellino, S., Petrillo, A., Cigolotti, V., Autorino, C., Jannelli, E., & Ulgiati, S. (2017). A Life Cycle Assessment of lithium battery and hydrogen-FC powered electric bicycles: Searching for cleaner solutions to urban mobility. *International Journal of Hydrogen Energy*, *42*(3), 1830–1840. https://doi.org/10.1016/j.ijhydene.2016.10.146

Nikolaidis, P., & Poullikkas, A. (2011). Journal of power technologies. *Journal of Power Technologies*, *97*(3), 220–245. http://papers.itc.pw.edu.pl/index.php/JPT/article/view/1096/776

Nordelöf, A., Messagie, M., Tillman, A. M., Ljunggren Söderman, M., & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *International Journal of Life Cycle Assessment*, *19*(11), 1866–1890. https://doi.org/10.1007/s11367-014-0788-0

Notter, D. A., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., & Althaus, H.-J. (2010). Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles. *Environmental Science & Technology*, *44*(19), 7744–7744. https://doi.org/10.1021/es1029156

Papavinasam, S. Corrosion control in the oil and gas industry. Elsevier, 2013.

Pérez, L., Sunyer, J., & Künzli, N. (2009). Estimating the health and economic benefits associated with reducing air pollution in the Barcelona metropolitan area (Spain). *Gaceta Sanitaria*, *23*(4), 287–294. https://doi.org/10.1016/j.gaceta.2008.07.002

Pero, F. Del, Delogu, M., & Pierini, M. (2018). Life Cycle Assessment in the automotive sector: A comparative case study of Internal Combustion Engine (ICE) and electric car. *Procedia Structural Integrity*, *12*, 521–537. https://doi.org/10.1016/j.prostr.2018.11.066

Petrauskienė, K., Skvarnavičiūtė, M., & Dvarionienė, J. (2020). Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania. *Journal of Cleaner Production*, *246*. https://doi.org/10.1016/j.jclepro.2019.119042

Puig-Samper, G., Bolonio., D., Ortega., M.F., García-Martínez, M.J. (2021). Comparative life cycle assessment of conventional, electric and hybrid passenger vehicles in Spain. Journal of Cleaner Production 291,125883.

Rani, B., Singh, U., Chuhan, A., Sharma, D., & Maheshwari, R. (2011). Photochemical Smog Pollution and Its Mitigation Measures. *Journal of Advanced Scientific Research*, *2*(4).

Ritchie, H. (2021). *Electricity mix*. https://ourworldindata.org/electricity-mix (accessed 26.03.21).

Rodriguez-Rey, D., Guevara, M., Paz-Linares, M., Casanovas, J., Salmerón, J., Soreta, A., Jorba, O., Tena, C., Pérez García-Pando C (2021). A coupled macroscopic traffic and pollutant emission modelling system for Barcelona. Transportation Research Part D: Transport and Environment 92, 102725

Sanfélix, J., Messagie, M., Omar, N., Van Mierlo, J., & Hennige, V. (2015). Environmental performance of advanced hybrid energy storage systems for electric vehicle applications. *Applied Energy*, *137*, 925–930. https://doi.org/10.1016/j.apenergy.2014.07.012

Simpson, A. G., & Walker, G. R. (2002). Lifecycle costs of ultracapacitors in electric vehicle applications. *PESC Record - IEEE Annual Power Electronics Specialists Conference*, *2*, 1015–1020. https://doi.org/10.1109/psec.2002.1022588

Sopha, B. M., Setiowati, S., & Ma'mun, S. (2016). Environmental Assessment of Motorcycle using a Life-Cycle Perspective. *Indonesian Journal of Life Cycle Assessment and Sustainability*, *1*(1), 22–28. https://doi.org/10.52394/ijolcas.v1i1.3

Soret, A., Guevara, M., & Baldasano, J. M. (2014). The potential impacts of electric vehicles on air quality in the urban areas of Barcelona and Madrid (Spain). *Atmospheric Environment*, *99*(2), 51–63.

https://doi.org/10.1016/j.atmosenv.2014.09.048

Superblocks, Barcelona’s plan to free itself from cars. https://kleinmanenergy.upenn.edu/wp-content/uploads/2019/06/KC-013-Superblocks-Barcelonas-Plan-Digest-singles.pdf 2019 (Accessed: 10.01.2022).

Suzuki. (2020). *Moto Burgman 125cc*. https://moto.suzuki.es/motos/scooter/2020/ burgman-125l (accessed 24.10.20).

The Motorcycle Industry in Europe, Acem statistical release - registrations of motorcycles in largest european markets continue increasingin the first nine monthsof 2021, exceeding pre-pandemic levels, https://acem.eu/images/publiq/2021/ACEM_statistical_release_-_January_-_September_2021.pdf, (Accessed: 10.01.2022).

Tobías, A., Carnerero, C., Reche, C., Massagué, J., Via, M., Minguillón, M. C., Alastuey, A., & Querol, X. (2020). Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. *Science of the Total Environment*, *726*, 138540. https://doi.org/10.1016/j.scitotenv.2020.138540

Torrot. (2020). *Muvi specifications*. https://torrot.com/es/motocicletas/5/68/muvi (accessed 12.03.2021).

Tseng, H. K., Wu, J. S., & Liu, X. (2013). Affordability of electric vehicles for a sustainable transport system: An economic and environmental analysis. *Energy Policy*, *61*, 441–447. https://doi.org/10.1016/j.enpol.2013.06.026

UNESPA, Los Veiculos de dos Ruedas en España https://www.anesdor.com/wp-content/uploads/2021/04/Los-veh%C3%ADculos-de-dos-ruedas-en-Espa%C3%B1a-Datos-2019-FINAL.pdf 2019 (Accessed: 10.01.2022).

Walker, P. D., & Roser, H. M. (2015). Energy consumption and cost analysis of hybrid electric powertrain configurations for two wheelers. *Applied Energy*, *146*, 279–287. https://doi.org/10.1016/j.apenergy.2015.02.009

Wu, Z., Wang, M., Zheng, J., Sun, X., Zhao, M., & Wang, X. (2018). Life cycle greenhouse gas emission reduction potential of battery electric vehicle. *Journal of Cleaner Production*, *190*, 462–470. https://doi.org/10.1016/j.jclepro.2018.04.036

Zhao, S., & You, F. (2019). Comparative Life-Cycle Assessment of Li-Ion Batteries through Process-Based and Integrated Hybrid Approaches [Research-article]. *ACS Sustainable Chemistry and Engineering*, *7*(5), 5082–5094. https://doi.org/10.1021/acssuschemeng.8b05902