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Key outcomes from Life Cycle Assessment of vehicles, a state of the art literature review

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Abstract

In this paper, an overview of the main findings in vehicle LCA is performed. This overview covers both methodological issues and results. The main challenges in terms of modelling the vehicle production, the vehicle use phase and the End-of-Life are addressed. For each of these vehicle life cycle phases, the main modelling approaches and data existing in the literature are studied. Finally, a comparison of vehicle LCA results from different sources is performed and the main result trends for different pollutants and/or impact categories are addressed. The paper points opportunities to improve the quality of vehicle-LCA studies.

Keywords: life cycle assessment, environmental impact, well-to-wheel, battery production

1 Introduction

Because of the increasing concern about the environmental burden of passenger transport, several vehicle LCA (life cycle assessment) studies have been performed. According to the goal and scope of these different studies, the LCA can cover a specific vehicle, an average vehicle or different vehicle technologies.

In general all the vehicle LCA studies include the different life cycle phases of a vehicle namely the raw material extraction, the manufacturing, the use, the maintenance, the end-of-life and the intermediate transports between these phases (Figure 1). The paper is structured accordingly and discusses the data and results for vehicle production, the well-to-wheel stage and the life cycle results.

The purpose of this paper is to give an overview of what has been done in the field of LCA on vehicles, exemplified with relevant results. The question is, what can we learn from previous LCA studies? The paper is structured following the life phases included in vehicle LCA.

Battery electric vehicles have a potential to reduce the climate change effect and improve urban air quality when compared with conventional vehicles [1]. However, impacts related to the production of electricity and the additional electric components for the electric powertrain of the vehicle need to be considered [2]. Since there is a concern about the environmental performance of passenger vehicles, several studies have been performed using the LCA (Life Cycle Assessment) methodology. Different results and interpretations are observed in literature when the environmental performances of passenger vehicles are compared.

Some studies promote the usage of battery electric vehicles to reduce environmental impacts and emphasize the importance of the selection of the energy source for electricity production [3]. Others studies focus on points to improve the environmental benefits of BEV [4].

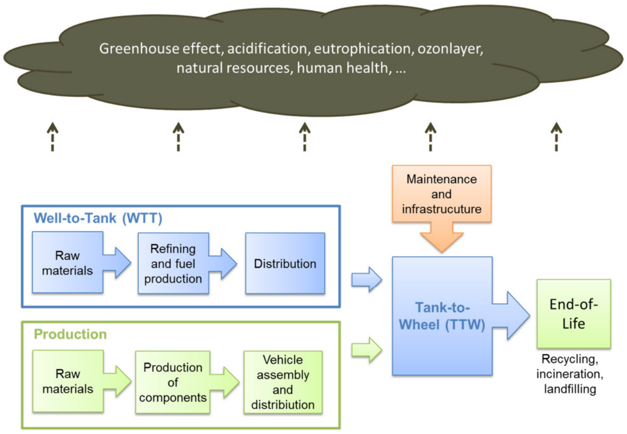


Figure 1: LCA of vehicle and fuels

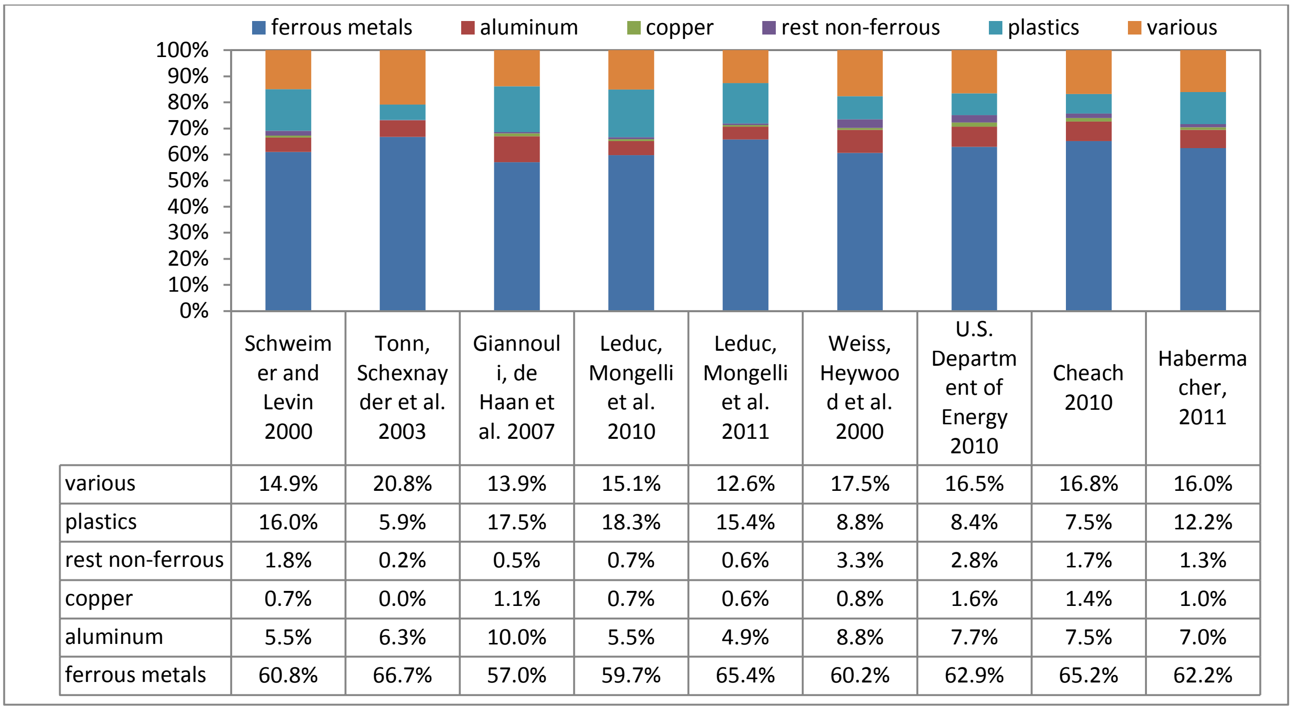
A short list of the main drivers of the environmental performance of a BEV is presented in [5]. The weight of the car, the battery production, the electricity mix, the technological advancements and the societal dynamics are seen as the most important drivers. A review of LCA studies on batteries demonstrates that there is a need for more data on production and material composition of various batteries and especially lithium based chemistries [6]. Depending on the goal and scope definition, the LCA of the various studies covers a specific vehicle, an average vehicle or different vehicle technologies. The selection of the individual vehicles that are compared in the study is from crucial importance and the interpretation of the end result should always take this into account. The various vehicle LCA studies include the life cycle stages of the vehicle, specifically the material production, the component production, the assembly, the usage, the maintenance and the end-of-life treatment are considered. Depending on the research questions and the scope of a particular study, the LCA can be focused to a specific component or life cycle stage.

Studies that are focusing primarily on energy related issues often limit the scope of the assessment to a well-to-wheel analysis, discarding effects during the production of the vehicle and the end-of-life treatment. Assessments with an emphasis on eco-design are often limited to the life cycle of the specific component under investigation, such as assessments of batteries for electric vehicles. An example can be found in [7]. The choices made in the life cycle inventory and the selection of the impact categories have a crucial influence on the interpretation of the end result. The various LCA studies examining the environmental performance of electric and conventional vehicles yield different results. The differences in goal and scope definition of the various studies can explain partly the spread in results. The spread in the result among various vehicle LCA studies can be explained due to the uncertainty in the electricity source, the energy consumption, the battery production and vehicle the production.

1.1 Vehicle production

The modelling of the vehicle production stage is a time consuming task. A life cycle inventory list, containing all materials and production processes, needs to be drawn up. A detailed LCI list of a specific vehicle is of interest for LCA studies, commissioned by the automotive sector, focused on integrating some environmental objectives in the development of a vehicle. According to [8], these environmental objectives can be: the ecodesign of a vehicle optimized for dismantling and recycling, reaching the recycling targets of the European End-of-Life directive of vehicles, the usage of recycled materials and the usage of lightweight materials. Most often the bill-of-material of a specific vehicle is confidential and reserved only for the manufacturer. This data unavailability might be a drawback for LCA studies that are not commissioned by the automotive sector. However, depending on the goal and scope definition of the LCA, other ways exist to model the vehicle production stage. When assessing an extensive vehicle fleet, it is impossible to have a detailed and specific LCI of each vehicle. An alternative way to manage the vehicle production stage is to model an average vehicle. The LCI of the average vehicle is used as a parameter to model the production stage of specific vehicles considering their various weights. The LCI of the average vehicles can be used to model alternative vehicles, such as battery electric vehicles, by modelling separately the manufacturing of specific components (such as batteries, electric motors and power electronics). Fortunately, there are some detailed vehicle LCI lists released by the automotive sector. The LCI of the Volkswagen Golf A4, provided by [9], is a well-known data source and often used in vehicle LCA studies in the EU.

In [9] a full life cycle inventory list is provided about the materials used to produce the Volkswagen car. The Volkswagen golf A4 is composed of 61% ferrous metals, 16% plastics and textiles and 2% non-ferrous metals. Figure 2 is based on the material breakdown found in [10], in which a literature review was conducted based on different studies [9], [11], [12] [13], [14], [15], [16]. The last column gives the average material composition calculated by [10].



	Schweimer and Levin 2000	Tonn, Schexnayder et al. 2003	Giannouli, de Haan et al. 2007	Leduc, Mongelli et al. 2010	Leduc, Mongelli et al. 2011	Weiss, Heywood et al. 2000	U.S. Department of Energy 2010	Cheach 2010	Habermacher, 2011
various	14.9%	20.8%	13.9%	15.1%	12.6%	17.5%	16.5%	16.8%	16.0%
plastics	16.0%	5.9%	17.5%	18.3%	15.4%	8.8%	8.4%	7.5%	12.2%
rest non-ferrous	1.8%	0.2%	0.5%	0.7%	0.6%	3.3%	2.8%	1.7%	1.3%
copper	0.7%	0.0%	1.1%	0.7%	0.6%	0.8%	1.6%	1.4%	1.0%
aluminum	5.5%	6.3%	10.0%	5.5%	4.9%	8.8%	7.7%	7.5%	7.0%
ferrous metals	60.8%	66.7%	57.0%	59.7%	65.4%	60.2%	62.9%	65.2%	62.2%

Figure 2: material breakdown of passenger vehicles in various studies, based on [10]

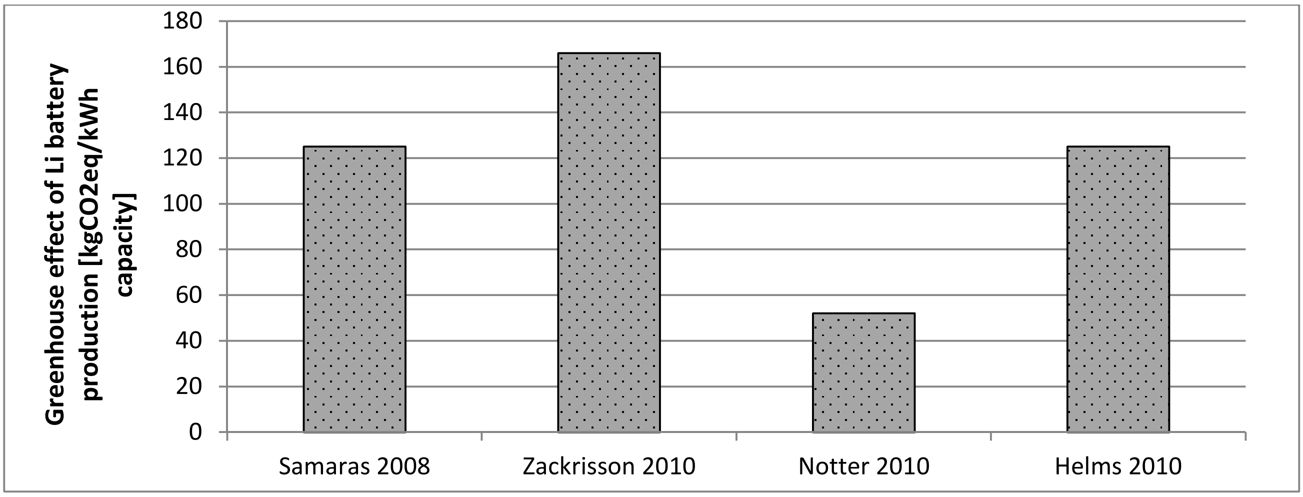


Figure 3: Greenhouse gas emissions related to the production of a lithium battery (kg CO_2 eq. per kWh capacity)

The battery is an important component to consider in the production stage of a battery electric vehicle. Most batteries used in today's electric vehicles are based on lithium chemistries and several papers go deeper in the production of the battery.

Figure 3 shows the climate change effect of the production of a lithium battery for a BEV. The results are in CO_2eq./ kg Li battery. Figure 3 shows the spread in the results of the various battery LCA studies. The results are taken from [17], [18], [7], [19], [20]. The battery LCA study of [19] shows that only 2% of the impact comes from the lithium extraction. The largest environmental impact relates to the production of copper and aluminium. The study from Samaras [20] used the US electricity mix, while the study of Notter [19] used European electricity mix.

1.2 The well-to-wheel stage

The well-to-wheel stage includes the energy consumption during operation and the tailpipe emissions. The driving behaviour varies and influences the emission performance of a vehicle. For European LCA studies the standardized New European Driving Cycle (NEDC) is used. The benefit of the NEDC cycle is that the fuel consumption and the emissions of all passenger vehicles entering the market can be compared mutually. However, the NEDC cycle underestimates the fuel consumption and the CO_2 by 10-20% [21]. To consider real-world driving conditions, the European ARTEMIS driving cycle can be used [22]. The COPERT software allows calculating several tailpipe emissions under real-life conditions. The calculation considers the engine specifications, the year of production of the vehicle, the driving mode (urban, rural and highway), the fuel type and the average speed [23].

The environmental performance of the Well-to-Wheel stage of an electric vehicle depends on the electricity consumption while driving and the type of electricity usage. According to [24], a BEV consumes between 0.11 and 0.20 kWh/km. According to [25], a BEV consumes 0.20 kWh/km of electricity. In [26] it is calculated that a BEV consumes 0.16 kWh/km in 2010, 0.13 kWh/km in 2020 and 0.11 kWh/km in 2030. The environmental performance of an electric vehicle also depends on the energy source that is used to produce the electricity. Depending on the technology and energy source the average CO_2 emissions during operation vary between 950g CO_2eq./kWh for lignite and 350g CO_2eq./kWh for a CCGT (combined cycle gas turbine) using natural gas. Renewable energy sources are assumed to emit no CO_2 emissions during operation [27].

The average CO_2 emissions in the EU is estimated to be 410–443 gCO_2/kWh, according to [24]. Towards 2030 the average emissions are expected to lower to 130 gCO_2/kWh [24]. Combining the electricity consumption with the CO_2 emissions density of electricity, the CO_2 emissions per kilometre are calculated in [27]. The results are given in Figure 4. The CO_2 emissions of the BEV are influenced by the energy source used to produce the electricity. In [27] the results of Figure 4 are benchmarked against an average EU passenger car emitting 160 gCO_2/km, at tailpipe level. The conclusion is that the BEVs powered with electricity from hard coal and lignite have more or less equal emission levels compared to current average conventional vehicles [27].

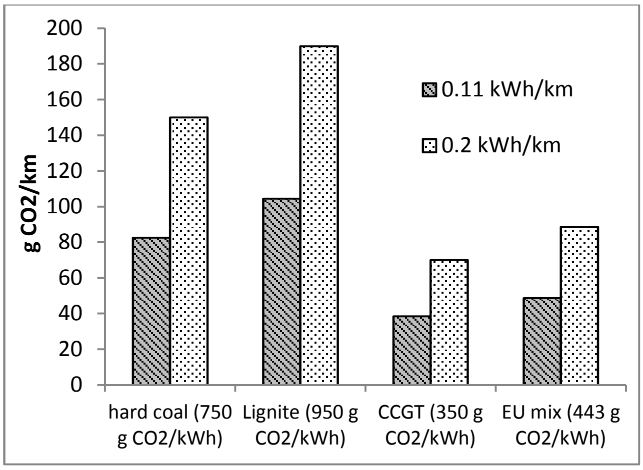


Figure 4: WTW CO_2 emissions for a BEV using various energy sources to produce electricity [27]

1.3 Life cycle results

In publications on vehicle LCA, methodological issues as well as results are discussed. The focus here is on the different results that are available in literature. Throughout the literature, the results are expressed in different units and based on different assumptions. Comparison of the results from different studies is not straightforward and should be interpreted with care. The comparison is only in terms of trends not exact numbers. Table 1 provides an overview of different vehicle LCA studies and their main assumptions of the vehicles on: weight, lifetime performance of the vehicle, battery weight, lifetime performance of the battery, battery chemistry, energy consumption and the energy sources to produce electricity. The description of the assumptions is not always fully documented. Secondly, the assumptions can vary greatly between various studies, leading to varying results. The results for climate change are presented in Table 1.

The selection of the individual vehicles, the energy source to produce the electricity and the lifetime of the vehicle influences the end result. The climate change effect of a BEV in the reviewed literature has a range of 0.04 – 0.32 kg CO_2eq./km. In Figure 5 the impact on climate change is given of a BEV driving on various electricity mixes. However, it must be specified that allocating electricity from coal fully to BEV is an extreme viewpoint and is overestimating the environmental impact of a BEV. Furthermore, it seems that Hawkins [4] is overestimating the environmental impact of a BEV as the electricity consumption is almost 50% higher compared to the NEDC values used in other studies and the critical electronic components are oversized. In Boureima

[28], a range of results is presented taking the market variability into considerations.

The main shortcoming in the reviewed literature is the lack of incorporating uncertainties and market variability. The environmental impacts are shown with single values, which is not a robust description of the end result.

The focus of literature is mostly on CO_2 emissions, while other impact categories are important to investigate. A full life cycle impact assessment should address various impact categories including: Climate change, Ozone Depletion, Terrestrial Acidification, Freshwater eutrophication, Marine eutrophication, Human toxicity, Photochemical oxidant formation, Particle matter formation, Terrestrial ecotoxicity, Marine ecotoxicity, Ionising radiation, Agricultural land occupation, Urban land occupation, Natural land transformation, Water depletion, Mineral resource depletion and Fossil fuel depletion.

Table 1: The main assumptions of various LCA studies dealing with the Climate change effect of a BEV

Author	**Electricity mix**	**Car weight (kg)**	**Lifetime performance car (km)**	**battery weight (kg)**	**Lifetime performance battery (km)**	**Electricity consumption (kWh/100 km)**	**Climate change (kg CO_2eq/km)**
Althaus 2011 [29]	Solar	1230	150000	400	na	20	0.08
	Natural gas						0.17
	Coal						0.32
	Nuclear						0.07
	Swiss mix						0.09
	UCTE mix						0.19
Ecolane 2006 [30]	UK mix	1000	na	na	na	22	0.14
	Renewable						0.04
Helms 2010 [18]	German mix	1600	120000	na	na	25	0.187
	Coal						0.266
	Natural gas						0.162
	Wind						0.058
Simons 2011 [31]	Swiss mix	1530	na	na	na	14	0.108
	UCTE mix						0.192
Hawkins 2012 [4]	EU mix	na	15000	273	150000	28	0.206
Held 2011 [32]	DE mix	1670	171600	400	114400	23	0.24
Lambrecht 2011 [33]	DE mix	na	150000	250	100000	22	0.225
Frischknecht 2011 [5]	Swiss mix	1632	150000	312	75000	20	0.15
Freire 2011 [34]	Portugese mix	1531	200000	329	100000	19	0.165
Boureima 2011 [28]	EU mix	1540	230500	300	160000	0.17	0.097

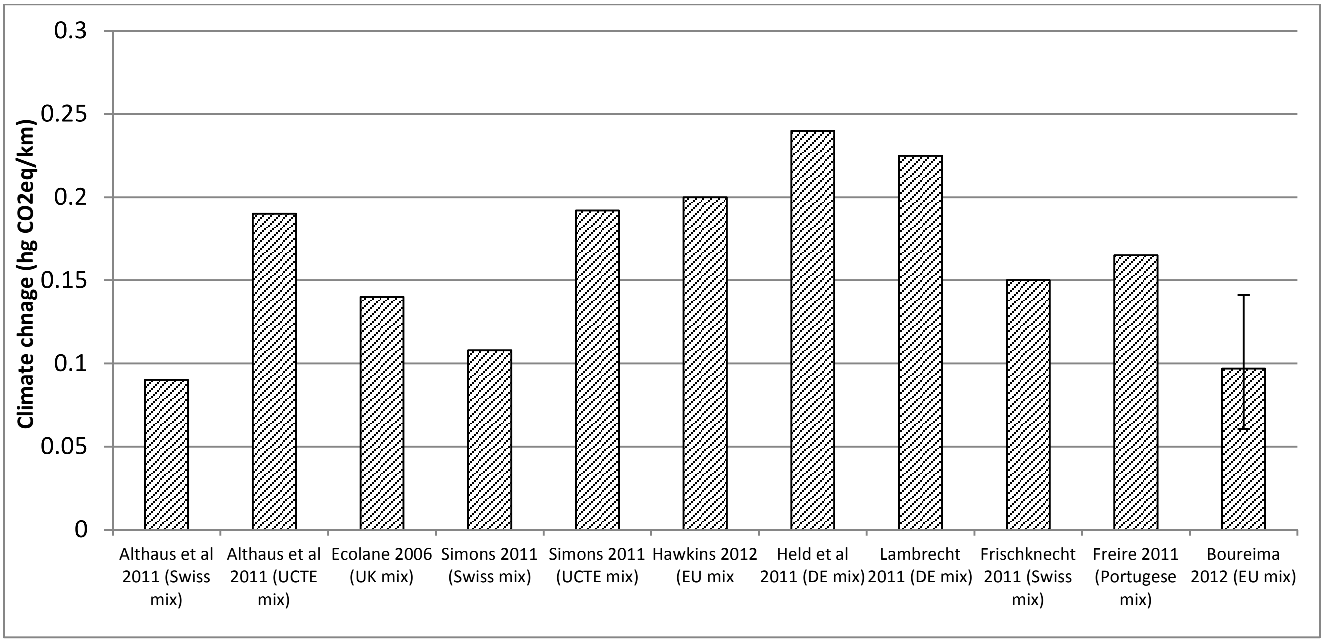


Figure 5: The climate change effect of a BEV various according to different LCA studies

1.4 Conclusions and recommendations

In this paper an overview is given of the results of vehicle LCA studies. The focus is on comparative LCA studies dealing with electric vehicles. The results of various vehicle LCA studies are compared mutually, with respect to the different methodological assumptions and data usage. As shown in the paper, diverging results exist among vehicle LCA studies.

What are the reasons that the results are divergent?

Firstly, the data used for the production of the vehicle, its components and electricity mixes differs among the selected studies, explaining the differences in the end result for a great deal. It is found in literature that the impact of producing a lithium battery varies from 50 to 170 kg CO_2eq./kWh$_{\text{battery capacity}}$. The electricity consumption of the BEV varies from 14 to 25 kWh/100km. The impact of producing one kWh of electricity varies greatly depending on the technology and feedstock.

Secondly, the assumptions taken to model the vehicle’s life cycle differ among the various vehicle LCA studies. Choosing a shorter lifetime of the vehicle increases the importance of the vehicle production stage in the end result. As the battery production has a significant influence on the impact of a BEV, choosing the lifetime of the battery is also of key importance. The temporal and geographical scope of the particular study should be considered when comparing results of various vehicle-LCA studies as this influences the electricity mix that is used. Taking the considerations into account on the data and assumptions we see that the climate change effect of the BEV ranges from 0.04 to 0.32 kg CO_2 eq/km.

The remaining question is: What are the opportunities to improve the quality of vehicle LCA studies? In this last part some recommendations are given for future research on LCA of BEV.

First, LCA of BEV highly depends on the level of detail of the used life cycle inventory (LCI). Therefore, it is of utmost importance to have a detail LCI of all the main components in a battery electric vehicle, including the battery, the power electronics, the electric motor and the charging infrastructure. There are various LCA studies available on automotive lithium batteries with varying levels of detail. However, data is especially lacking on the power electronics, the electric motor and the charging infrastructure.

Secondly, in the future it is expected that impacts related to manufacturing of components of electric vehicles can be improved. An increased scale of production will reduce the price of components such as batteries but will also reduce production efforts. Forthcoming LCA studies on BEV should address futuristic production trends and their opportunities to lower the environmental impact of components.

Thirdly, proper recycling of vehicles and especially of components of electric vehicles should be addressed more in the future in the end-of-life treatment of vehicles. The recycling of lithium batteries of electric vehicles is yet to be proven on a large scale. The final waste treatment of all electronic equipment should be handled with care. The production of print boards and their components containing rare earth materials are adding significantly to the environmental impact of a BEV. A proper waste treatment can help reduce the impacts and the post-BEV usage of lithium batteries should be investigated.

Fourthly, from the literature overview it is clear that the technology and feedstock to produce the electricity highly influences the environmental impact of the BEV. Since the electricity supply mix can vary every hour; the environmental performance of an electric vehicle is influenced by the time the vehicle is charged. Managing the charging period of the electric vehicles could bring extra benefits. Together with a growing share of renewable electricity the impact of a BEV can be further lowered.

Fifthly, when comparing BEV with conventional vehicles the influence of an increasing share of shale oil should be investigated.

Sixthly, a BEV shifts the environmental burden from the TTW stage (in a conventional vehicle) to the manufacturing and the WTT stage. This means that impacts are pushed up-stream processes and in other impact categories compared to climate change. The focus of literature is mostly on CO_2 emissions, while other impact categories are important to investigate. A full life cycle impact assessment should address various impact categories including: Climate change, Ozone Depletion, Terrestrial Acidification, Freshwater eutrophication, Marine eutrophication, Human toxicity, Photochemical oxidant formation, Particle matter formation, Terrestrial ecotoxicity, Marine ecotoxicity, Ionising radiation, Agricultural land occupation, Urban land occupation, Natural land transformation, Water depletion, Mineral resource depletion and Fossil fuel depletion.

Seventhly, the New European Driving Cycle (NEDC) does not resemble real driving conditions. The main European LCA studies on vehicles use the NEDC test to have values for the energy consumption and tailpipe emissions (for the conventional vehicles). The NEDC test mainly underestimates the consumption levels and tailpipe emissions. Prospective vehicle LCA studies should address the difference between the real life values and the NEDC values for energy consumption and tailpipe emissions.

Lastly, the main shortcoming in the reviewed literature is the lack of incorporating uncertainties and market variability. The environmental impacts are shown with single values, which is not a robust description of the end result. This approach approximates the environmental impact of a vehicle, but fails to provide a wider view on the possible effects. The complexity, uncertainty and variability of the system are not well approximated with one single value. Uncertainties are an inherent part of LCA and should not be avoided but embraced and made explicit in the result. Identifying and integrating uncertainties in the result gives a more robust interpretation.

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