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Life Cycle Assessment in the automotive sector: a comparative case study of Internal Combustion Engine (ICE) and electric car

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Abstract

Transportation represents one of the major contributors to several environmental burdens such as Green-House-Gas (GHG) emissions and resource depletion. Considering the European Union, light duty vehicles are responsible for roughly 10% of total energy use and air emissions. As a consequence, the need for higher fuel/energy efficiency in both conventional and electric cars has become urgent and the efforts across industrial and research players have proposed a range of innovative solutions with great potential.

This study presents a comparative Life Cycle Assessment of Internal Combustion Engine (ICE) and electric vehicles. The analysis follows a "from cradle-to-grave" approach and it captures the whole Life-Cycle (LC) of the car subdivided into production, use and End-of-Life stages. The inventory is mainly based on primary data and the assessment takes into account a wide range of impact categories to both human and eco-system health. The eco-profile of the different vehicle configurations is assessed and the main environmental hotspots affecting conventional and electric cars are identified and critically discussed. The dependence of impacts on LC mileage is investigated for both propulsion technologies and the break-even point for the effective environmental convenience of electric car is determined considering several use phase electricity sources. The analysis is completed with a comparison of GHG emissions with the results of previous LCA studies.

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1. Introduction

The air emissions in the transportation sector account for about 23 % of total antropogenic CO_2 emissions on a global scale (UNECE, 2015). Considering that light-duty vehicles ownership is expected to increase from roughly 1.3 billion by 2030 to 2 billion by 2050 (World Business Council for Sustainable Development, 2004), a dramatic increase in gasoline and diesel demand is foreseen for the coming years with implications on energy security, climate change and urban air quality.

Against this background, sustainability has become a critical issue for the automotive industry, motivating more significant reductions to the overall environmental impact of cars. This trend adds more pressure on the original equipment manufacturers, with the development of new solutions that allow meeting environmental targets additionally to the traditional ones such as safety, performance, functionality and structural integrity. Many countries have issued regulations in order to reduce fuel consumption and air emissions, including high taxes on fuels to promote energy conservation. Great emphasis has been also placed on the decarbonization of the transport sector and, among different transport alternatives, Battery Electric Vehicles (BEVs) have emerged as a viable solution for reducing the dependence on fossil fuels (Zackrisson et al., 2010). In this context, effective comparisons between innovative technologies and conventional ones are necessary in order to support decision-making within the automotive sustainability field. Literature provides several studies that compare the eco-profile of vehicles with different propulsion technologies such as internal combustion engine, pure electric, hybrid and plug-in hybrid cars. There are Life Cycle Assessment (LCA) studies that focus only on specific components of BEVs, such as traction battery and power electronics (Van den Bossche et al., 2006; Matheys et al., 2008; Daimler AG, 2010; Majeau-Bettez et al., 2011; Ellingsen et al., 2014), mostly basing on confidential LC inventories. On the other hand, several works evaluate the environmental effect of introducing electric and hybrid cars by taking into account the whole vehicle (Samaras and Meisterling, 2008; Frischknecht and Flury 2011; Faria et al., 2012, 2013; Bartolozzi et al., 2013; Donateo et al., 2013; Nanaki and Koroneos, 2013; Girardi et al., 2015; Casals et al., 2016). Many of these researches make use of inventories based on aggregated data from published sources and investigate the production of BEV powertrain/battery with different levels of detail and transparency; additionally some of them deal with only specific phases of car Life Cycle (LC), such as use or vehicle production. The most accurate papers that perform the environmental comparison of conventional and electric cars are Notter et al., 2010, Hawkins et al., 2012, Bauer et al., 2015, Tagliaferri et al., 2016 and Lombardi et al., 2017. These studies assess the entire vehicle LC including both the high-voltage battery and the rest of car components, by means of different environmental impacts and basing on well-detailed inventories and model parameters.

The state-of-the-art analysis reveals that BEVs undoubtedly allow reducing tailpipe emissions with respect to Internal Combustion Engine Vehicles (ICEVs), and this contributes to lower the level of air pollution especially in urban areas. On the other hand, it must also be clear that the use stage of electric cars is not zero-impact; indeed, despite BEVs present no local emissions during operation, the production of electricity for battery charging is strongly energy intensive and it involves air emissions, thus causing a not negligible environmental burden. Past studies show also that, while the Global Warming Potential (GWP) of ICEVs is mainly determined by operation, the manufacturing and disposal of the electric powertrain as well as the high-voltage battery involve a quota of impact comparable with the one of use phase. At the same time investigating the environmental profile of a car basing only on the climate change would lead to unrealistic conclusions, as the load of further impact categories could be mainly located in the production or End-of-Life (EoL) stages. As a consequence, the LCA cannot provide a simple and univocal answer but only a trade-off among different environmental impacts. That said, it becomes clear that a proper environmental assessment of different propulsion technologies requires the investigation of all car LC stages (including both energy production and emissions during operation, as well as burdens involved by raw materials extraction and production, components manufacturing, dismantling and materials disposal) by means of a wide range of impact categories. Another interesting point that arises from literature regards the inventory of the production when dealing with the LCA of complete vehicles: as a relevant amount of information are required, the most challenging issue is collecting as much data as possible regarding vehicle manufacturing (materials, masses and production processes) in order to minimize the use of aggregated published inventories as well as the number of assumptions.

This paper presents a comparative environmental assessment of an ICEV and Lithium-ion BEV and it represents an extension of the research already presented in Delogu et al. (2018). The study considers all the stages of vehicle LC, from raw materials extraction and production till the final disposal. Unlike most of literature studies, the inventory is mainly based on primary data; in particular, the use stage consumption is determined through a simulation model of vehicle dynamic tailored in order to reproduce the real driving conditions of the car. Another strength of the work is that the assessment is based on a wide range of impact categories to both human and eco-system health. Starting from LCA results, the study evaluates the break-even mileages for the effective environmental convenience of BEV with respect to ICEV; moreover, the effect of grid mix composition for the production of electricity consumed by BEV is evaluated, thus increasing the robustness of the environmental outcomes.

2. Materials and method

LCA is an environmental accounting methodology which allows identifying, quantifying and assessing the impacts involved by the entire LC of a product/process basing on the inventory of all environmentally relevant flows (i.e. emissions, natural resources, material and energy, waste) exchanged with the ecosystem. The LCA study contains four iterative steps: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation of results. The LCA of ICEV and BEV is performed according to the ISO standards 14040. In the following paragraphs, the study is described in detail step by step.

2.1. Goal and scope definition

The goal of the study is evaluating the environmental profile of the reference car for the ALLIANCE project (Delogu et al., 2018) in both ICE and electric configurations and performing a comparative analysis.

The functional unit used in this study is the function of 150000 km driven by the car. The system boundaries comprehend the entire LC of the vehicle, including production, use, and EoL. The use stage takes into account the whole well-to-wheel impact, which covers the LC steps from energy resource extraction to the energy conversion in the vehicle (i.e. driving). Finally the EoL is evaluated basing on the current state-of-the-art regarding disposal processes within the European automotive sector. Performing the analysis in this way allows the comparability of the different propulsion, thus isolating the core differences between ICEV and BEV. Joining manufacturing processes, transportation during production and vehicle maintenance are excluded from the system boundaries as their influence to total LC impact is negligible and no specific information is available for these activities.

For the impact assessment, the selection of the characterization methods is based on the International reference Life Cycle Data system (ILCD) recommendations (EC-JRC, 2011) considering the following impact categories:

- Acidification;
- Climate change (excluding biogenic carbon);
- Climate change (including biogenic carbon);
- Ecotoxicity freshwater;
- Eutrophication freshwater;
- Eutrophication marine;
- Eutrophication terrestrial;
- Human toxicity midpoint (cancer effects);
- Human toxicity (non-cancer effects);
- Ionizing radiation;
- Land use;
- Ozone depletion;
- Particulate matter/Respiratory inorganics;
- Photochemical ozone formation;
- Resource depletion water;

- Resource depletion, mineral, fossils and renewables.

2.2. Life Cycle Inventory

The inventory consists into the collection and processing of all the necessary data to analyze the system under study. These are exchanges with the ecosphere that are triggered during vehicle LC: energy and raw materials, atmospheric emissions, waterborne emissions, solid wastes, and other releases attributed to car LC are quantified and allocated to the defined functional unit. The inventory is mainly based on primary data coming from a detailed information gathering; secondary data are retrieved from the GaBi 6.3. database (Thinkstep, 2015). Below the LCI data collection is described for each LC stage.

Production stage. The production covers the entire construction process, from raw materials extraction till the manufacturing of car components. For this stage data collection consists into the determination of typology and quantity of materials as well as manufacturing processes for each vehicle component. To this end the ALLIANCE reference car is divided into assemblies, components and mono-material parts through a breakdown approach. The ICEV is based on the virtual model of the car developed within the SuperLightCar European project (Horen et al., 2015); the electric configuration is derived from the ICE one thus representing a conversion design. Data gathering is performed by means of specific questionnaires concerning materials, masses and manufacturing technologies referring to the specific mono-material parts. Table 1 reports assemblies and masses for both conventional and electric vehicle configurations.

Table 1. Assemblies of ICEV and BEV modelled in LCA

Assembly	**Mass [kg]**	
	ICEV	**BEV**
BiW	292.7	303.6
Closures	176.5	170.0
Suspension/chassis	252.7	252.5
Interiors	173.9	177.1
Drivetrain	222.5	459.8
Electronics	56.7	53.0
Total vehicle	**1175.0**	**1415.7**

Use stage. The use includes both sub-stages of car operation, that are energy production and emissions during operation. The first one consists of all transformation processes upstream to fuel consumption: fuel production from recovery or production of the feedstock, transportation, conversion of the feedstock to the final fuel and subsequent storage, distribution, and delivery to the vehicle tank. The quantification of impacts due to energy supply chain is based on resources depletion as well as emissions involved by the production of fuel (ICEV) and electricity (BEV) consumed during operation. For the environmental modelling of these processes, secondary data from the GaBi 6.3. database are assumed (Thinkstep, 2015); in particular the European average energy mix is assumed for the production of electricity consumed by the BEV. Considering the exhaust and evaporative emissions during operation, no impact is involved by the electric vehicle while for the ICEV this contribution is determined basing on fuel consumption and EURO 5 standard emission values through the following equations (Del Pero et al., 2017):

$$emiss_i = emiss_{i\_km} * mileage_{use}$$

$$emiss_{SO2} = emiss_{SO2\_km} * mileage_{use}$$

$$emiss_{SO2\_km} = \frac{ppm_{sulphur}}{1000000} * 2 * FC_{use}$$

Where:

$emiss_i$ = amount of emission i during operation [g] (considered emissions: benzene, CH_4, CO, CO_2, N_2O, NH_3, NMVOC, NO, NO_2, particulate)
$emiss_{i\_km}$ = per-kilometre amount of emission i [g/km] (considered emissions: benzene, CH_4, CO, CO_2, N_2O, NH_3, NMVOC, NO, NO_2, particulate)
$mileage_{use}$ = use stage mileage during operation [km]
$emiss_{SO2}$ = amount of SO_2 emission during operation [kg]
$emiss_{SO2\_km}$ = per-kilometre amount of SO_2 emission [kg/km]
$ppm_{sulphur}$ = Sulphur content in fuel [ppm]
FC_{use} = amount of vehicle Fuel Consumption during operation [kg/km]

Table 2 shows the specific emission values for the ICEV adopted as reference for the environmental modelling.

Table 2. Euro 5 emission levels for the environmental modelling of emissions during operation (ICEV)

Technical features	**ICEV**
CO_2 emissions	136 g/km
Benzene	0.000997 g/km
CH4 emissions	0.000648 g/km
CO emissions	0.594 g/km
N_2O emissions	0.000452 g/km
NH3 emissions	0.0405 g/km
NMVOC emissions	0.00706 g/km
NO emissions	0.0538 g/km
NO_2 emissions	0.00283 g/km
Particulate emissions	0.00195 g/km
Sulphur content in fuel	10 ppm

For both vehicle configurations the energy consumption due to use stage is calculated through an analytical simulation model based on vehicle dynamic and implemented in the AMESim software environment (Siemens PLM software, 2015). The model estimates torque at wheels basing on the speed profile of a specific driving cycle by simulating the operation of all the components that determine the total vehicle consumption (Delogu et al., 2016). The automotive network is modeled by the two model sections drivetrain and control logic, which are composed by different sub-models. The model of the ICEV includes the following sub-models: engine, clutch, gearbox, vehicle dynamics (drivetrain section) and mission profile, driver, control unit (control logic section). Considering the electric configuration, the drivetrain section is composed by electric motor and vehicle dynamics sub-models while the control logic section includes control unit, driver, mission profile and high-voltage battery/electric loads. The calculation of use stage energy consumption is performed assuming the speed profile of the Worldwide harmonized Light-duty Test Cycle (WLTC); developed by the Working Party on Pollution and Energy group (GRPE) within the framework of the Worldwide harmonized Light Vehicles Test Procedure (WLTP), the WLTC defines a global harmonized standard for the assessment of emission levels and fuel economy of light-duty vehicles in Europe (Tutuianu et al., 2013). An overview of model components as well as main vehicle technical features adopted as reference for calculation are reported in Figure 1.

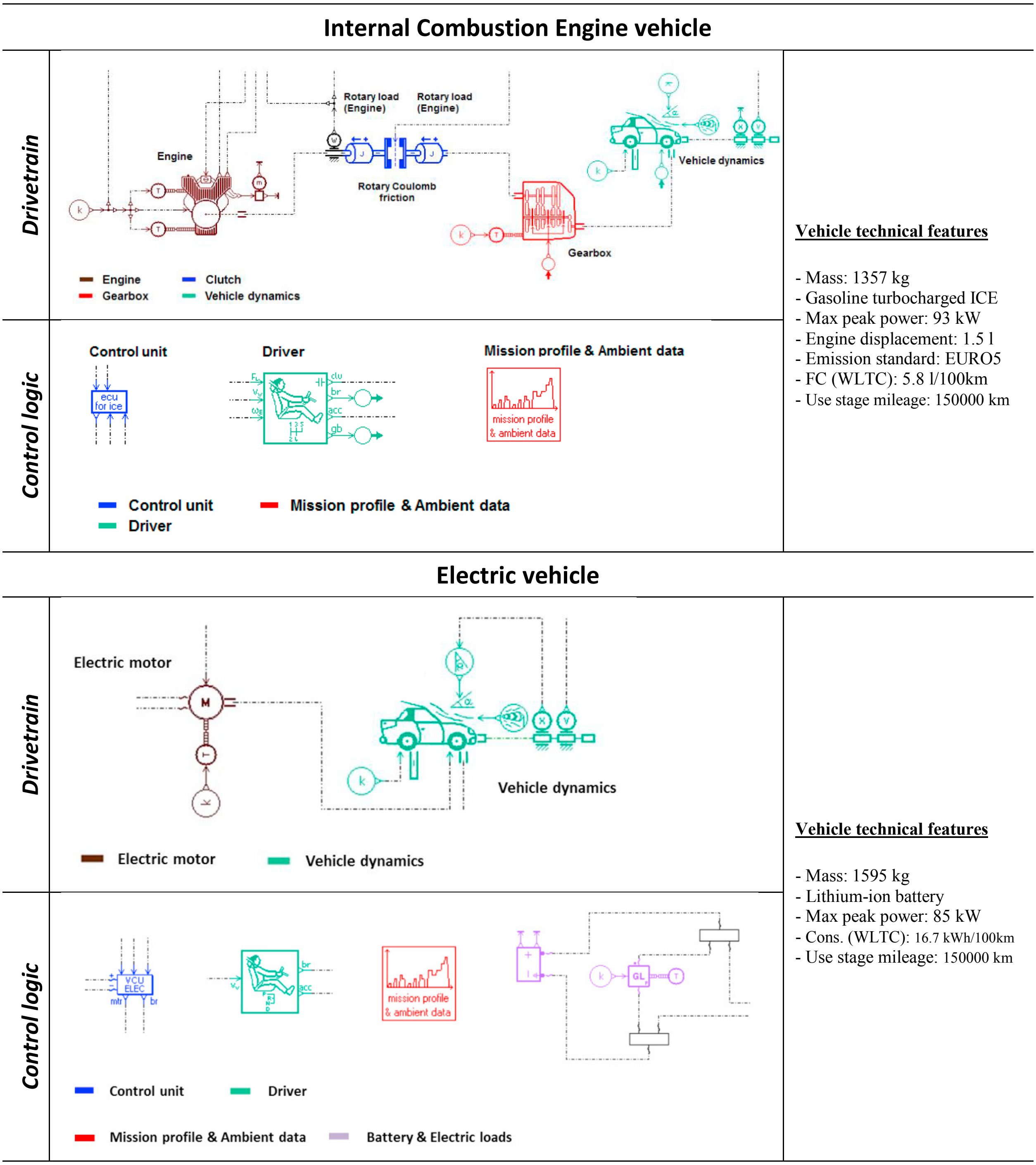


Figure 1. Use stage simulation model and main technical features for the calculation of use stage energy consumption

End-of-Life. The EoL stage is modelled taking into account principles of 2000/53/EC Directive and ISO standard 22628:2002 “Road Vehicles Recyclability and Recoverability: Calculation Method” (ISO 22628, 2002) which divide the EoL of vehicles into four distinct steps: depollution, dismantling, shredding and post-shredding. The environmental impact of EoL is modelled considering energy consumption required by dismantling/recycling/landfill processes, credits arising from recyclable material and energy flows, releases to the environment due to waste landfilling. Figure 2 reports the allocation of the main car components as well as materials to the different EoL processes.

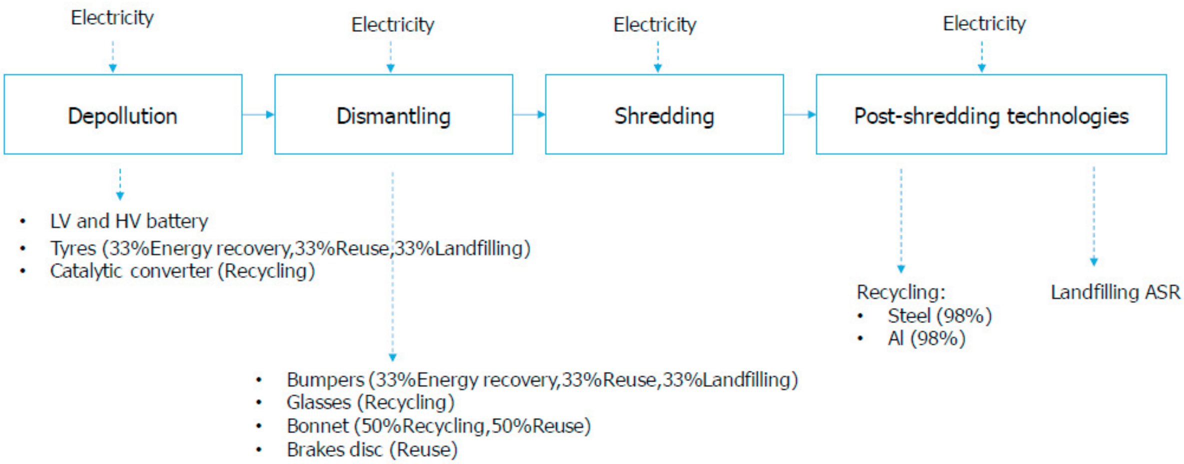


Figure 2. Allocation of components and materials to EoL processes

The EoL of car batteries (both low voltage and high voltage battery) is excluded from the analysis, as batteries are assumed to be removed from the vehicle in the depollution stage and forwarded to secondary use (Genikomsakis et al., 2013), which is out of system boundaries.

3. Results and discussion

3.1. Impact assessment results

Table A1 in the SI appendix shows the LCIA results for both ICEV and BEV; additionally to total LC impact, contributions of production, use and EoL stages are also reported. Discussion section below takes into account the following selected indicators considered as being relevant in the road mobility sector:

- Acidification;
- Climate change (including biogenic carbon);
- Human toxicity (non-cancer effects);
- Particulate matter/Respiratory inorganics;
- Photochemical ozone formation;
- Resource depletion, mineral, fossils and renewables.

Figure 3 compares the different vehicle configurations by reporting LCIA results of ICEV and BEV; total LC impact is divided into contributions from the single LC stages. Figure 4 and 5 show the influence of each vehicle assembly to the production stage impact respectively for ICEV and BEV. Results stress that the environmental burden is essentially involved by production and use stages while contribution of EoL is negligible for all the considered impact categories. Below the allocation of impact to LC stages as well as vehicle assemblies is critically discussed in details.

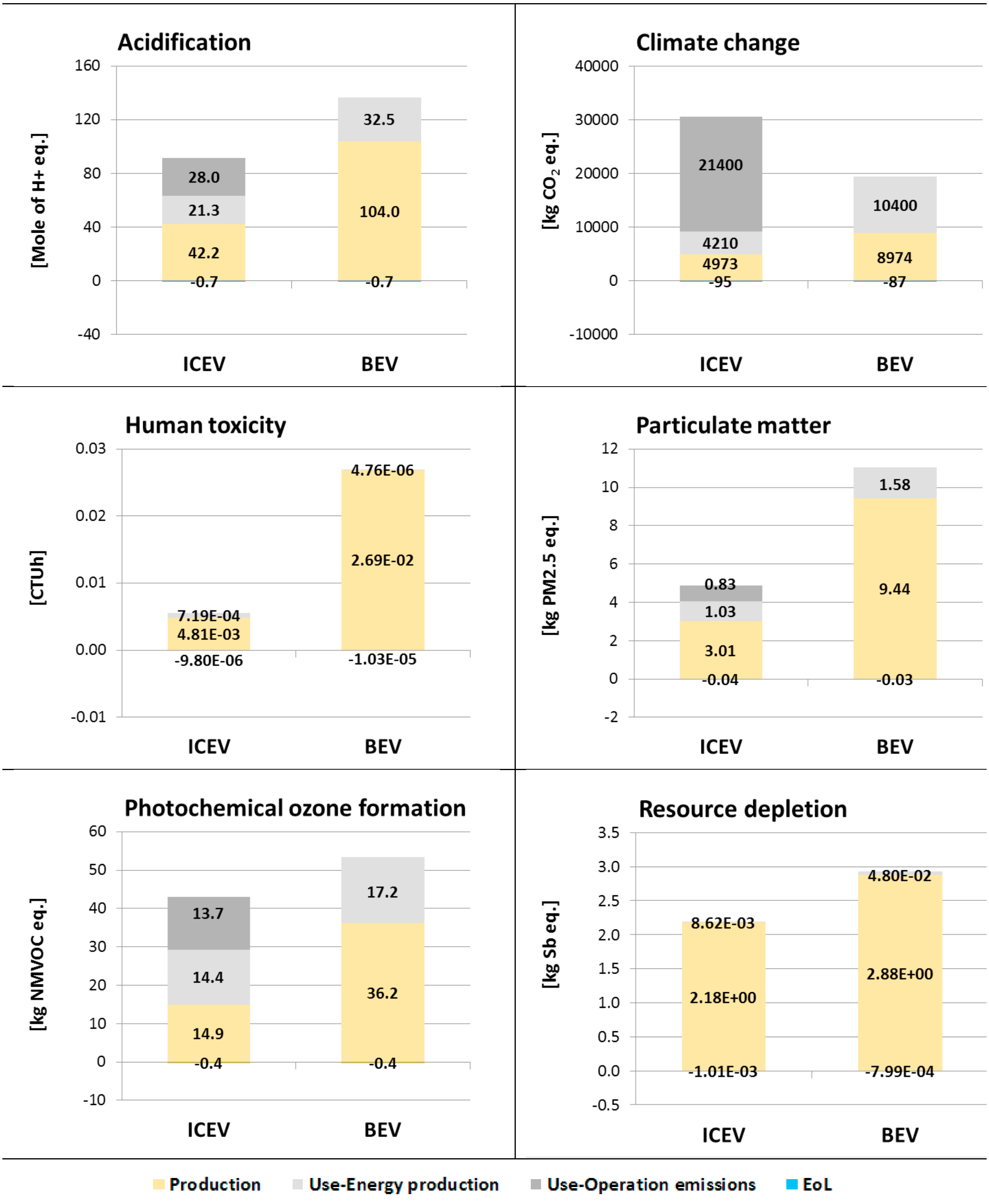


Figure 3. LCIA results of ICEV and BEV: contribution analysis by LC stage

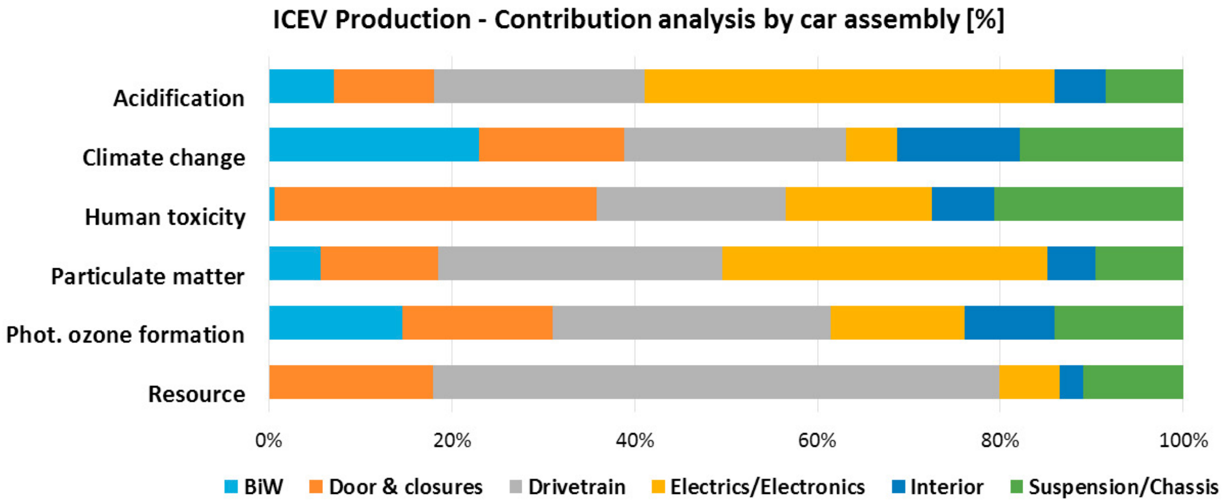


Figure 4. Contribution analysis by vehicle assembly of production impacts (ICEV)

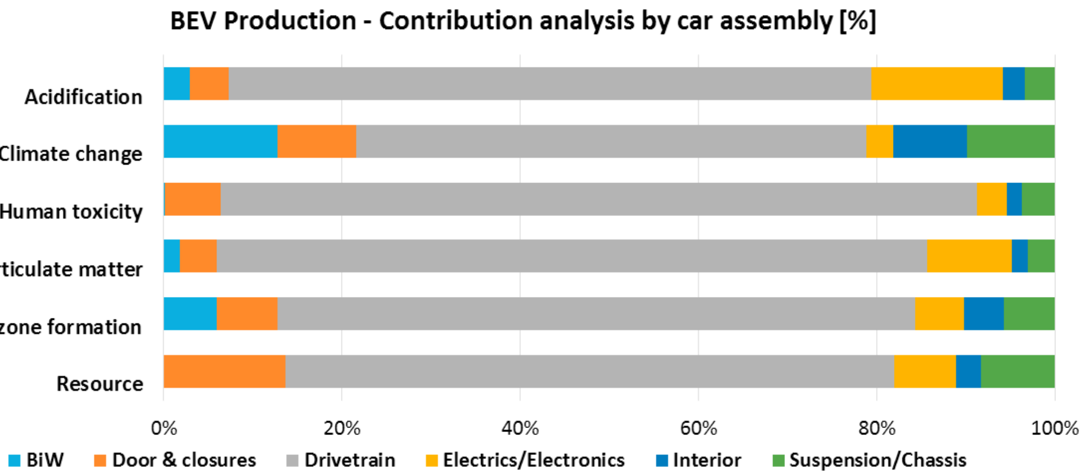


Figure 5. Contribution analysis by vehicle assembly of production impacts (BEV)

Climate change. The major part of ICEV impact (more than 80 %) is attributable to the high burdens associated with the use stage. Exhaust gas missions during operation represent the main contribution to use (about 71 %) while the remaining part is involved by the fuel supply chain. The impact of ICEV production is almost equally distributed between assemblies which present a preponderant quota of metal materials (body-in-white, doors and closures, drivetrain, suspension/chassis) with minor shares from electrics/electronics and interior. On the other hand, the environmental burden of BEV is attributable primarily to production and use phases with a slightly higher quota for the second one. The manufacturing impact of BEV is definitely higher with respect to the one of ICEV (+80 %) while the allocation of climate change to the specific vehicle assemblies reveals that the most influential one is the drivetrain; this is due to the high contribution from production of battery and electric motor as well as other powertrain components (inverters and passive battery cooling system) which present a high content of aluminum. That said, the greater load in the production of BEV is largely compensated by the lower use stage impact, which leads to a 36 % reduction of total LC impact with respect to ICEV. The reason for this is the absence of exhaust emissions during operation as well as the lower environmental burdens involved by electricity production with respect to the fuel supply chain. Figure 6 compares the climate change LCIA impacts of the study with the most recent literature papers that deal with the environmental comparison between ICEV and BEV.

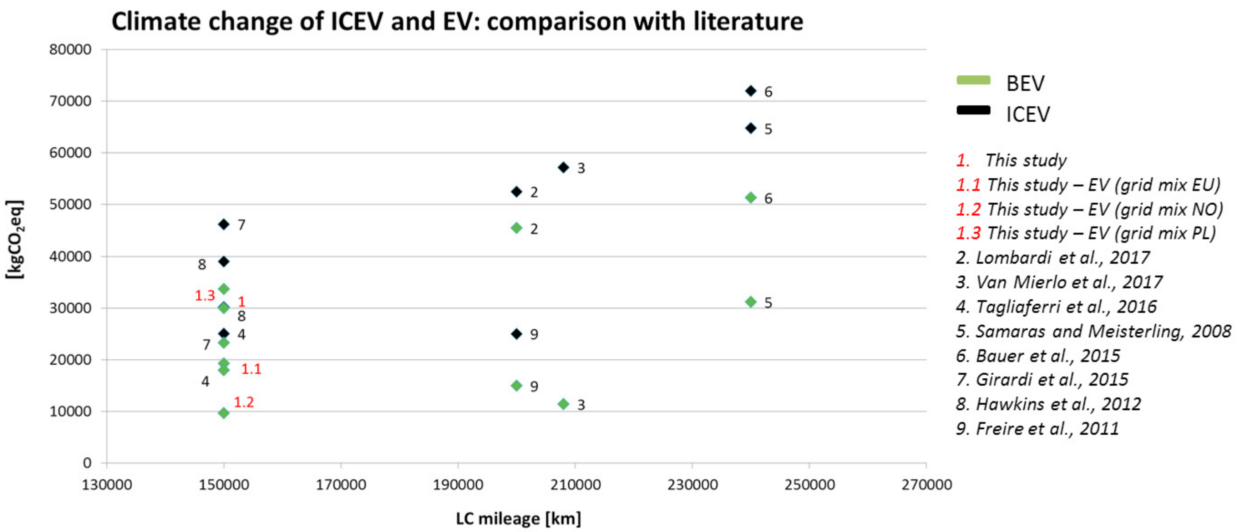


Figure 6. Climate change of ICEV and EV: comparison with literature

It can be noted that results are extremely heterogeneous and diversified; this is mainly due to different choices regarding system boundaries, level of detail in data collection (primary sources, aggregated published data) and modelling assumptions; the results presented in this study are in line with impacts of ICEVs and BEVs already published.

Other impact categories. The acidification impact of BEV is significantly higher with respect to the one of ICEV (+51 %). This is primarily due to the high contribution of high-voltage battery and motor production which involves the adoption of relevant amount of aluminum, copper, and nickel. Considering the ICEV, the acidification is equally distributed between production and use stages. The major part of production impact is attributable to emissions involved by the production of platinum used for the manufacturing of the exhaust catalyst system; on the other hand, the environmental load of use phase is primarily involved by SO_2 emissions during operation while fugitive emissions from the fuel supply chain determine the remaining quota.

For the human toxicity the impact of BEV is about five times greater with respect to ICEV. This is almost fully attributable to the production stage; in particular the emissions involved by mining processes of raw materials as well as manufacturing of chemicals and metals (aluminum, copper, nickel and platinum) used in the electric drivetrain (Lithium-ion battery, electric motor and power electronics) are the main responsible for the toxicological effect. Similarly to the BEV, the production stage of ICEV represents by far the highest quota, the main influential vehicle assemblies being doors/closures, drivetrain and suspension/chassis; on the other hand the use accounts for a minor share of total LC impact (about 15%).

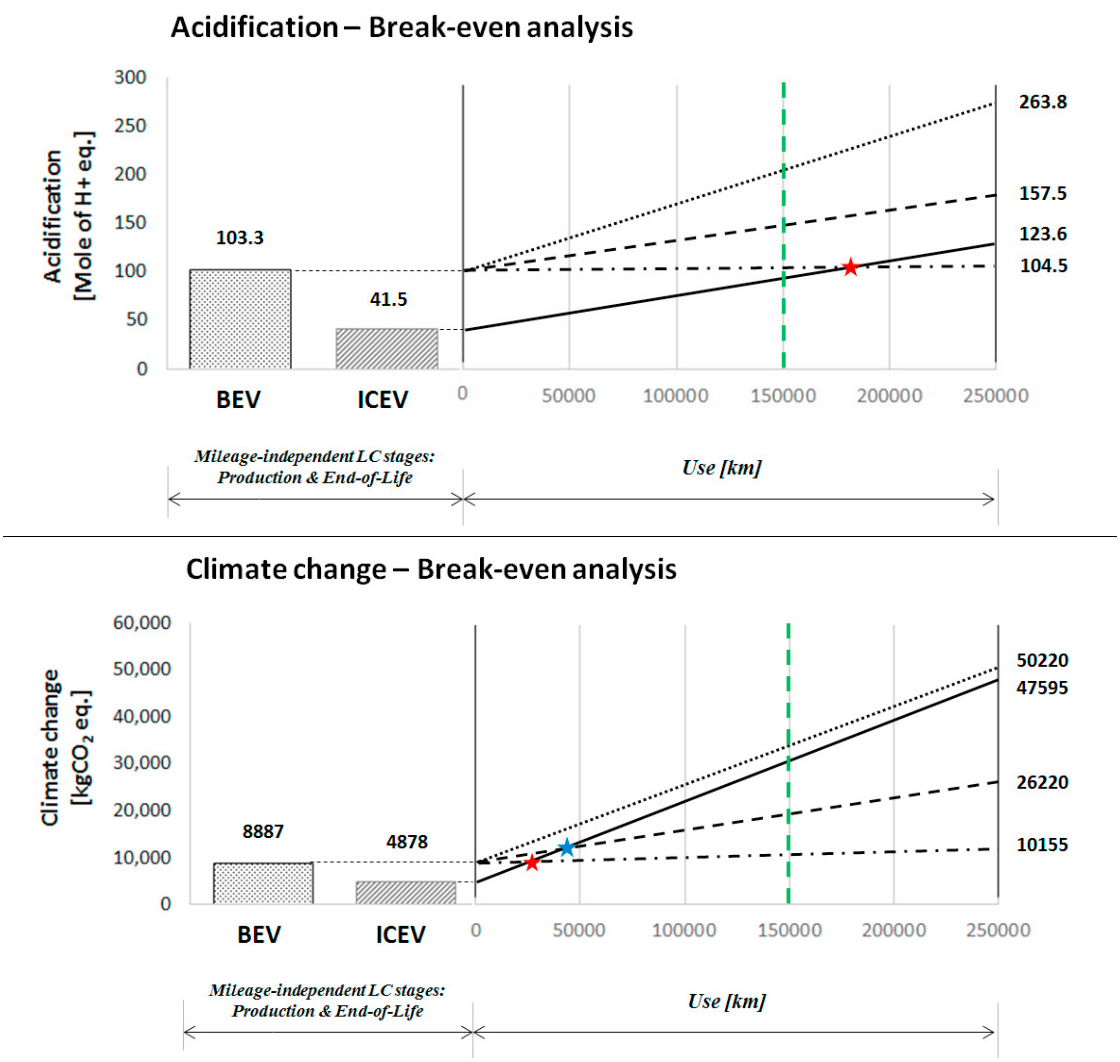
Particulate matter shows a trend analogous to the one of human toxicity. In this case as well, BEV load is more than double with respect to the ICEV and the impact is dominated by the production stage for both propulsion technologies. The contribution of use phase is not negligible, as it accounts for about 38 % and 14 % of total LC impact respectively for conventional and electric configurations with the use stage of ICEV equally distributed between fuel supply and operation emissions. The remarkable influence of BEV production is attributable to the supply chain of metals with the most relevant assembly being the drivetrain while emissions from coal power plants in the electricity production represents the main contributor to the use stage.

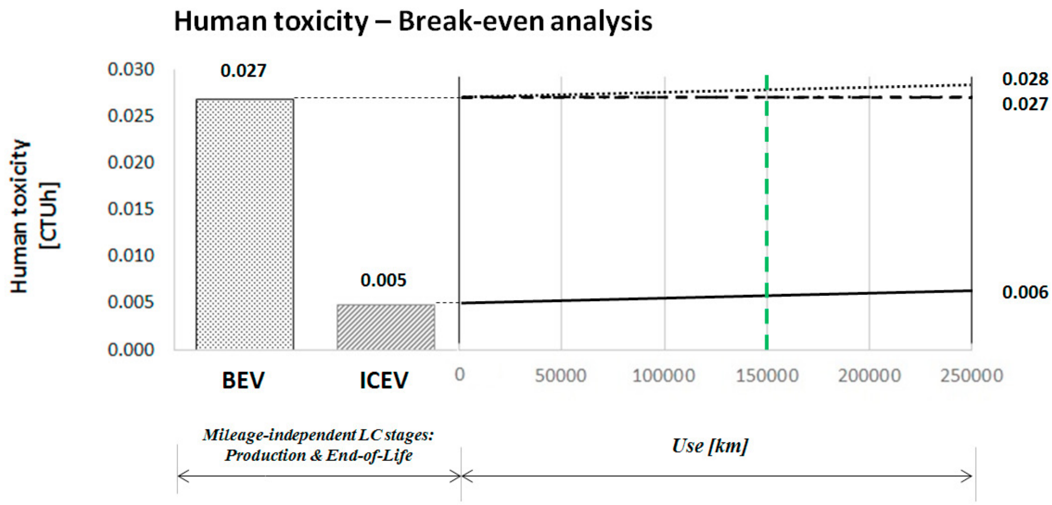
For the photochemical ozone formation, the impact of BEV is slightly higher with respect to the one of ICEV (+26 %). For both propulsion technologies NOx emissions are the principal responsible of the impact. For the ICEV the most influential LC stage is the use, with a quota of fuel production (refining and distribution of fossil fuels) comparable to the one of emissions during operation. On the other hand, the impact of BEV is dominated by production for which the most relevant assembly is the drivetrain, blasting in mining activities being the predominant cause.

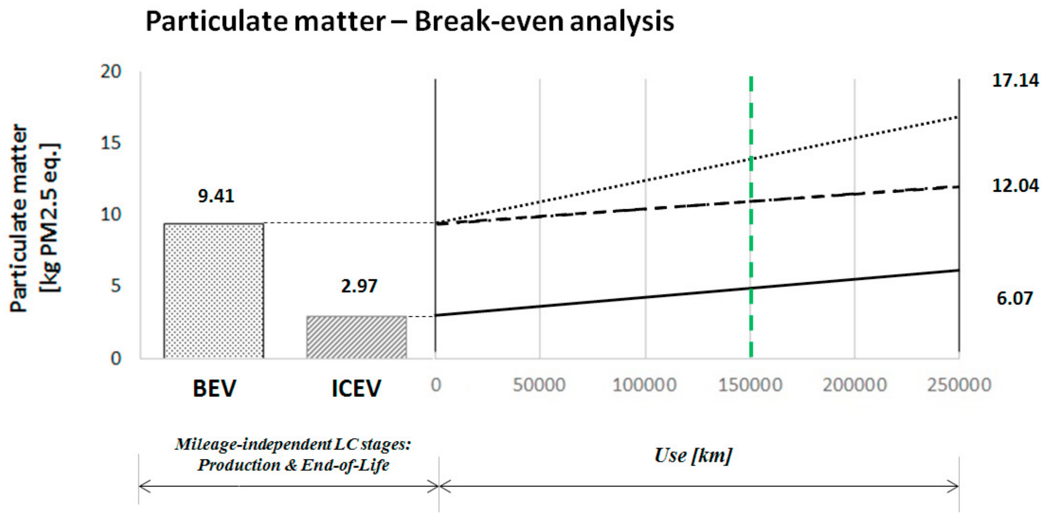
For both propulsion technologies the production covers almost the total amount of resource depletion impact category with the biggest contribution coming from the drivetrain. The total LC burden of BEV is higher with respect to the ICEV (+32 %) due to the strong dependence on rare metals of the electric powertrain.

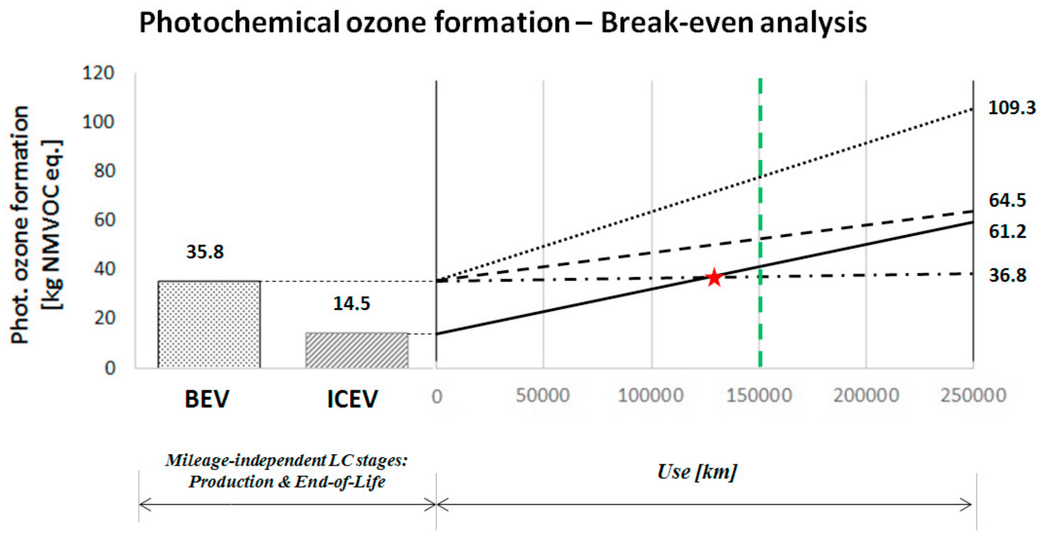
3.2. Use stage break-even analysis

Figure 7 investigates the dependence of impact on LC mileage by reporting the break-even analysis for the entire car LC. The left end of the diagrams reports the contribution of the mileage-independent LC stages, that are production and EoL; on the right hand, the impact of use stage is showed in function of car mileage. Considering that use phase impact of BEV is strongly influenced by the source of electricity, three different grid mixes for the electricity production are considered: average European (reference for this study), Norwegian and Polish grid mixes. The choice for the two additional grid mixes is that they present opposite environmental profiles (electricity produced by renewable resources for the Norwegian grid mix and energy supply mainly based on fossil fuels for the Polish grid mix), thus allowing a comprehensive overview on the environmental effects of the electricity supply chain.




Human toxicity – Break-even analysis
Human toxicity [CTUh]
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.027
0.005
BEV
ICEV
0
50000
100000
150000
200000
250000
0.028
0.027
0.006
Mileage-independent LC stages: Production & End-of-Life
Use [km]


Particulate matter – Break-even analysis
Particulate matter [kg PM2.5 eq.]
20
15
10
5
0
9.41
2.97
BEV
ICEV
0
50000
100000
150000
200000
250000
17.14
12.04
6.07
Mileage-independent LC stages: Production & End-of-Life
Use [km]


Photochemical ozone formation – Break-even analysis
Phot. ozone formation [kg NMVOC eq.]
120
100
80
60
40
20
0
35.8
14.5
BEV
ICEV
0
50000
100000
150000
200000
250000
109.3
64.5
61.2
36.8
Mileage-independent LC stages: Production & End-of-Life
Use [km]

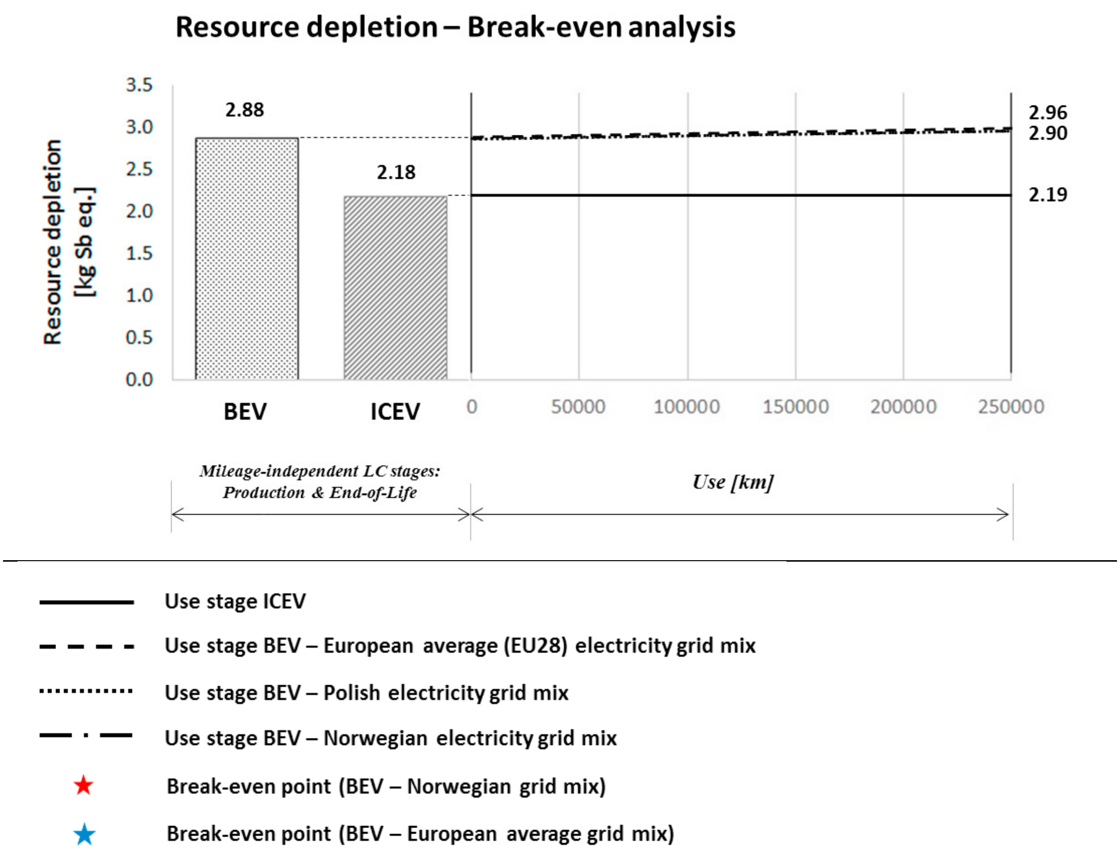


Figure 7. Comparison ICEV – BEV: break-even analysis

Considering the climate change, the analysis of the break-even point reveals that the environmental convenience of the electric configuration occurs at low value of mileage (about 45000 km) if compared to the total LC distance (150000 km). This is due to the fact the average European electricity grid mix has a very low GHG intensity in comparison to fossil energy resources used for fuel production. Assuming the Norwegian electricity grid mix, the break-even point decreases at about 30000 km while the result is totally reversed if the Polish grid mix is taken into account, as no break-even point occurs within the considered mileage range (0 – 250000 km).

Considering the other impact categories, the break-even analysis reveals that for acidification the BEV presents a worse environmental profile with respect to the ICE configuration; the impact of electric car results higher at any value of LC mileage with the exception of BEV powered by electricity produced with the Norwegian grid mix. This is mainly due to the independence of Norwegian electricity production on fossil fuels; however, it has to be noted that the break-even point is located at about 180000 km, a considerably higher value with respect to the assumed LC mileage (150000 km). Photochemical ozone formation shows a similar trend with respect to acidification: ICEV results preferable at any vehicle kilometrage, except the BEV with the Norwegian grid mix for which the cleaner electricity production leads to a break-even point near the end of car life-time (about 130000 km). Finally, regarding human toxicity, particulate matter and resource depletion no threshold mileage between ICEV and BEV is detected; for these categories the contribution of mileage-independent LC stages is higher for the electric car and, considering that use stage confirms this trend, ICEV results definitely preferable from an environmental point of view. The adoption of different electricity grid mixes has a relevant influence on the particulate matter, mainly based on the dependency on fossil fuels (42 % impact increase at 250000 km assuming the Polish grid mix) while it is negligible for human toxicity and resource depletion.

3.3. Final remarks and policy implications

BEVs have the potentiality to substantially reduce the impact on climate change in comparison with ICEVs. This is true only if the electricity consumed by car is produced from non-fossil energy sources. On the contrary the use of fossil energy carriers for electricity production can strongly reduce the environmental benefit of BEVs and even lead to an increase in GHG emissions; in this case only local pollution decrease can be achieved and the emissions are moved from the road to specific areas rather than achieving an effective reduction on a global scale. As a consequence, electric mobility should be strongly promoted only where electricity is produced primarily from clean energy sources; on the other hand, in areas with electricity grid mix characterized by high share of coal power BEVs could be counter-productive and limiting the use stage exhaust gas emissions of conventional cars appears as the most effective strategy for achieving impact reduction. However, it has to be considered that the quota of renewable sources in the electricity grid mix will progressively increase in the near future, thus boosting the potentiality of electric mobility to lower global warming and fossil depletion. That said, basing the comparative analysis only on the climate change impact category does not allow to appreciate some key differences between ICEVs and BEVs, thus leading to wrong general conclusions. Indeed, the electric cars appear to involve higher LC impacts for acidification, human toxicity, particulate matter, photochemical ozone formation and resource depletion. The main reason for this is the notable environmental burdens of the manufacturing phase, mainly due to toxicological impacts strictly connected with the extraction of precious metals as well as the production of chemicals for battery production. In order to avoid problem shifting from one impact category to another, the highest room for improvement of BEVs lies in the technological development of innovative processes for battery production able to offer high efficiencies, innovative eco-efficient materials and component recyclability. Considering the use stage, a viable way to improve the eco-efficiency of BEVs is increasing the LC mileage which would involve a further reduction in terms of specific impact (i.e. per-kilometre impact). Another relevant point that arises from the study is the importance to perform the comparative assessment taking into account the entire vehicle LC, including car production and EoL. As seen above, the exclusion of manufacturing would lead to incorrect findings and incomplete results for the major part of the considered impact categories.

It can be concluded that market penetration of BEVs would occur taking into account several antithetical aspects; vehicle manufacturing, composition of electricity grid mix, high-voltage battery production and LC mileage are key aspects that need to be contemporarily considered when evaluating the environmental effects involved by the substitution of conventional with electric cars.

4. Conclusions

The study provides a comparative environmental assessment of a gasoline turbocharged ICEV and a Lithium-ion BEV by means of the LCA methodology; the analysis deals with the entire LC of the vehicles and the assessment is based on a wide range of impact categories to both human and eco-system health. Unlike most of literature works, the inventory of the production stage is mainly based on primary data while the consumption during operation is determined through a dedicated simulation model reproducing real car driving conditions in order to reduce the uncertainty as much as possible.

Results of the impact assessment show that the BEV allows achieving significant impact reduction in terms of climate change thanks to the absence of exhaust gas emissions during operation; the investigation of different grid mixes for electricity production shows that this advantage significantly grows at increasing share of renewable sources. On the other hand, the manufacturing of BEV has a greater load with respect to ICEV, especially for the large use of metals, chemicals and energy required by specific components of the electric powertrain such as the high-voltage battery. The other considered environmental impacts (acidification, human toxicity, particulate matter, photochemical ozone formation and resource depletion) result higher for the BEV than the ICEV, primarily due to the major environmental loads of powertrain construction and manufacturing.

In the light of previous considerations it appears clear that the assessment of electric cars cannot be performed using a single indicator but it should be rather based on a more complex evaluation system. For this reason market penetration of BEVs must be accompanied by a cautious policy which takes into consideration all the aspects of the LC management. To date electric mobility appears as an effective strategy for reducing GHG emissions in regions where electricity is produced from sources with limited contribution of fossil sources. However, production phase represents the main barrier for achieving the full maturity of this technology in the environmental perspective. Future clean electricity grid mixes and the development of more sustainable production processes could strongly contribute to the convenience of BEVs by minimising GHG emissions as well as countering potential setbacks in terms of other environmental impacts.

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SI appendix

Table A1. LCIA results for both ICEV and BEV

	ICEV				BEV			
	Production	Use	EoL	Total LC	Production	Use	EoL	Total LC
Acidification midpoint [Mole of H+ eq.]	4.22E+01	4.93E+01	-7.07E-01	9.08E+01	1.04E+02	3.25E+01	-6.50E-01	1.36E+02
Climate change midpoint, excl biogenic carbon [kg CO_2 eq.]	4.97E+03	2.54E+04	-9.51E+01	3.02E+04	8.96E+03	1.04E+04	-8.72E+01	1.93E+04
Climate change midpoint, incl biogenic carbon [kg CO_2 eq.]	4.97E+03	2.56E+04	-9.52E+01	3.05E+04	8.97E+03	1.04E+04	-8.71E+01	1.93E+04
Ecotoxicity freshwater midpoint [CTUe]	2.18E+05	3.43E+03	-1.31E+01	2.22E+05	6.39E+05	3.15E+02	-1.31E+01	6.39E+05
Eutrophication freshwater midpoint [kg P eq.]	2.77E+00	9.07E-02	1.51E-02	2.87E+00	1.58E+01	2.89E-02	1.16E-02	1.59E+01
Eutrophication marine midpoint [kg N eq.]	4.34E+00	1.17E+01	-1.44E-01	1.59E+01	1.22E+01	6.54E+00	-1.38E-01	1.86E+01
Eutrophication terrestrial midpoint [Mole of N eq.]	4.37E+01	1.81E+02	-1.56E+00	2.23E+02	1.13E+02	6.61E+01	-1.48E+00	1.77E+02
Human toxicity midpoint, cancer effects [CTUh]	4.17E-04	1.53E-04	-1.48E-07	5.69E-04	1.80E-03	8.61E-06	-1.65E-07	1.81E-03
Human toxicity midpoint, non-cancer effects [CTUh]	4.81E-03	7.17E-04	-9.80E-06	5.52E-03	2.69E-02	4.76E-06	-1.03E-05	2.69E-02
Ionizing radiation midpoint, human health [kBq U235 eq.]	3.49E+02	9.52E+01	-8.25E+00	4.36E+02	8.62E+02	5.10E+03	-6.66E+00	5.96E+03
Land use midpoint [kg C deficit eq.]	2.73E+03	9.26E+03	-4.88E+01	1.19E+04	9.72E+03	5.42E+03	-4.88E+01	1.51E+04
Ozone depletion midpoint [kg CFC-11 eq.]	1.50E-04	8.93E-10	5.26E-08	1.50E-04	4.82E-04	4.63E-08	5.18E-08	4.82E-04
Part. matter / Resp. inorganics midpoint [kg PM2.5 eq.]	3.01E+00	1.86E+00	-3.71E-02	4.83E+00	9.44E+00	1.58E+00	-3.41E-02	1.10E+01
Phot. ozone formation midpoint, human health [kg NMVOC eq.]	1.49E+01	2.80E+01	-4.09E-01	4.25E+01	3.62E+01	1.72E+01	-3.89E-01	5.30E+01
Resource depletion water, midpoint [m^3 eq.]	4.43E+01	4.07E+01	-6.85E+00	7.81E+01	1.03E+02	6.98E+02	-6.64E+00	7.94E+02

Resource dep., mineral, fossils and renew., midpoint [kg Sb eq.]	2.18E+00	8.61E-03	-1.01E-03	2.19E+00	2.88E+00	4.80E-02	-7.99E-04	2.93E+00

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