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Resource depletion in an electric vehicle powertrain using different LCA impact methods

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ABSTRACT

The growing demand for electric vehicles entails an increased consumption of critical energetic and non-energetic abiotic resources, necessary for an optimal performance of the vehicle. The depletion of these resources and the future availability to meet their demand appears to be a potential limitation for the expansion of the electrified vehicle industry. The goal of this study is to perform a detailed life cycle analysis, including manufacturing, use and disposal, of key components of EV powertrains, identifying materials and processes responsible for abiotic depletion impact. This study also investigates the sensitivity of the results to the choice of Life Cycle Assessment (LCA) impact methods. For this, a LCA is performed on an integrated electric drive, by considering seven impact methods. Results show that energetic resources consumption generate the largest impact, followed by metals and lastly by mineral resources. The consumption of electricity in each life cycle is a crucial factor in the generation of total impact. There are agreements among methods on the materials and processes contributing the most to depletion, given the differences in approach used by each impact method.

1. Introduction

The availability of energetic and non-energetic resources is essential in modern society. The proper functioning of technology and industrial activities often relies on specific and irreplaceable resources, and in some cases, specific business sectors depend entirely on their supply.

Such is the case of abiotic resources and the industry of electrified vehicles. The advantageous properties of particular resources, i.e lithium for battery energy storage, rare earth metals in the magnets for the electric motor, and precious metals for power electronics, makes them valuable for the optimal functioning of electric powertrains. As the demand for electrified mobility increases, so it is the demand for these critical materials, potentially reducing their stocks on earth crust to the point where supply becomes limited (Wadia et al., 2011; Kushnir and Sandén, 2012).

Different authors have already addressed this issue, shedding light on the matter of present availability, future demand, and the potential supply-demand imbalance, as per (Alonso et al., 2012; Grosjean et al., 2012; Gruber et al., 2011). A review of key critical raw materials reports for emerging technologies (European Commission, 2014; Fromer et al., 2011; Jin et al., 2016; Moss et al., 2011; U.S. DoE, 2010; WWF, 2014) reveals a consensus on potential limiting resources for the electrified vehicles industry. Here, rare-earth, platinum group and precious metals are frequently identified as critical for the manufacturing of powertrain technology. These studies rely on reserves estimations and models of future supply and demand behaviour, considering all potential end-market actors; however they do not consider consumption of resources required in other life stages of the components, such as their use and disposal, possibly neglecting other critical materials.

Another approach to this issue is adopted by environmental scientists, in the application of the Life Cycle Assessment (LCA) methodology. This methodology estimates the potential environmental impact produced by the extraction of fossils, metals and minerals used in any particular product system along its entire life cycle. LCA allows the calculation of potential impact for a wide

Abbreviations: CExD, cumulative exergy demand; CEENE, cumulative exergy extraction from the natural environment; CF, characterization factor; CML, center for environmental science, University of Leiden Netherlands; ELU, environmental load unit; EoL, end-of-life; EPS, environmental priority strategies in product design; EV, electric vehicle; ILCD, International Reference Life Cycle Data System; ISO, International Organization for Standardization; LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life cycle impact assessment; MSWI, municipal solid waste incineration; PWB, printed wiring boards; UBP, points of environmental burden (Umweltbelastungspunkte).

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range of resources extracted, by multiplying the consumption of the resource (mass) with a characterization factor. The problem of abiotic resources depletion, however, has been interpreted in several ways inside the LCA community, leading to the development of significantly different characterization factors for each LCA impact method. Consequently, a user's choices of impact method may over- or deemphasize the depletion impact of a particular resource (Rørbech et al., 2014).

A significant number of studies have analysed and compared the various impact methods available, in order to contribute with informed selection, and development of more comprehensive ways to assess resources in LCA, including (Berger and Finkbeiner, 2011; Klinglmair et al., 2014; Rørbech et al., 2014; Swart and Dewulf, 2013; Vadenbo et al., 2014; Van Caneghem et al., 2010). The wide majority of these studies state that there is no one single method that can be applicable to all case studies, but rather that there are advantages and disadvantages to all methods, and thus their selection must be done with care, understanding the approach, assumptions and limitations inherent to each method.

The LCA methodology has been applied in numerous studies focused on electric vehicles and electric vehicle technology. However, as identified by (Nordelof et al., 2014), only a small percent of the studies include any type of assessment specific to the depletion of abiotic resources. Moreover, with the exception of some battery analysis (Majeau-Bettez et al., 2011; Notter et al., 2010), these studies are not focused on the powertrain components, but rather on the vehicle as a whole. Some papers, such as (Lewis et al., 2014), have looked at the reduction of mass, at vehicle and powertrain level, and have proved positive the replacement of materials, in this case steel by aluminum, to reduce life cycle greenhouse emissions and energy consumed. As pointed out by (Hawkins et al., 2012), there are few LCA studies analysing in detail other key components of the electric vehicles' powertrain. The studies analysing electric motors and power electronics are not focused on the issue of abiotic resources depletion, and they often rely on simplified inventory data, which may not be fully representable of advanced state of the art designs, and may result in misleading findings for impact generated during manufacturing stage. There is a need then for further assessments and inventories with focus on electric motors and power electronics, in order to identify specific hotspots due to resources consumption, along the life cycle of these components.

The aim of this paper is to cover the gap identified in the previous studies, by performing a comprehensive life-cycle assessment for an integral electric drive designed for a hatchback rear axle driving vehicle. For this analysis, detailed primary data is used, identifying specific materials and processes responsible for abiotic resources depletion in the powertrain of electric vehicles. In addition, this paper includes a methodological analysis on life cycle impact methods, to clarify how selecting among the different methods can influence the results to total depletion impact. This study is carried out in the frame of the activities for the EU FP7 project SyrNemo ("www.SyrNemo.com," n.d.) (Gragger et al., 2016), whose aim is to develop an innovative, rare-earth free innovative synchronous reluctance machine with high power density and high driving cycle efficiency, ensuring low environmental impact throughout its life cycle.

The results focus on abiotic resource depletion hotspots for electric motors and power inverter, and on possible eco-design measures that can be applied to decrease their environmental footprint.

2. Methodology

The goal of this study is to perform a complete life-cycle assessment for an integral electric drive with a focus on abiotic resources depletion. The study aims at comparing the results from the traction electric motor and the power inverter, and at evaluating energy efficiencies influence on them. To achieve this, a life cycle assessment (LCA) is performed. The assessment is conducted according to ISO 14040 ("I.S. ISO 14040 – Environmental Management – Life Cycle Assessment – Principles and Frameworks.," 2006) and 14044 ("I. S. ISO 14044 International Standard assessment—Requirements and guidelines.," 2006) standards, and the International Reference Life Cycle Data System (ILCD handbook)—General guide for life cycle assessment (JRC European commission, 2011).

Table 1
Materials in the electric motor.

Materials	Mass	Unit
Electrical steel	25	kg
Other steel	2	kg
Aluminium	24	kg
Copper	7	kg
Insulation materials	0,5	kg
Impregnation resin	1	kg
Plastic	0,5	kg
Ferrite magnets	2	kg
Total	63	kg

Energetic resources are considered: fossil fuels (coal, gas and oil), as well as non-energetic resources: metals and minerals, and their impact to total abiotic depletion is estimated by the use of a selected number of widely applied impact assessment methods.

The system under study includes a ferrite permanent magnet assisted synchronous reluctance machine, and an integrated inverter, designed for an a/b-segment electric vehicle application. The motor provides a maximum torque performance of 133 Nm at 3700 rpm and a maximum power of 56.7 kW at 4900 rpm, with peak efficiency above 96%. The inverter offers maximum power of 70 kW, and the combined efficiency of motor and inverter reaches 93–94%. The integrated machine is designed to be used in a small size fully electric vehicle or be implemented in a medium size hybrid vehicle. For a 200 km electric range, the vehicle would require a battery with 25 kWh capacity, based on a lithium iron phosphate chemistry.

A functional unit of 1 kW has been defined for the study. The components service life is equal to 10 years, with no maintenance expected during this time. It is also considered that, while driving under standard European conditions, the components will work for 219,000 km during their lifetime (Pasaoglu et al., 2012).

2.1. Boundaries and data sources

The assessment will be performed on an integrated design of inverter and synchronous reluctance electric motor, designed for a hatchback rear axle driving vehicle. The life cycle stages considered in this study are production, use, and end-of-life. In the powertrain, the battery, DC/DC converter for auxiliary power and the transmission are not considered in the assessment, as no primary data is available. The assessment includes the life cycle stages of production, use, and end of life for electric motor and inverter. Specific geographical locations are not defined, consequently transportation of the assembled components to the users, and the collection of the components from the users to the recycling and disposal centres are not included in the assessment.

A detailed bill of materials is obtained from the designers and manufactures of the integrated drive, taking part inside the SyrNemo project (Gragger et al., 2016). Due to confidentiality agreements with project partners, this detailed bill of materials is not presented. Instead a simplified bill of materials for the manufacturing of the electric motor and power inverter is shown in Tables 1 and 2, as guidance for the reader.