The 22nd CIRP conference on Life Cycle Engineering

Life Cycle Assessment of Electric Vehicles – A Framework to Consider Influencing Factors

Patricia Egede\textsuperscript{a,c*}, Tina Dettmer\textsuperscript{a,c}, Christoph Herrmann\textsuperscript{a,c}, Sami Karab\textsuperscript{b,c}

\textsuperscript{a}Chair of Sustainable Manufacturing & Life Cycle Engineering, Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, Langer Kamp 196, 38106 Braunschweig, Germany

\textsuperscript{b}Sustainable Manufacturing & Life Cycle Engineering Research Group, School of Mechanical & Manufacturing Engineering, The University of New South Wales, Sydney, NSW 2052 Australia

\textsuperscript{c}Joint German-Australian Research Group on Sustainable Manufacturing and Life Cycle Engineering

* Corresponding author. Tel.: +49-531-391-7145; fax: +49-531-391-5842. E-mail address: P.Egede@tu-braunschweig.de

Abstract

The environmental impacts of electric vehicles (EVs) partially depend on the parameters of their site of operation. Variations of average driving patterns in different geographic locations and the use of heating and cooling due to local climate conditions have an impact on the energy consumption of EVs. In combination with the regional electricity mix these factors influence the environmental impact of EVs. Hence, these influencing factors must be included in an ecological assessment. The Life Cycle Assessment (LCA) method is used for the quantitative ecological assessment. An LCA can e.g. serve as a decisions support tool in vehicle engineering. This paper proposes a framework to consider influencing factors for the ecological assessment of EVs. A case study is used to demonstrate the capability of the framework.

© 2015 The Authors. Published by Elsevier B.V. Peer-review under responsibility of the International Scientific Committee of the Conference "22nd CIRP conference on Life Cycle Engineering.

Keywords: Life Cycle Assessment; Electric Vehicles, Framework, User-specific, Regional

1. Introduction

Motorized vehicles have a significant impact on the global greenhouse gas emissions. One option to reduce the environmental impact is electric vehicles (EVs). Like all reduction measures the implementation of EVs must be evaluated carefully to avoid problem shifting or rebound effects. Mostly Life Cycle Assessment (LCA) is used to quantify the environmental impact along the entire life cycle from raw material extraction to the end-of-life. However, calculating the environmental impact with LCAs for EVs is challenging. Results from different EV studies vary greatly [1]. With these results it is possible to derive general conclusion (e.g. “EVs can have lower environmental impacts than conventional vehicles.”). Yet, more specific questions are more challenging to answer. It is difficult to determine for which situations and under which conditions these conclusions apply. This makes it challenging to base decisions on these results and to answer specific questions (e.g. “How long is the ecological amortisation time for lightweight materials for a specific market?”).

One reason for the difficulty of the calculation and the variability of results is the lack of transparency of the influencing factors of the LCA of EVs. The electricity mix, use patterns and the material composition of the vehicles are examples for important influencing factors of LCA results of EVs. Usually the LCA practitioner does not have access to primary data from the entire life cycle of the EV. Different stakeholders are involved in the making, the use and the disposal of the vehicle, which disperse the required information over the entire supply chain and over time. Confidentiality issues, complex supply chains, a variety of possible use patterns and unknown future developments increase the challenge of gathering the required data and interdependencies, hence carrying out an LCA of an EV.
2. Electric Vehicles and Life Cycle Assessment

2.1. Electric Vehicles

The term EV covers a range of vehicles types, e.g. hybrid EVs and battery EVs. Hybrids have an electric and a combustion engine. Depending on the type of hybrid the vehicle can be charged from the grid such as Plug-In Hybrids. This paper focuses on battery EVs which have an electric motor and a battery which is charged externally (besides recuperation). [1], [2] EVs are seen as an option to reduce or eliminate the downsides of using today’s fossil fueled vehicles. Their characteristics offer advantages which solve problems caused by conventional vehicles. These are the independence from fossil fuels, the reduction of noise and the elimination of tail pipe emissions. [3], [4] Their ability to run on many types of energy sources via electricity storage in batteries provides the opportunity for fossil fuel free mobility. The use of EVs causes hardly any local emissions and causes little noise. In mega cities which suffer from severe air pollution and high noise levels these advantages are very valuable. The disadvantages of EVs are mainly associated with the driving range and the cost of the vehicles. [3], [4] Another concern is the change of use of resources in comparison to conventional vehicles due to use of Lithium-Ion batteries and electric engines with permanent magnets. This leads to a more intense use of metals like lithium, manganese or cobalt as well as rare earth metals like neodymium. [2], [15] Currently, the driving range of EVs is significantly lower than for conventional vehicles. Even though this range is sufficient for the majority of daily travel needs, many customers judge the driving range of EVs as not sufficient. In addition the use of heating and cooling devices can reduce the range significantly as these auxiliaries are very energy intensive. The purchase price of EVs is higher than for conventional vehicles of comparable size. However, despite of their disadvantages EVs are successful even in places with conditions which could be considered unfavourable. An example is Norway which has a climate that requires intensive heating which reduces the range. However, due to incentives offered such as tax reductions and a municipal charging infrastructure, EVs have been adopted very well in the Scandinavian countries. [5]

As seen in figure 1 a high share of the environmental impact of the EV occurs in the use phase and is directly linked to the energy consumption during usage in combination with the energy mix. The energy consumption of EVs depends on different parameters which can be divided into three groups: driving resistances, the use of auxiliaries and losses. Driving resistances must be overcome to achieve and maintain a certain velocity. Examples are the rolling, acceleration and aerodynamic resistance. Vehicle characteristics like weight and the frontal area influence the resistances. In addition the use of auxiliaries such as heating, air conditioning and ventilation increase the energy consumption. Also losses occur in the process of converting electric energy into mechanical energy due to the efficiencies of the different components. [6], [7]
2.2. Life Cycle Assessment

In order to identify the environmental impact of EVs, the mass and energy fluxes of the respective product systems need to be compared throughout their life cycles using the LCA methodology according to ISO 14040 [8]. LCA has proven to be a useful method for analysing and quantifying the environmental impacts of products. It became generally accepted in the last two decades and is internationally approved and standardised (ISO 14040 [8], ISO 14044 [9]).

The LCA procedure consists of four successive steps: the goal and scope definition, the inventory analysis, the impact assessment and the interpretation of the results. The procedure has to be understood as an iterative process rather than one exercise. For instance intermediate results obtained from the inventory analysis, impact assessment and interpretation may require a modification of the goal and scope definition.

During goal and scope definition, the intended application (i.e. the questions to be answered by the study), the motivation for carrying out the study and the intended audience have to be defined (ISO 14040 [8]). Furthermore, the product system under study needs to be clearly described including system boundaries and functional unit (the quantified performance of the system). Furthermore, a number of additional methodological details and choices have to be documented for transparency reasons.

Life Cycle Inventory Analysis aims at understanding and accounting for input and output flows within the observed system and its interaction with the environment (elementary flows). Petri-net based material flow nets can help to finally calculate all incoming and outgoing flows crossing the system boundaries. This input-output balance referenced to the functional unit is called a Life Cycle Inventory.

Based on the Life Cycle Inventory, the potential environmental impacts resulting from extracted resources and from emitted pollutants are determined during Life Cycle Impact Assessment. First, emissions are classified according to their contribution to the different impact categories. Second, their potential contribution is expressed in terms of impact equivalents, e.g. in CO2-equivalents (CO2-eq) for climate change.

In the interpretation phase, results of the study are plotted to present the significant issues. Additionally, the reliability of the study is scrutinized in sensitivity and uncertainty analyses complemented by consistency and completeness checks. Finally, recommendations are derived based on the findings of the study.

2.3. Life Cycle Assessment of Electric Vehicles

As complexity of a product have a significant impact on the complexity of the respective LCA study, LCA on EVs are a challenging task. In recent years, a number of LCAs have been published on EVs (e.g. [2], [10], [11], [12], [13]) or EV specific components like Li-ion batteries (e.g. [12], [14], [15], [16], [17]). Hawkins et al. [2] as well as Nordelöf et al. [1] provided comprehensive reviews on LCAs of EVs. They identified 55 and 79 relevant studies, respectively, including full reports, journal papers and conference papers. They both report widely diverging results which somehow have to be expected for a complex product in an emerging market. The divergence can be further explained by differences in methodological choices and also by unavailability of primary data. The guidelines of the project E-Mobility Life Cycle Assessment Recommendations (eLCAr) [18] aim to harmonise the methodological approach and to enhance transparency of methodological choices.

As modern EVs have been introduced to the market recently and there are plenty of ongoing research activities to further develop the necessary key technologies (e.g. for energy storage), most LCA studies focus on vehicle production and related raw material acquisition. Therefore due to the lack of long-time measurements/monitoring/experiences, only few LCAs address the use phase in particular (i.e. [19], [20]). Use profiles are mainly derived from standard driving cycles and the associated energy consumption is calculated generically as documented, e.g. in the eLCAr guidelines [18]. Modelling of use phase scenarios based on real life data and especially site specific measurements have not been published yet.

3. Framework

The environmental impacts of EVs depend on various parameters related to the vehicle’s characteristics, their location of use and user influences. Variations of driving patterns of different users and the use of heating and cooling due to local climate conditions have an impact on the energy consumption of EVs (see section 2.1.). In combination with the regional electricity mix these parameters influence the environmental impact of EVs. Therefore, the vehicles must be seen as a part of the setting with which it interacts to answer specific LCA questions. When neglecting these interdependencies, important aspects might be missed and left out. Connecting external influences with the use phase of the vehicles assists the LCA practitioner to evaluate the influence of parameters on the environmental impact. Setting up a descriptive framework allows the LCA practitioner to translate external influencing factors into environmental impacts reducing the uncertainty of LCAs.

Figure 2 shows the proposed framework and illustrates the EV as an element in a larger system of influencing factors and highlights the connection of energy consumption and external factors. The material and energy flows over the entire life cycle necessary to manufacture and operate the vehicle define the life cycle of the EV (mid-level). The setting of external factors in which the EV is deployed (top level) influences the life cycle and the LCA results. These external factors can be divided into three groups: the user, the infrastructure and the surrounding conditions. In this paper we focus on the influence of these external factors on the use phase, i.e. the energy consumption. External factors and also internal factors (characteristics of the vehicle like the weight of the vehicle or the size of the frontal area influencing the aerodynamic resistance) affect the energy consumption in the use phase (bottom level).
3.1. Influencing factor: Vehicle

In the use phase specific characteristics of the vehicle influence the energy consumption (as described in part 2.1). These factors are considered internal in this framework as they are inherent properties of the vehicle.

3.2. Influencing factor: User

The user of the EV influences the environmental impact of the EV through the driving and charging behaviour as well as through the intensity of the use of auxiliaries. A more aggressive driving style leads to a higher energy consumption whereas a more cautious driving style results in a more efficient use of energy. Depending on the charging behaviour and the willingness to install renewable energy specifically for the EV (e.g. in the form of solar panels), the share of renewable energy can be increased significantly compared to the use of grid energy in many countries. Finally, the use of heating and cooling to achieve the desired temperature has a significant influence on the energy consumption. The willingness to accept a warmer vehicle temperature in the summer and a cooler temperature in the winter is directly linked to a lower environmental impact.

3.3. Influencing factor: Infrastructure

The electricity mix is one of the most crucial parameters for the LCA calculation. Using a mix based entirely on renewable energies delivers a completely different result than an energy mix based on fossil fuels. Choosing the adequate mix which reflects the real world situation and leads to fair and reliable results is challenging. [18] In many LCAs an energy mix is used which is based entirely on renewable energy. However, often it is not clear if this represents the actual grid situation or if it is a case of crediting renewable energy to the EV rather than a different use. In the latter case it must be considered if the crediting can be justified. The charging of EVs can in principle often be carried out at regular household plugs. Yet, often more sophisticated solutions are required at workplaces or in public areas to allow adequate and safe charging. Depending on the conditions of the site the installation of these charging stations demands major building activities. These activities can be significant for specific scenarios in which only one or a few vehicles use one charging station. The available charging infrastructure also influences the options of smart charging. Smart charging applications can increase the share of renewable energy used to charge the EV.

3.4. Influencing factor: Surrounding conditions

The surrounding conditions influence the environmental impact of EVs. The climate, the topography and the type of road are identified as significant factors for the energy consumption. The climate influences the need for heating and cooling appliances in the vehicle. The temperature varies both on a seasonal as well as on a daily level leading to a fluctuation of the energy consumption. Depending on the interaction of temperature and humidity the wind shield of the car can fog up and require ventilation or the use of the air conditioning and/or heating. Currently, resistance heating is mostly applied in EVs. Alternative technologies like a heat pump can reduce the energy consumption for heating. A flat topography leads to a lower energy demand, than a hilly landscape. It is important also to consider the breaking recuperation when calculating the energy consumption. The type of road such as city streets or highways, define parameters such as the speed limit and the frequency of stops e.g. at traffic lights. These parameters influence the consumption.

3.5. Fields of application of framework

The framework serves as a support for LCA practitioners by providing the necessary technical background on EVs. It can be applied to various LCA studies. The influencing factors have to be discussed in the goal and scope section of...
the study. Examples for possible areas are comparative assessments with other vehicle technologies and design decisions. EVs compete with conventional vehicles as well as vehicles with other alternative propulsion systems or fuels. Analyzing the environmental impact in detail helps to identify use cases and regions for which EVs are particularly useful. This can allow policy makers or consumers to make robust choices in increasingly diverse markets. Another decision context is a design choice for EVs. When evaluating design alternatives influencing factors can be significant for the environmental sensitivity. Problem shifting can occur from one phase to another or from one vehicle component to another. To evaluate the possible environmental benefit of design options a detailed analysis of the entire system and its parameters is necessary to ensure robust results. This is relevant for automotive manufacturers and their suppliers.

4. Case Study

The following case study shows the relevance of the framework. The goal of the case study is to determine if and how influencing factors impact the comparison of different EV. A lightweight vehicle is evaluated with regard to its ability to reduce the overall global warming potential (GWP) in a range of countries with differing electricity mixes. The results of Germany, Brazil and Spain are discussed in detail. The purpose of using lightweight materials is to reduce the car weight and consequently the energy consumption in the use phase and/or to increase the driving range with the same battery size. However, the use of lightweight materials usually comes with higher environmental impacts during the raw material and manufacturing phase compared to traditional materials. The end-of-life phase is not considered for reasons of clarity. Two vehicles are compared, one with a steel and another with an aluminium chassis. To evaluate the impact of the influencing factors three scenarios with differing external factors are defined. The internal influencing factor vehicle lifetime is analyzed by calculating results for driving distances of 100,000 km, 150,000 km and 200,000 km.

The case study is performed as a delta analysis. The relevant figures for the analysis are the weight reduction of the aluminium vehicle and the CO2-eq of the material supply of steel and aluminium. Following the LCA of Das [22] the aluminium chassis achieves a weight reduction of 67%. The CO2-eq/kg of steel is fixed as 5.7 based on [23] and the Ecoinvent 3.01 database. [24] Ehrenberger et al. [25] show the range of CO2-eq for primary aluminium production. Based on this review and Das [22] the CO2-eq for aluminium is set as 13 CO2-eq/kg. The CO2-eq of the electricity mixes of 71 countries (and regions) are extracted from Ecoinvent 3.01. [24]

4.1. Scenario descriptions of external factors

Three scenarios of external influencing factors are defined for which the energy consumption is determined. Four different influencing factors are considered: Driving behaviour, desired temperature (both influencing factor user), topography (influencing factor surrounding conditions) and type of road (influencing factor infrastructure). Table 1 shows the influencing factors and their specification for each scenario. Scenario A depicts a rather cautious driver who moves around in a flat city area. The need for heating and air conditioning is low. The scenario characteristics result in a rather low average velocity. Summed up, the average consumption is therefore small at around 10 kWh/100km. Scenario B shows a driver with an average driving behaviour who mostly drives in a hilly city area. The requirement of heating and cooling is medium. The scenario characteristics result in a medium average velocity. Altogether, the average consumption is therefore medium at around 15 kWh/100km. Scenario C describes a dynamic driver travelling on highways in a hilly area. The demand for heating and cooling is high. The scenario characteristics result in a rather high average velocity. As a consequence of these characteristics, the average consumption is therefore high at around 20 kWh/100km.

Table 1: Description of scenarios A, B and C

| Influencing factor            | Scenario A | Scenario B | Scenario C |
|------------------------------|------------|------------|------------|
| Driving behaviour            | Cautious   | Average    | Dynamic    |
| Desired temperature          | Low        | Medium     | Medium     |
| Topography                   | Flat       | Hilly      | Hilly      |
| Type of road                 | City       | City       | Highway    |
| Energy consumption [kWh/100km]| -10        | -15        | -20        |

4.2. Results

The results of the case study are presented in figure 3. The chart shows for which number of countries the material choice steel has a lower environmental impact than aluminium (blue bars) and vice versa (orange bars). The three scenarios A, B and C are calculated for the three lifetime expectancies of the vehicles. The comparison of the scenarios reveals that the lower environmental impact of one material in comparison to another depends not only on the electricity mix but also on the energy consumption in the use phase. For the medium life time expectancy the advantageousness switches in 17 countries from steel to aluminium as the consumption increases. With a shorter life span of the vehicle the number increases to 36. In the last example with the longest life span the result changes for 11 countries. As the life time of the vehicle increases the differences between the scenarios A, B and C diminish. Eventually the higher impact of the production of the aluminium pays off regardless of the energy consumption per kilometre. The lightweight design becomes more and more relevant as the vehicle is used longer and longer.

For the countries Brazil, Germany and Spain the results are is exemplified. Brazil has an energy mix with rather low CO2 emissions as it is mainly based on hydro power. Germany has an energy mix with medium CO2 emissions with a rather diverse mix of energy sources. The CO2 emissions of the Spanish energy mix lie in between the other two countries. In Brazil the material choice of steel causes lower emissions than the choice of aluminium. Only in the case of a 200,000 km...
driving distance and a high consumption in scenario C the choice of aluminium pays off. For Germany, the opposite is the case. Aluminium is the better choice except for the case of a low consumption (Scenario A) and a short driving distance (100,000 km). In the case of Spain, the result is not as clear. For a long driving distance the choice of aluminium pays off. In the other two cases of medium and low driving distances (150,000 km and 100,000 km) aluminium only pays off for a high consumption (Scenario C) or for a medium and high consumption (Scenarios B and C). It becomes clear that the external factors can influence whether a material choice pays off in a specific country or not. Considering average values for the consumption can lead to misleading results of a study. Sensitivity analysis can reveal the robustness of results. However, including external factors systematically can help to reduce the uncertainty of the use phase by narrowing down the possible energy consumption and increase the reliability of LCAs for EVs.

Summary and Outlook

This paper presents a framework for the LCA of EVs to consider influencing factors of the use phase. The vehicle was identified as an internal factor; the user, infrastructure and surrounding conditions were defined as external factors. In a case study the relevance of the identified factors was shown. The advantageousness of an aluminium lightweight design changed for a number of countries depending on the parameter value of the influencing external factors and the resulting energy consumption per kilometre. Following the approach of the framework, e.g. car manufacturers could more precisely define design strategies for their different target markets and governments could include their countries’ characteristic to environmentally meaningful tailor respective regulation and policies.

The necessity to include or exclude these influencing factors in an LCA study depends on the defined goal and scope. Improvements of the framework can be achieved by determining quantitative relations between the influencing factors and the energy consumption. Furthermore, the impact of the external factors on the remaining life cycle phases can be analyzed.

References

[1] Nordelöf A, Messagie M, Tillman, AM, Ljunggren Söderman M, van Mierlo J. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int J Life Cycle Assess 2014;19:1866–1890.
[2] Hawkins TR, Singh B, Majeau-Bettez G, Stromman AH. Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 2013;17(1):53–64.
[3] Kampker A, Vallée D, Schnettler A. Elektromobilität – Grundlagen einer Zukunftstechnologie. Berlin-Heidelberg, Springer Vieweg; 2013.
[4] Betram M, Rongard S. Elektromobilität im motorisierten Individualverkehr – Grundlagen, Einflussfaktoren und Wirtschaftlichkeitsvergleich. Wiesbaden, Springer Vieweg; 2014.
[5] EV Norway, http://www.evnorway.no/, Last accessed Nov-13-2014.
[6] Ayoubi M, Eilemann A, Mankau H, Pantow E, Repmann C, Seiffert U, Wawzycki M, Wiebelt A. Fahrzeugphysik. In: Braess HH, Seiffert U, editors. Vieweg Handbuch Kraftfahrzeugtechnik. Wiesbaden: Springer; 2013;47:118.
[7] Küçükay F. Low Energy and CO2 Vehicle, Hybrid and Electric Vehicle , 1st Symposium, Braunschweig, 2014.9-45.
[8] ISO 14040:2009-11 Environmental management – Life cycle assessment – Principles and framework, 2009.
[9] ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines, 2006.
[10] Faria R, Moura P, Delgado J, de Almeida AT. A sustainability assessment of electric vehicles as a personal mobility system. Energy Convers Manag 2012;61:19–30.
[11] Messagie M. Environmental performance of electric vehicles, a life cycle system approach. Thesis for the award of the degree of Doctor in engineering, Vrije Universiteit Brussel, Belgium 2013.
[12] Notter DA, Gauch M, Widmer R, Wäger P, Stamp A, Zah R, Althaus HJ. Contribution of li-ion batteries to the environmental impact of electric vehicles. Environ Sci Technol 2010;44(17):6550–6556.
[13] Samaras C, Meisterling K. Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy. Environ Sci Technol 2008;42(9):3170–3176.
[14] Majeau-Bettez G, Hawkins T, Hammer Stromman A. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. Environ Sci Technol 2011;45(10):4548–4554.
[15] Ellingsen L AW, Majeau-Bettez G, Singh B, Srivastava AK, Valen, LD, Stromman, AH. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. J Ind Ecol 2014;18(1):113–124.
[16] Sullivan JL, Gaines L. Status of life cycle inventories for batteries. Energy Convers Manag 2012.58:134–148.
[17] Zackrisson M, Avellan L, Orlenius J (2010) Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles—critical issues. J Clean Prod 2011;18(15):1517–1527.
[18] Duze AD, Egede P, Öhlschläger G, Dettmer T, Althaus H-J, Butler T, Szczochowicz E e LCar—guidelines for the LCA of electric vehicles. January 31, 2013: Proj.no. 285571. (Report from project “E-Mobility Life Cycle Assessment Recommendations”, funded within the European Union Seventh Framework Programme—FP7/2007-2013).
[19] Faria R, Marques P, Moura P, Freire F, Delgado J, de Almeida AT. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. Renew Sust Energ Rev 2013;24:271–287.
[20] Geyer R, Stoms D, Kallaf J. Spatially-explicit life cycle assessment of sun-to-wheels transportation pathways in the U.S. Environ Sci Technol 2013;47(2):1170–1176.
[21] TLK Thermo, Institut für Werkzeugmaschinen und Fertigungstechnik, 2013.
[22] Das S. Life Cycle Energy and Environmental Assessment of Aluminum-Intensive Vehicle Design, SAE Int. J. Mater. Manf. 2014;7(3):588-595.
[23] Das S. Life cycle assessment of carbon fiber-reinforced polymer composites. Int J Life Cycle Assess 2011;16:268–282.
[24] Ecoinvent 3.01 Database, Swiss Center for Life Cycle Inventories, 2013.
[25] Ehrenberger S. Life Cycle Assessment of Magnesium Components in Vehicle Construction, German Aerospace Centre e.V, 2013.