

The role of efficiency in the environmental performance of power electronics in electric vehicles.

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Summary

A genuine transition towards green mobility requires a continuous environmental assessment of all innovative solutions used in EV technology. This paper investigates the role of power electronics in the environmental performance of EVs, from a life cycle perspective. The influence of efficiency and electricity mix used is investigated, as well as the main materials and components responsible for environmental impact. Energy consumption is identified as a large contributor to environmental impact, during manufacturing and powering of the power electronics. Improvement of this impact can be obtained by increasing efficiency and by introducing green energy sources along the life cycle.

Keywords: electric drive, inverter, energy, environment, LCA.

1. Introduction

The impact associated to battery electric vehicles (BEVs) is closely tight to the percentage of green energy sources used for electricity in the charging of the battery [1]. In the cases where a big part of the electricity mix is provided from fossil sources, then the actual environmental improvement of electric vehicles over conventional ICE vehicles can be questionable. The full potential for green mobility comes with a further inclusion of green energy into our electric grids. Moreover, several studies [2] [3] [4] have raised concerns regarding the damage generated from mine tailings and processing of toxic materials for EVs, and the potential danger of resources depletion without effective recycling processes [5], [6].

It is clear that comprehensive assessments on electric vehicle technology are necessary to clarify environmental hotspots, and to prevent, to the reach of possibilities, major environmental impacts. Numerous publications address the issue of environmental impacts of electric vehicles and compares it to ICE vehicles, and other emerging technologies, however, as stated by [7], there is still a need for specific assessments and inventories on powertrain technology, including batteries, control electronics, electric motors and transmissions.

So far studies have mainly focused on the use stage of the vehicle, and just recently studies began addressing manufacturing impacts. With the exception of studies at battery level [8], [9], just few studies focus on other key EV powertrain components [7].

While considerable work has been carried out assessing the environmental impact of consumer's electronic components in general [10] (i.e. mobile phones, laptops, desktop computers, TVs, etc.), the assessment of power electronics in electric vehicles remains limited.

The aim of this paper is to contribute to the understanding of environmental impact generated by state of the art power electronics in electric vehicle applications, by identifying all responsible parameters associated to its manufacturing, use and disposal. For this, the inverter, used in an integrated drive for a hatchback rear axle driving vehicle, is analyzed. The paper focuses on the role of efficiency in the life cycle of the components. This study is performed in the frame of activities for the EU FP7 project SyrNemo [11], whose aim is to develop and innovative, rare-earth free synchronous reluctance machine with high power density and high driving cycle efficiency, ensuring low environmental impact throughout its life cycle.

The paper includes the life cycles of manufacturing, use and end of life of the inverter. All materials, processes and components producing high environmental impact are identified, and some eco-design measures are proposed accordingly, in order to ensure the lowest environmental impact possible in power electronics in EVs.

2. Methodology

This study is performed according to the LCA methodology, defined in ISO 14040 (2006) [12] and 14044 standards (2006) [13], and the International Reference Life Cycle Data System (ILCD handbook)—General guide for life cycle assessment [14].

The impact assessment includes the damage generated by the inverter to: ecosystems, human health and resources availability, expressed in several impact categories according to Recipe2008 v1.11 method. A focus is given to three impact categories along the life cycle, climate change, human toxicity and abiotic resources depletion.

A power inverter is used for the study, for a small-segment light duty battery electric vehicle. Maintenance is not foreseen for the components during the 10 years' service life defined. The component is considered to be manufactured, used and disposed according to standard European conditions.

All materials and mass for each electronic and electromechanical component in the inverter design are defined, as well energy requirements for the manufacturing of each component and final assembly. The inverter has a total mass of about 1,5 kg, where the power module is significantly one the biggest components by mass. Passive electronic components such as capacitors, resistors and inductor have a larger share of the total mass, while diodes, transistors and other active components have a smaller share.

2.1 Life cycle of the inverter

2.1.1 Inverter manufacturing

For the production of the inverter primary data is used, the bill of materials and energy requirements for the manufacturing of the inverter is defined accordingly. All active and passive components are surface-mount directly onto the surface of the printed circuit board.

The production of the inverter includes the extraction of raw materials, manufacturing of components, and final assembly in labour conditions representative of the European average. This includes the transportation of the raw materials delivered to a European plant for its final processing.

Secondary data for background processes, and the complete techno-sphere linkages, is obtained from Ecoinvent v2.2 database.

2.1.2 Use stage

The use stage considers all energy consumption required by the inverter during vehicle operation. For estimation of this energy consumption, the New European Driving Cycle (NEDC) [15] is implemented. The NEDC allows the representation of typical car usage in Europe, however, as it has been pointed out by [16] and [17], its usage can be an underestimation of real energy consumption, as it is based on ideal driving behaviors. Nevertheless the NEDC is used as it remains among best techniques for this purpose, and this underestimation is considered for the analysis and conclusion of the study. For each time step set of the driving cycle, the motive force (F_m) and the power at the wheel (P_{wheel}) are calculated using equations (1) and (6), respectively [18], [19]:

$$F_m = (F_g + F_{roll} + F_{ad} + F_{acc}) \quad (1)$$

Where:

$$\text{Gravitational force:} \quad F_g = m \times g \times \sin(\alpha) \quad (2)$$

$$\text{Rolling resistance:} \quad F_{roll} = m \times g \times C_r \times \cos(\alpha) \quad (3)$$

$$\text{Aerodynamic drag force:} \quad F_{ad} = 0,5 \times \rho \times C_d \times A_F \times V^2 \quad (4)$$

$$\text{Acceleration force:} \quad F_{acc} = m \times \frac{dV}{dt} \quad (5)$$

for ($\alpha=0$)

$$P_{wheel} = F_m \times V \quad (6)$$

In the equations, m : vehicle mass (kg), g : gravity (m/s^2), α : slope angle, a : acceleration (m/s^2), C_r : coefficient of rolling resistance, ρ : air density (kg/m^3), C_d : aerodynamic drag coefficient, A_F : frontal area of the vehicle (m^2), v : vehicle velocity (m/s), and t : time (s). Inputs for these parameters are obtained from [20].

Drivetrain efficiencies (η_t transmission efficiency, η_m motor efficiency, and η_c power electronics efficiency), and the extra power required for auxiliary equipment (P_{aux}), are considered to calculate the electric power supplied and recovered by the battery (eq. (7) and (8)). The power recovered by the battery, given by the regenerative braking, is the kinetic energy of the vehicle transformed into electric energy and stored in the battery.

$$P_{el.supply} = P_{aux} + \left(\frac{P_{wheel}}{\eta_t \cdot \eta_m \cdot \eta_c} \right) \quad (7)$$

$$P_{el.recover} = P_{wheel} \cdot (\eta_t \cdot \eta_m \cdot \eta_c) - P_{aux} \quad (8)$$

The total average tank-to-wheel (TTW) energy to be supplied by the vehicle battery (Wh/km), for the cycle driving distance (D_{total}), is calculated with equations (9) and (10).

$$E_{avg} = \begin{cases} \frac{\int P_{el.supply} \times dt}{D_{total}} & \text{for } (P_{wheels} > 0) \\ \frac{\int P_{el.recover} \times dt}{D_{total}} & \text{for } (P_{wheels} < 0) \end{cases} \quad (9)$$

$$(10)$$

The energy consumption of the vehicle is calculated using equation (11):

$$E_{cons.battery} = \frac{E_{avg}}{\eta_{battery}} \quad (11)$$

An EU-28 electricity mix from 2012 is assumed for the powering of the powertrain during its use [21].

2.1.3 End of life

During the end of life scenario modelled, a percentage of materials in the power electronics are recycled, as per [22]. The remaining materials, particularly plastics, are considered to be disposed in landfilling facilities. The end-of-life accounts for the energy required for disassembly and shredding of the components. After these process, some of the materials is the power inverter are recovered by means of a metallurgical process for printed wiring boards. Ecoinvent 2.2 data is used to represent the processes of shredding, recycling, and disposal.

For the assessment it is considered that the materials recycled are used in another product as secondary metals. However, no credit or positive environmental impact is included in this study, but only the negative environmental impact related to energy and resources consumption during recycling process. This last is intended to avoid false assumptions in the efficiency of recycling of electronic components of EVs, so as to keep a conservative “worst-case scenario” approach.

3. Impact assessment

From the defined life cycle inventory, the overall impact of the inverter design was calculated. As previously mentioned, the LCA study includes the stages of production, use and the end of life of the different inverter component parts. The results obtained are presented at midpoint level using Recipe2008 impact method [23].

Fig. 1 shows the relative impact generated by the inverter in each of its life cycle stages. It is clear from this figure that, for the majority of impact categories, the largest share of impact is given by the use of the inverter. This impact ranges between 91%, 86% and 84% of the total impact generated on categories such as climate change (kg CO₂-Eq), particulate matter formation (kg PM₁₀-Eq) and photochemical oxidant formation (kg NMVOC) respectively. The impact generated during this stage is a consequence of electricity consumption, mainly given that almost half of EU-28 electricity is generated for fossil fuels, leading to the emissions of dangerous gases during production, transport and combustion of these fossil fuels.

For the categories of metal depletion and toxicity of water bodies and humans, the impact of manufacturing is more significant. This impact is produced mainly during mining and processing of raw materials that will later be used in the manufacturing of each inverter components. The leakage of toxic substances during mining, especially in copper metal extraction, is identified as having particular impact contribution for the manufacturing stage.

From Fig. 1 is also noticeable that the end-of-life processes, including shredding of the inverter, recycling of metals and final disposal, contribute in very small percentages to the overall impact of the power electronic. The small impact identified is associated to the metallurgical recycling process for valuable metals. Taking this into account, further recycling rates of power electronic components is highly advisable, as it could decrease manufacturing impact in other products.

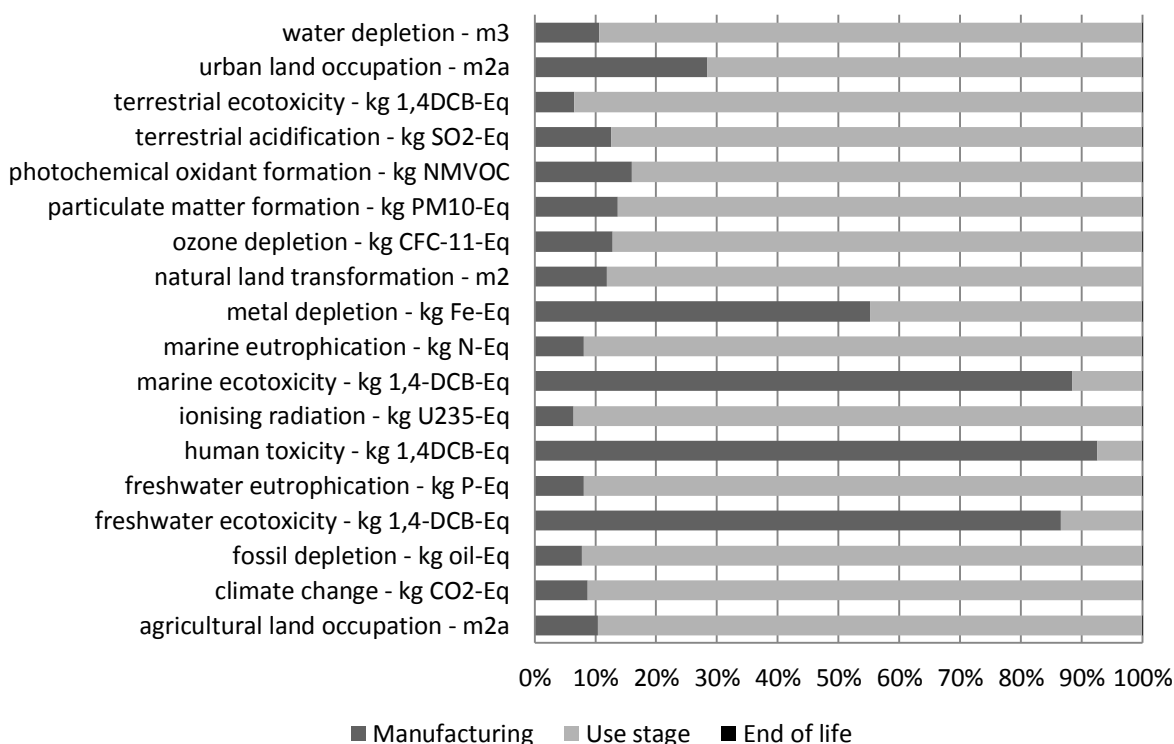


Figure 1. Relative contribution total impact in each life cycle of the inverter

The impact of manufacturing, and the particular component parts and materials responsible for this impact, are studied in further detail. Table 1 shows, for the categories of climate change, human toxicity and metal depletion, the main parts in the inverter contributing to environmental damage and depletion of resources. For the three mentioned impact categories, in overall the same components are the main contributors to impact. The power module is the largest contributor, followed by the interface controller, the circuit board, capacitors and productive device. There is strong correlation between the mass of the component parts and the total impact they generate. The mentioned components account for about 92% of the total mass of the inverter. Smaller components, including resistors, inductor, diodes, and other, all together generate about 3% of impact for these categories. Clearly, the components of the inverter with larger masses contribute the most to the environmental impact, as more material and energy efforts are required for producing them.

In general, for all component parts in the inverter it was found that the energy required for their manufacturing is the most significant parameter generating environmental damage. The manufacturing of electronic and electromechanical components is very energy intensive. Even though the parts have a relative small mass, their manufacturing requires larger quantities of energy, and this is particularly true for active electronic components whose manufacturing requires up to 10 times more electricity than passive electronic components per unit of mass. The contribution to impact in passive components is mainly given by the use of precious metals (gold and silver), as well as palladium and tantalum in some of its components, as well as their bigger mass comparing to active components.

When analyzing capacitor types, tantalum capacitors have a much more relevant contribution to impact, mainly due to the use of tantalum powder, silver, and the electricity required for its production. Resistors have very little contribution to impact, due to their very small sizes. The differences in impact between resistor types are due to variations in the use of gold, palladium and energy in their manufacturing.

Table 1. Main contributing components to the categories of climate change, human toxicity and metal depletion.

	Inverter components					
Impact categories	Power module	Interface controller	Circuit board	Protective device	Capacitors	Others
climate change (%)	76,4	5,2	5,2	1,6	8,7	2,8
human toxicity (%)	82,6	7,0	2,3	2,5	1,5	4,1
metal depletion (%)	77,0	9,6	2,9	2,1	2,1	6,4

When considering the positive environmental impacts of recycling, the total environmental impact of the inverter can be reduced. This positive impact is the consequence of replacing raw materials for the production of primary metal. The recovered materials from the inverter are used in a next product system. Recycling rates from electronic components in general remains low, as a result of challenges of minituarization and complexity for the recovery of valuable metals. Nevertheless, it is found that recycling of the power inverter can lead to a reduction of about 13% of total metal and fossil depletion impact.

3.1 Efficiency and power electronics

Fig. 2 shows the effect of efficiency in the environmental performance of the power electronics, for the same three impact categories. This figure shows that the general tendency is positive in regards to an increase in components efficiency, with larger or smaller impact depending on the impact category considered. In the case of climate change, an increase in 5% of the inverter's efficiency can reduce by 50% the total emissions of CO₂-Eq in the life cycle. Similarly, the same increase in efficiency can reduce by 43% the emissions of kg PM10-Eq, and 42% the ones of kg NMVOC. The effect is less significant for the categories of human toxicity and metal depletion.

Human toxicity impact is improved in a smaller degree because it is mainly generated during the manufacturing of the inverter, thus it is independent from improvements in efficiency. The case of metal depletion is similar, as it is mainly generated during manufacturing stage. In both cases, higher efficiency translates into less electricity required for the powering of the vehicle, which is eventually reflected in a reduced need for infrastructure for production and transport of electricity, thus smaller toxicity generated and metals depleted.

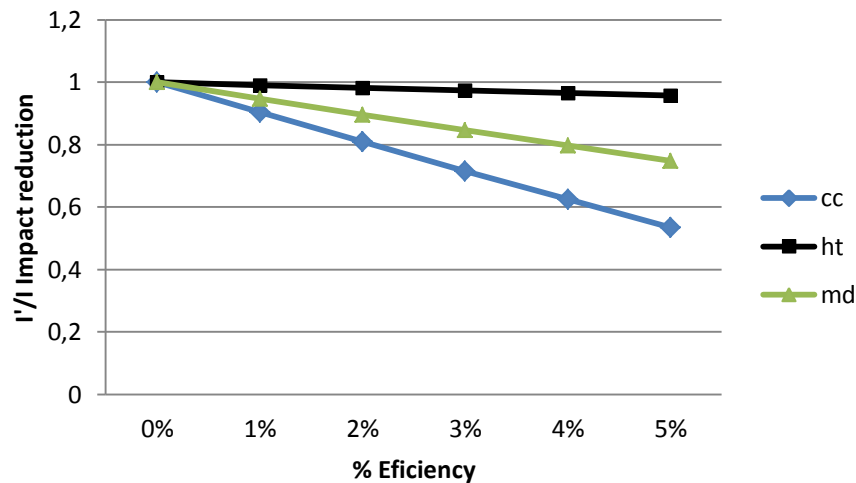


Figure 2. Effect of increasing efficiency versus decrease impact

And alternative to improving efficiency, for achieving better environmental impact, is the replacement of fossil fuels in the production of electricity all along the life cycle. Fig. 3 shows the total impact generated by the inverter, if exclusively wind energy is used for the powering of the vehicle.

For climate change, the reduction of total impact is about 88% comparing to an EU-28 based electricity mix. For impacts in ionizing radiation and photochemical oxidant formation, reductions are expected up to 99% and 98% respectively. For the large majority of impact categories, replacing a fossil fuel based electricity mix, by renewable energy sources, can potentially reduce pollutant generation during the use stage. The improvement for human toxicity is less evident with a reduction of the total impact of about 5%. In metal depletion, the use of wind energy increases the total impact by 14%, this is due to additional metal materials for the infrastructure of wind power plants comparing to conventional EU-28 2012 mix electricity.

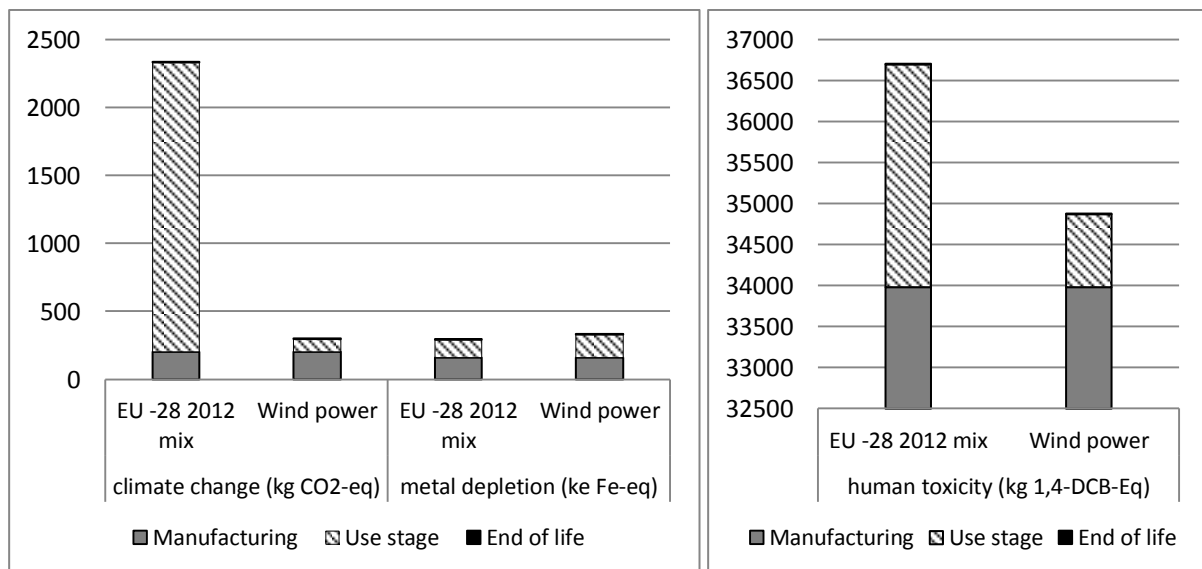


Figure 3. Total environmental impact using EU-28 electricity mix vs wind energy for powering of the vehicle.

A comparison with relevant studies of other powertrain components is performed, in order to add information on the relevance of power inverters manufacturing. For this, the impact category of climate change is selected. The studies of Notter et al. [9] and Majeau-Bettez et al. [8] are identified to benchmark the results obtained, for the manufacturing of Li-ion batteries for EV applications. The comparison shows that the manufacturing of the inverter contributes to 0,9 g CO₂-eq/km, whereas the manufacturing of a Li-ion battery emits about 7 and 12 g CO₂-eq/km, as reported by [8] and [9], respectively. When comparing against the electric motor manufacturing, Hernandez et al. [18] report an emission of 1,1 g CO₂-eq/km. This brief benchmarking suggest that the battery manufacturing has the largest contribution to climate change impact among powertrain components, while the electric motor and power electronics generates a lesser environmental impact. This result can be expected given the mass, and thus amount of materials and energy, required for the manufacturing of a traction battery comparing to the smaller power electronics and motor.

4. Conclusions

This paper presents a LCA study of a state of the art inverter for powertrain in a hatchback rear axle driving electric. Three impact categories selected, climate change, human toxicity and metal depletion, show the impact generated by the inverter and the effect of efficiency improvements over the total environmental performance of the vehicle.

According to the results obtained, the use stage of the electronic components is the largest contributor to total impact. This impact depends on the efficiency of the motor and the presence of fossil fuels in the electricity mix powering the vehicle. Both improvements in the efficiency, and replacements in the electricity mix by renewable energy sources, have an important potential to reduce the total impact created.

Electricity consumption is also identified as problematic in the manufacturing of the components in the inverter. In spite of the relative small mass of the components, their manufacturing is very energy intensive, generating high amounts of emissions and depletion of energetic and metal resources. The use of precious metals and materials such as palladium, tantalum and copper is also identified as problematic in the manufacturing of the inverter component parts. In order to improve the environmental profile of the inverter, the amount of these metals used, particularly in bigger size components, should be reduced as much as possible.

Further recycling of electronic components can also improve significantly total inverter impact, by decreasing the need for processes of raw materials extraction, and refinement in the next product system.

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