Life Cycle Analysis of the Climate Impact of Electric Vehicles

Author: Dr. Maarten Messagie – Vrije Universiteit Brussel - research group MOBI

1. Background and objective

The lifecycle environmental impacts of electric cars are a topic of increasing controversy often originating from biased publications and misused reports. This report considers the life cycle performance of conventional and electric vehicles in Europe.

Life cycle assessment (LCA) is a methodology, commonly used for the environmental assessment of vehicle technologies (or any other product/system). LCA studies consider, all the environmentally significant processes throughout the life cycle of vehicles, from raw material extraction, production of components, assembly, transport, vehicle use to the end-of-life treatment. Since all the life stages are covered from a cradle to grave perspective, LCA prevents problem shifting. However, the key question is how to make robust policy decisions when vehicle-LCA literature consists sometimes of divergent results. To help the debate, the document contains key findings from literature on vehicle-LCA and specific calculations of scenarios in which the influence of the carbon footprint on the performance of electric vehicles in Europe is discussed.

2. Literature review

What are the reasons that the LCA results are divergent? Many LCA studies exist on the vehicle technologies, including battery electric, CNG, FCEV, hybrid electric, etc. However, only a few vehicle-LCA review papers exist. Different results and interpretations are observed in vehicle-LCA literature. The article of Nordelöf investigates the 'lessons learned' from literature and reviews 79 different vehicle LCA papers, reports the main findings and explain the reasons of divergence in literature [1]. The divergence is explained by: (1) variations in systems boundaries, (2) differences in allocated average or marginal electricity mixes and (3) the usage of NEDC or real-life monitored tailpipe emissions for comparisons. Other variations can be explained by: (4) the assumptions of the Life Cycle Inventory of the glider and the lifetime of the vehicle. Choosing a shorter lifetime (e.g. 150,000 instead of 200,000) of the vehicle increases the relative importance of the vehicle production stage. (5) 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 together with the battery chemistry.

One of the most important observations in literature is the variation in system boundaries in LCA, which has a significant impact on the interpretation of the

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[1] Nordelöf, A., Messagie, M., Tillman, A-M., 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? The International Journal of Life Cycle Assessment. 21 Aug 2014

results. On one hand, “well-to-wheel” (WTW) studies cover only the life cycle of the energy carrier (i.e. fuels or electricity) used to drive the vehicles. On the other hand, the “complete LCA” includes the production of the equipment cycle.

From Well-to-Wheel studies we can learn that the **electricity production** and the **degree of electrification** is important. Figure 1 shows the minimum and maximum impact on climate change (in gCO_2/km) that is observed in WTW studies [1].

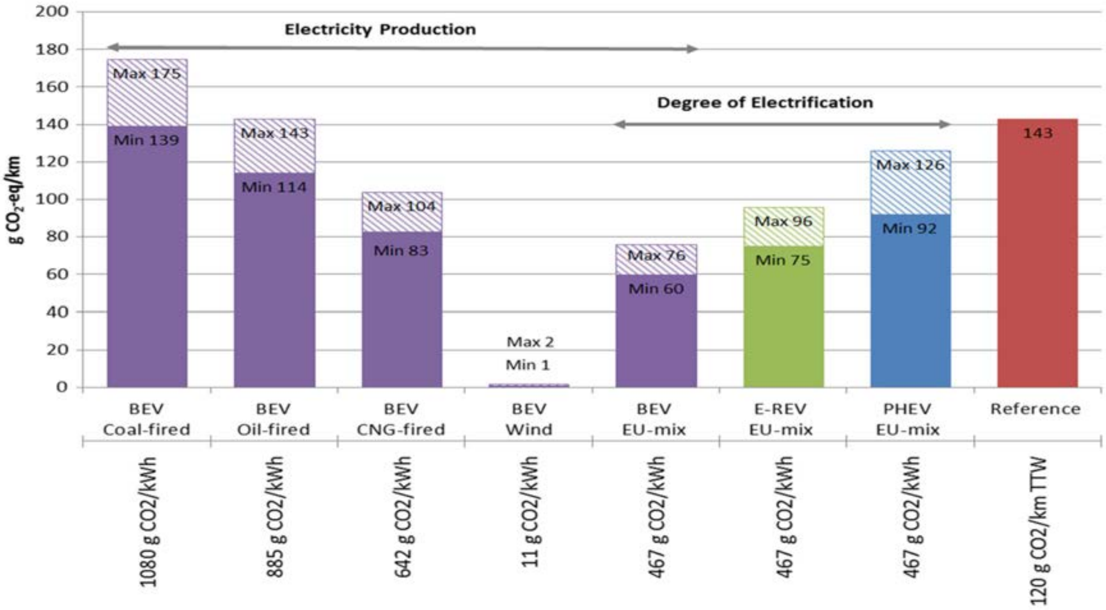

Figure 1 WTW GHG emissions for different electricity production and degrees of electrification [1]

Figure 2 shows an example of such a WTW study, which examines the Greenhouse gas emissions of a conventional petrol vehicle compared to BEV, HEV and PHEV operating in different **traffic conditions**. The results of HEV, PHEV and ICE represent large family cars and the BEV is represented by a small family car. The results for three driving modes, namely city, suburban and highway, are shown. City driving refers to slow driving with many starts and stops in highly congested traffic, which suits perfectly for the Brussels capital region context. Suburban driving refers to a scenario with less congestion, allowing for higher speeds. Apparently, the highway driving refers to high speed driving on the motorways, without any stop. Results clearly show that the electrified vehicles prove to be beneficial for driving in an urban context, where there are many stops, due to traffic and congestion. The benefits of regenerative breaking to recover energy while braking can maximize the energy performance of the BEVs. In addition, at standstill, conventional ICE vehicles keep idling the internal combustion engines whereas battery and hybridized (start stop capabilities) vehicles automatically turn off [2].

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[2] Kobayashi, S., Plotkin, S., Ribeiro, S. Energy efficiency technologies for road vehicles vol. 2, no. 2, p.125–137, 2009

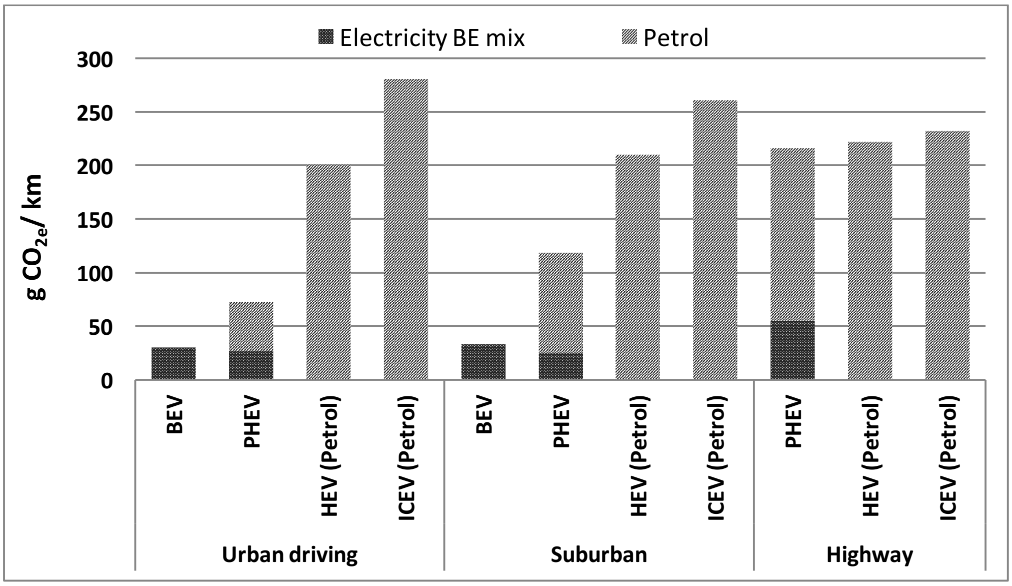

Figure 2 Impact of real world driving and traffic conditions on the WTW environmental performance of vehicles [3] (Data for BEV are obtained from [4])

According to the literature review done by [5], there is compelling evidence that official laboratory tested (NEDC) fuel consumption and CO_2 tailpipe emissions do not correspond well to **real-life driving conditions**. A difference of 30%-40% is reported between official measurements and real-life driving are found for conventional vehicles. Many factors contribute to the differences including: vehicle characteristics (power, configuration, air drag, weight, auxiliaries, tyre pressure), traffic conditions, driving behaviour, altitude, road surface and weather conditions. Emissions from electric cars are highly impacted by the electricity mix and its carbon footprint which is continuously changing in function of the demand supply (in Belgium a factor 2 difference is observed) [6], the charging profile itself can influence the GHG emissions of BEVs [7].

The relevance of the inclusion of the **equipment cycle** (the GHG emissions resulting from the equipment production) is discussed in [1]. This review study reveals that 85% of reviewed articles that included the equipment cycle in the LCA reported that electrification increases the impact of the equipment cycle, of which the battery is the most contributing component. However, all

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[3] Raykin, L., MacLean, H. L., Roorda, M. J. Implications of driving patterns on well-to-wheel performance of plug-in hybrid electric vehicles, vol. 46, no. 11, 2012

[4] Faria, R. , Pedro, M., Moura, P., Freire, F., Delgado, J., Almeida, A. T. Impact of electricity mix and use profile in the life cycle assessment of electric vehicles. Renewable and Sustainable Energy Reviews, vol. 24, pp. 271-287, 2013

[5] Fontaras G., Zacharof N., Ciuffo B. Fuel consumption and CO2 emissions from passenger cars in Europe – Laboratory versus real-world emissions. Prgress in Energy and Combustion Science 60, p97-131, 2015

[6] Messagie, M., Mertens, J., Oliveira, L. M., Rangaraju, S., Coosemans, T. C., Van Mierlo, J.,Macharis, C. The hourly life cycle carbon footprint of electricity generation in Belgium, bringing a temporal resolution in life cycle assessment. Applied Energy. 134, p. 469-476 8 p. 2014

[7] Rangaraju ,S., De Vroey , L., Messagie, M., Mertens, J., Van Mierlo J. Impacts of electricity mix, charging profile, and driving behavior on the emissions performance of battery electric vehicles: A Belgian case study. Applied Energy. http://dx.doi.org/10.1016/j.apenergy. 2015

these studies also reported that the WTW was dominating life cycle stage for the impact. The impact of the equipment cycle is sensitive to the life time driven distance, when it is reported per kilometre. Various studies exist on manufacturing electric vehicles (including the glider and powertrain) [8, 9, 10]. When they would consider a life time driven distance of 150.000 km the GHG of producing the equipment adds to 46-81 g CO_2/km depending on the source. If a longer life time is considered, 250.000 km, the impact of the equipment cycle drops to 28-49 g CO_2/km. 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. An alternative approach, often used in LCA studies, to manage the vehicle production stage is to model an average vehicle. The Life cycle inventory (LCI) of the average vehicle is then 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 [11], is a well-known data source and is often used in older vehicle LCA studies.

In the equipment cycle, it is clear that the production of the lithium battery plays an important role. A large battery LCA review paper [12] reveals that depending on the literature source and chemistry (LFP, LTO, LCO, LMO, NCM, NCA) [13], the impact of producing a lithium battery can vary from 40 to 350 kg CO2/$kWh_{\text{battery capacity}}$, with an average of 110 kg CO2/$_{\text{kWhbattery capacity}}$, see figure 3. A technical review paper discussing these various battery chemistries is to be found in [14].

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[8] Notter, DA., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., H-Jr A. Contribution of li-ion batteries to the environmental impact of electric vehicles. Environ Sci Technol 44(17):6550– 6556 2010

[9] Samaras, C., Meisterling, K. Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy—supporting Online Information. Carnegie Mellon University, Pittsburgh, Pennsylvania, USA. (Supporting Information for Environmental Science & Technology) 2008

[10] Hawkins, TR., Singh, B., Majeau-Bettez, G., Strømman, AH. Corrigendum to: Hawkins, T. R., B. Singh, G. Majeau-Bettez, and A. H. Strømman. 2012. Comparative environmental life cycle as- sessment of conventional and electric vehicles. J Ind Ecol 17(1): 158–160 2013

[11] Schweimer, G., Levin, M. Life cycle inventory for the Golf A4 (internal report), Volkswagen AG. Online available on: http://www.wz.uw.edu.pl/pracownicyFiles/id10927-volkswagen-life-cycle-inventory.pdf

[12] Peters, J., Baumann, M., Zimmermann, B., Braun, J., Weil, M. The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renewable and Sustainable Energy Reviews 67, p. 491-506, 2017

[13] lithium iron phosphate (LFP), lithium titanate oxide (LTO), lithium cobalt oxide (LCO), lithium manganese oxide (LMO), nickel cobalt manganese (NCM), nickel cobalt manganese (NCM), nickel cobalt aluminium (NCA)

[14] Gopalakrishnan, R., Goutam, S., Da Quinta E Costa Neves De Oli, L. M., Timmermans, J-M. P., Omar, N., Messagie, M., . Van Mierlo, J. A Comprehensive Study on Rechargeable Energy Storage Technologies. Journal of Electrochemical Energy Conversion and Storage, 13(4), 040801. [JEECS-16-1121]. DOI: 10.1115/1.4036000. 2017

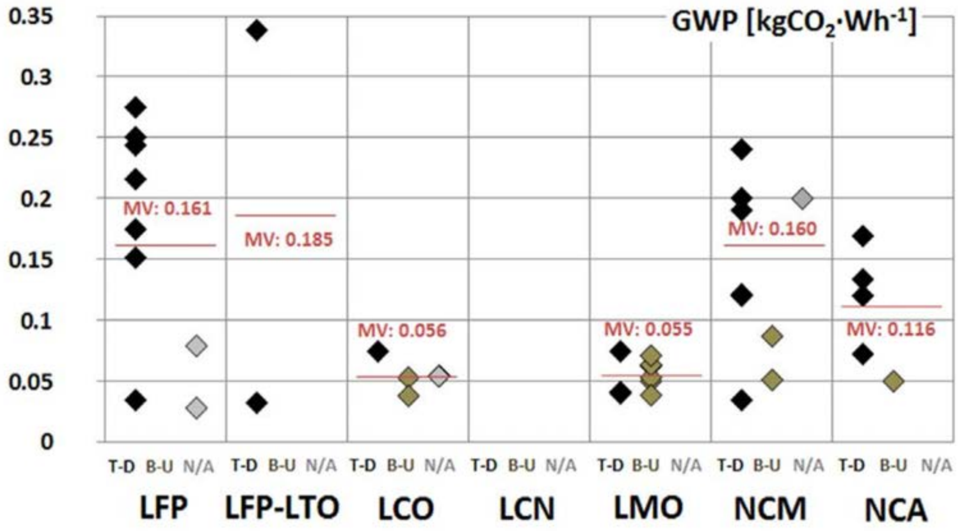

Figure 3: Global Warming potential of manufacturing various Lithium battery chemistries – a review [12]

Although 113 different papers are examined, only seven papers contain original life cycle inventories of batteries as many studies build further on the existing knowledge. To increase the statistical relevance and quality of the LCA of electric vehicles there is a need for more original papers on the LCI of battery chemistries (and especially newer chemistries). The parameters that play a key role in the environmental impact of the production of a 1kWh lithium battery are: cycle life, calendric life, Depth of Discharge (DoD), efficiency and energy density. Table 1 summarizes the key findings.

Table 1: Key parameters influencing the global warming potential of producing various lithium batteries [12]

Average	**LFP**	**LFP-LTO**	**LCO**	**LMO**	**NCM**	**NCA**
cycle life (80%DoD) [cycles]	2575	7917	967	1006	1659	2832
efficiency [%]	92,4	93	91	93	93,8	91,6
energy density [kWh/kg]	0,105	0,07	0,172	0,118	0,135	0,103
Climate change [kgCO2/kWh]	0,161	0,185	0,056	0,055	0,16	0,116

The majority of battery-LCA studies focus on climate change, but other impact categories (mainly toxicity) are also relevant. Toxicity levels are primarily a function of the mining activities of the raw materials and the primary processes. The LFP battery is expected to score best on toxicity, compared to other chemistries, due to the absence of nickel and cobalt, whose mining creates a large environmental burden [15]. Figure 4 summarize literature findings on the toxicity potential of manufacturing lithium batteries [12]. It is expected that in the near future, the usage of materials will be fine-tuned and production processes will be optimised when traction batteries are mass produced, a projection of production optimization and its effects on cost erosion are discussed in [16] and could be seen as exemplary for other impacts. Sales prices of batteries packs are expected to go down to 100$/kWh between 2025 and 2030.

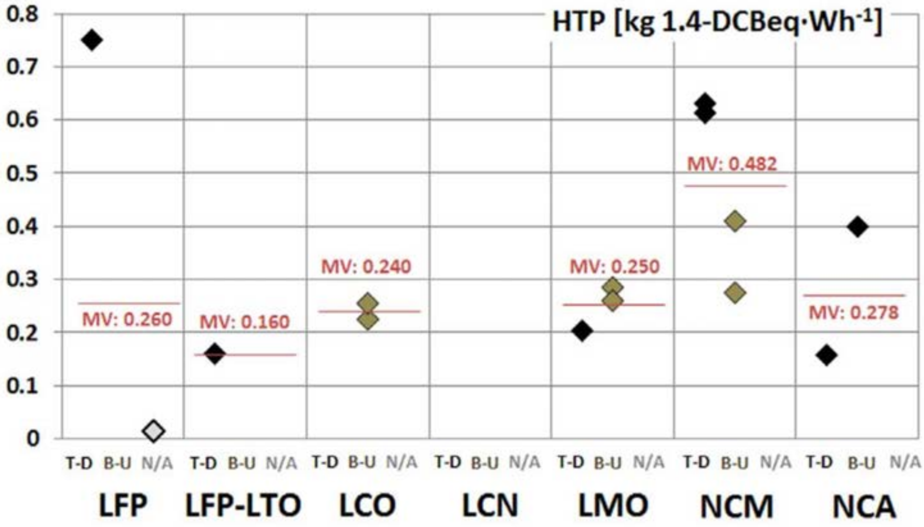

Figure 4: Human Toxicity Potential of manufacturing various Lithium battery chemistries – a review [12]

Urban air quality is a serious problem for human health. As electric vehicles have no tailpipe emissions while driving in a city centre, they have an opportunity to improved local air quality at a level that is impossible for conventional and alternative combustion engines, even with stricter Euro emission regulations. However, to evaluate the toxicity levels it is of importance to include regulated, non-regulated (like polyaromatics and volatile organic compounds, …), exhaust and non-exhaust (like tyre, brake and road abrasion) emissions; their specific chemical composition and fate in a toxicity modelling framework. A calculation of 'Disability adjusted Life years' (Daly) is used in [17] to aggregate the impact of the various chemicals on human health. It is concluded that electric vehicles perform up to eight times better than a recent Euro 6 diesel vehicle when it comes to impact on human health expressed in DALY, even when considering abrasion and emissions from electricity generation.

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[15] Da Quinta E Costa Neves De Oliveira, L. M., Messagie, M., Rangaraju, S., Sanfelix Forner, J. V., Hernandez Rivas, M. & Van Mierlo, J. Key Issues of Lithium-Ion Batteries – From Resource Depletion to Environmental Performance Indicators Journal of Cleaner Production. 108A, p. 354-362 9 p., JCLP5668, 2015

[16] Berckmans, G., Messagie, M., Smekens, J., Omar, N., Vanhaverbeke, L., Van Mierlo, J. Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030. Energies 2017

[17] Hooftman, N., Oliveira, L., Messagie, M., Coosemans, T. C., Van Mierlo, J. Environmental Analysis of Petrol, Diesel and Electric Passenger Cars in a Belgian Urban Setting Energies. 9, 2, 24 p., 84 2016

Often the environmental impact of a vehicle calculated with life cycle assessment is shown as one single value. This approach approximates the environmental impact of one vehicle, but fails to provide decision-makers with a wide view on the possible effects of their decisions. The complexity, uncertainty and variability of the system are not well approximated with one single value. For instance, when choosing one single car and comparing it with another car, the full quality of the comparison falls or stands with the chosen set of vehicles. The variation of one single parameter such as fuel consumption or the weight of a car within one given vehicle technology and segment can lead to different results and interpretations. It is therefore essential to consider the influence of the vehicle parameters on the LCA results. Uncertainty is an inherent part of LCA and should be considered in the end result. Hence, to provide a more robust interpretation on the LCA results of a group of vehicles, a range-based modelling system is developed that include among other sources of uncertainty the market variability of vehicles [18].

3. LCA calculation of different scenarios.

To answer specific questions on LCA of electric vehicles and to consider various scenarios of electricity production, a meta-model has been made combining key parameters and data from literature.

What is the relative importance of the different stages of the life cycle? Figure 5 gives an overview of the life cycle stages of an electric and a conventional vehicle. The complete life cycle of the vehicle summarized into four parts: 1) Well-to-Tank (WTT) stage - the fuel supply chain, 2) Tank-to-Wheel (TTW) - energy conversion in the vehicle, 3) Glider – manufacturing, maintenance and recycling of the vehicle, and 4) the powertrain – manufacturing the motor, battery and electronics. The selected battery electric vehicle emits during a full functional life, half the amount of CO_2 compared to a conventional reference vehicle. Around 70% of the impact of the electric vehicle originates from the production of the electricity (E28 mix of 2015: 300 gCO_2/km), the remaining 30% of the impact is evenly split among the production of the glider (15%) and the lithium battery (around 15%). The impact of the battery production is significant and can be reduced by using cleaner electricity sources. When only renewable electricity (wind energy) is used during the production, the impact lowers to 65% of original impact. Recycling has also an important role to play in reducing impacts of battery manufacturing (when a crediting system is used) as it lowers the usage of primary materials. The production of primary materials is an energy intensive and toxic process, that can be avoided in the future when new batteries use secondary materials obtained from obsolete batteries When

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[18] Messagie, M., Boureima, F-S., Coosemans, T. C., Macharis, C. & Van Mierlo, J. A Range-Based Vehicle Life Cycle Assessment Incorporating Variability in the Environmental Assessment of Different Vehicle Technologies and Fuels. Energies. 7, 3, p. 1467-1482 16 p. 2014

recycling is combined with the usage of renewable energy the GHG emissions during the manufacturing can be reduced towards 35% of the original impact.

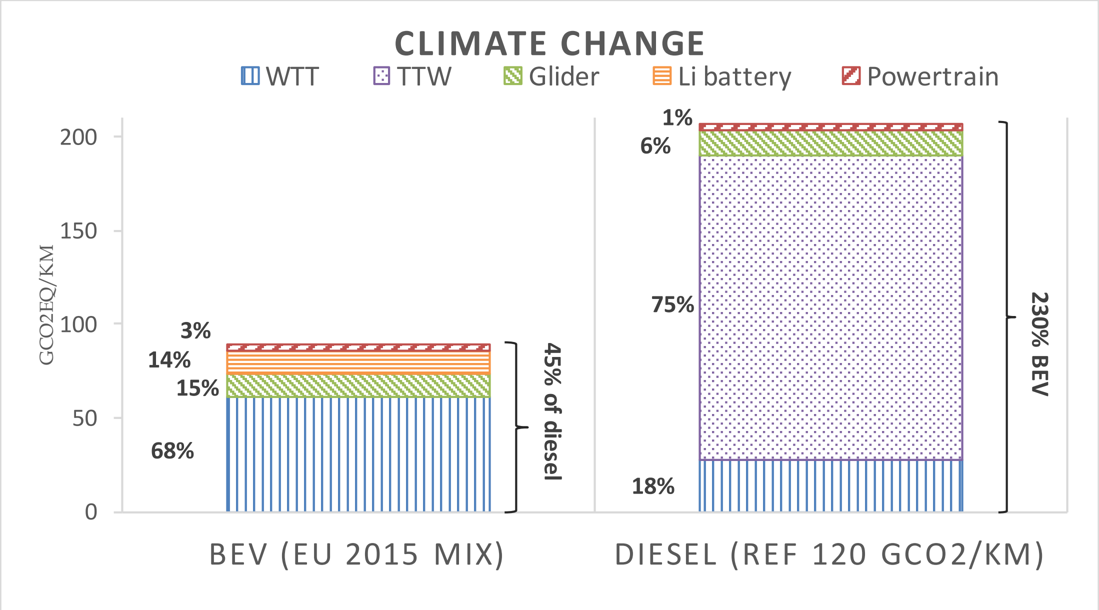

Figure 5: Significance of the various life cycle stage
The basic assumptions are: a life time driven distance of 200.000km and a weight of the glider of 1200kg. For the battery electric vehicle following assumption are considered: a real-life electricity consumption of 0,2 kWh/km [19] and a 30kWh LMO battery (average of 55 kgCO_2/kWh [12]); 1,5 battery replacement is needed over the life time of the vehicle [20, 17]. The reference diesel vehicle emits 120 gCO_2/km on NEDC, which is augmented with 35% to reflect real life driving conditions [5]. The EU 28 mix of 2015 emits 300gCO_2/kWh [21].

Electric vehicles can be fuelled by a wide variety of primary energy sources – including gas, coal, oil, biomass, wind, solar and nuclear – reducing oil dependency and enhancing energy security. The carbon footprint of the allocated electricity to electric vehicles is of utmost importance for the overall environmental performance. Different scenarios are calculated to investigated the effect of change the electricity mix with the same reference vehicles as discussed in figure 5.

Following scenarios are investigated:

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[19] De Cauwer, C., Messagie, M., Heyvaert, S., Coosemans, T. & Van Mierlo, J. Electric Vehicle Use and Energy Consumption based on Real-World Electric Vehicle Fleet Trip and Charge Data and its Impact on Existing EV Research Models 28th International Electric Vehicle Symposium and Exhibition 2015, EVS 2015. Korean Society of Automotive Engineers, p. 645-655 2015

[20] Aguirre, K., Eisenhardt, L., Lim, C., Nelson, B., Norring, A., Slowik, P., Tu, N. Lifecycle analysis comparison of a battery electric vehicle and a conventional gasoline vehicle. Calif Air Resour Board 2012.

[21] European Commission. EU Reference Scenario 2016 Energy, Transport And GHG Emissions Trends To 2050. DOI: 10.2833/001137. 2016

a) The intensity of grid electricity in different European countries
b) The carbon intensity of specific power plants
c) The effect of anticipated improvements in the carbon intensity of electricity.

The assumptions for the carbon footprint of the different European countries are based on the report [20] and depicted in figure 6. Sweden and France have a low carbon intensive electricity mix, due to the inclusion of renewables and nuclear sources respectively. Belgium and Spain have an electricity mix with a carbon footprint of 200-290 gCO$_2$/kWh, while in Germany 410 gCO$_2$ are emitted per produced electricity. Poland has the highest GHG emissions to produce electricity (650 gCO$_2$/kWh) due to the inclusion of hard coal power plants. The average European (28 member states) carbon footprint of electricity is 300 gCO$_2$/kWh in 2015 and is expected to drop significantly to 200 gCO$_2$/kWh in 2030 and 80 gCO$_2$/kWh in 2050.

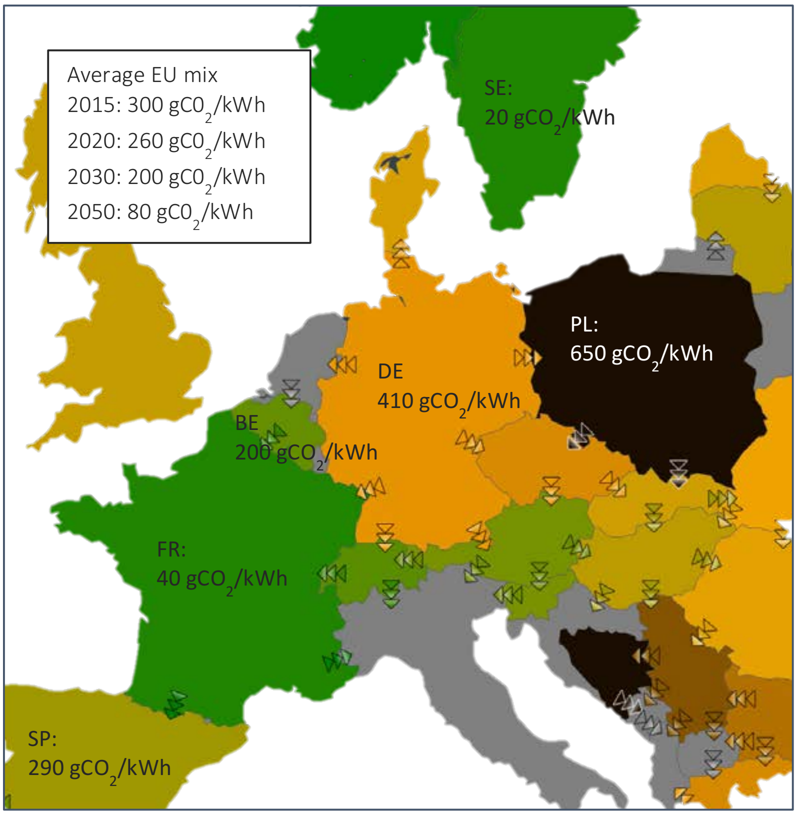

Figure 6: carbon footprint of European member states in 2015, and prognosis of EU mix in 2015, 2020, 2030 and 2050. Based on data from [21]

Figure 7 shows the influence of the carbon intensity of the national grid electricity on the impact of electric vehicles in comparison with a benchmark conventional vehicle. It is clear from the picture that the carbon intensity of the electricity grid plays an important role. Although electric vehicles using electricity from the grid in Poland have the highest GHG emissions compared to other BEVs, still the associated GHG emissions are 25% lower compared to the benchmark diesel vehicle. The electricity grids with the lowest carbon footprint offer a GHG emissions up to 85% compared to the benchmark.

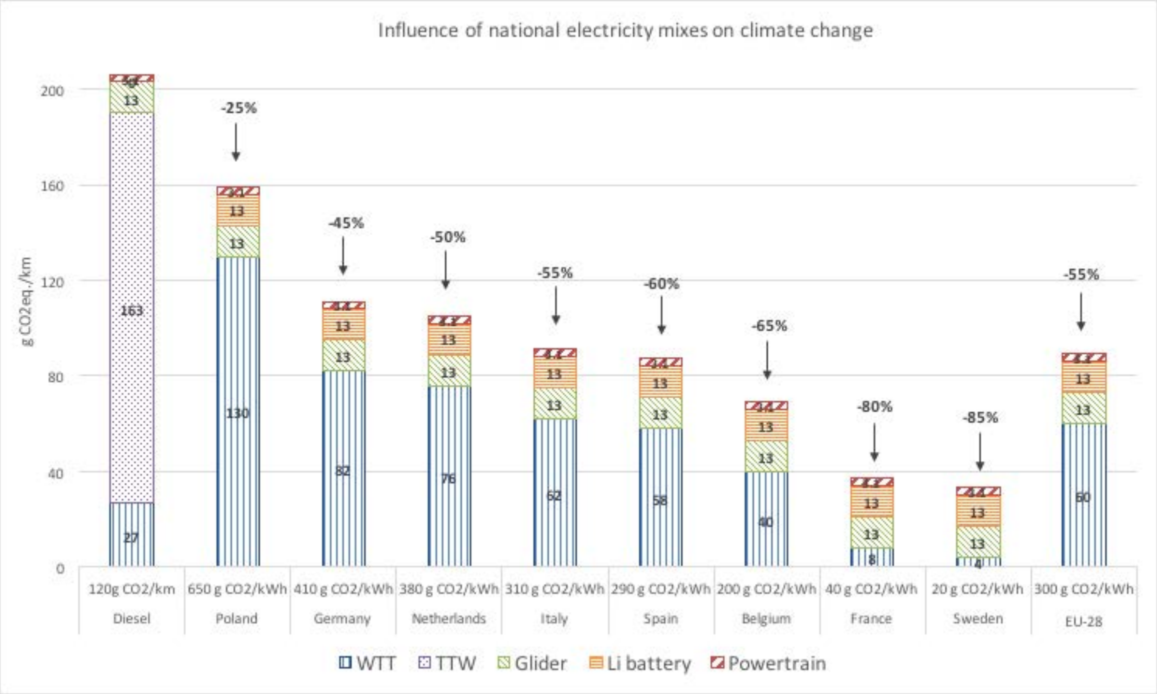

Figure 7: Influence of the carbon footprint of national electricity grids on the comparison of life cycle GHG emissions of BEV, according to the electricity mixes in [21].

Figure 8 shows (1) the carbon intensity of various production units (hard coal, gas, nuclear, wind, solar …) and (2) the anticipated improvements of the EU carbon intensity of grid electricity in the period between 2015 and 2050. As the carbon intensity of the European average grid is expected to dramatically reduce, the GHG emissions allocated to electric vehicles will considerably drop every decade.

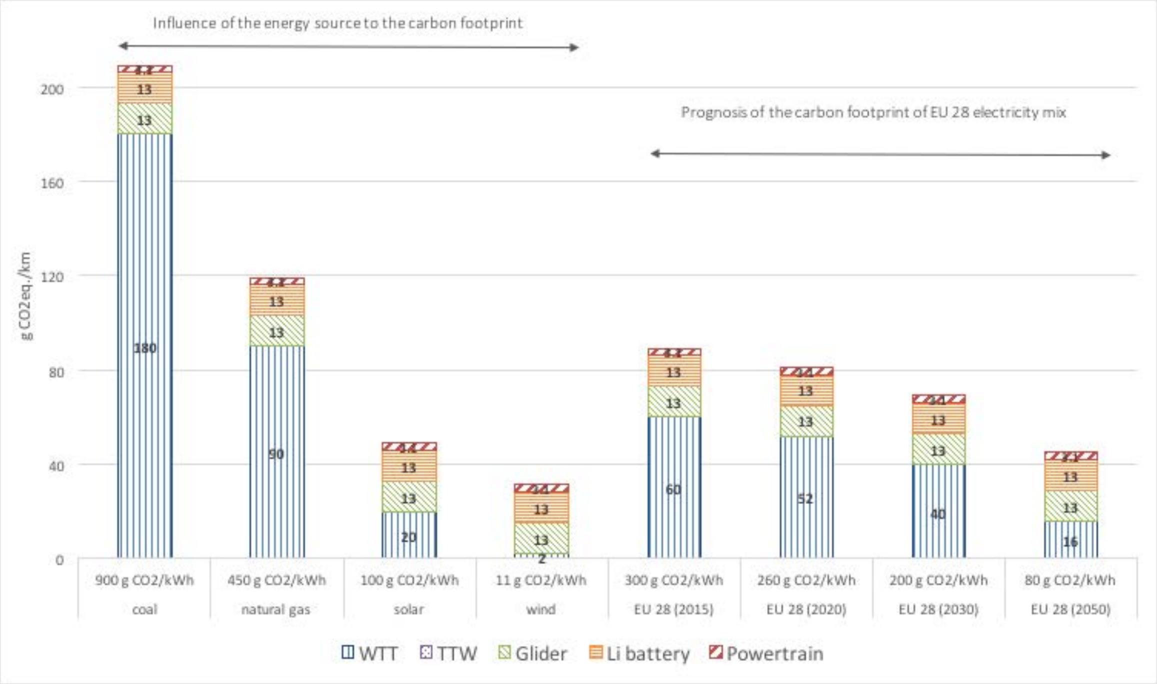

Figure 8: GHG emissions of electric vehicles depending on the energy sources and the prognosis of the reduction in carbon intensity. Electricity based on [21]

This part can be concluded as follows:

1. BEVs have significant lower impact on climate change and urban air quality, compared to conventional vehicles.
2. The single most important opportunity to improve the BEV's impact lies in the supply mix of the electricity. Ensuring the usage of more renewable energy will drastically reduce the impact of the BEV. The decarbonisation of the electricity grid will reduce numerous impacts of a BEV, most drastically it will lower the impact on climate change. Phasing out coal based power plant and substituting it with natural gas and renewables will significantly improve the performance in Eastern Europe.
3. A reduction of the weight of a BEV and the related electricity consumption will drastically reduce the impacts linked to electricity generation. A weight reduction should come from the substitution of the steel chassis with a material with a lower weight and from increasing the energy density of the battery.
4. To lower the environmental impact of the manufacturing stage of all components of a BEV, the use renewable energy (electricity as well as heat) plays an important role for further reduction.
5. New chemistries for lithium batteries that avoid the usage energy intensive and toxic materials can significantly reduce the impact. The fine-tuning (minimization of material usage in cathode and anode) and the optimization of production process (larger volumes) of existing battery technologies will improve the overall impact of the BEV.

6. The recycling of a lithium battery of a BEV has a positive impact as it helps saving materials and avoids the carbon intensive process of manufacturing primary material in the future. It is recommended that European policy makers couple the vehicle end-of-life directive with the battery end-of-life directive in order to increase the mandatory recycling efficiency of a vehicular battery.

4. . How to read and perform LCAs

Following points are of utmost importance in understanding and making a vehicle LCA study.

1. **A clear goal and scope definition** should be given, making the purpose of the study clear to the audience. Following questions should be answered in an LCA report.
    a. Goal
        i. What is the objective of the study?
        ii. What is the intended use of the results?
        iii. Who is the target audience?
        iv. Who is the commissioner?
        v. Who are the stakeholder and what are their interest and involvement?
        vi. What is the functional unit?
    b. Scope
        i. What are the system boundaries?
        ii. What is the temporal and geographical scope of the study?
        iii. What are the data quality targets?
        iv. Who will review the report?
2. **The modelling framework and system boundaries** highly influence the end result. For instance, the performance of the BEV depends highly on the allocated electricity source. Which electricity mix should be considered when performing an environmental assessment of electric vehicles? In literature both average and marginal electricity mixes are allocated to electric vehicles, resulting in unclear recommendations to decision-makers. The marginal system modelling approach falsely claims to model all the consequences that the new and additional customer (the BEV) has on the extra needed capacity in the electricity grid. However, the determination of the technologies that change the future installed electricity capacity is constrained by many issues not related to a change in demand: political targets, business perspectives, emission trading systems, emission ceilings, physical limitations and demand of co-products. Therefore, the change in installed capacity can’t be allocated solely to an additional consumer and should be allocated to the full market.
3. **The impact categories:** The focus of literature is mostly on climate change and CO_2 eq. emissions, while other impact categories are important to investigate. A full life cycle impact assessment should

address various impact categories to avoid shifting problems from one impact category to another. Examples of impact categories: 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.

4. **Data quality:** The quality of a Life Cycle Assessment depends highly on the quality of all the data and assumptions that are used in the modelling phase. An important example is: 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.
5. **Uncertainty propagation:** One of 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. A range-based vehicle-LCA model is developed in [18].