Assessment of Electric Vehicles Lifetime Emissions Methodologies Including Suggestions for their Future Evolution

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Abstract.
To compare the life cycle emissions from EV (electric vehicle) and ICE (internal combustion engine) car is very important task. Results will influence general perception of EV potential buyers as well as policy makers. The methodologies to properly calculate LCA (life cycle assessment) emissions for EV and ICE are subject of development and their applications differ across the studies.

Some of the suggestions for LCA methodologies adjustments as suggested by this article includes novum, other (like battery recycling, battery second life, longer EV life span) occurs already today in different LCA analyses, however there is still rather a big diversity of the ways of their application.

The suggestions have a methodological nature, should open wider debate related to LCA methodologies development and possibly might inspirate future research work in their application. By working on this paper, the author finds out that due to the methodological robustness of LCA, country specific inputs (mainly for the energy mix), diversity of LCA applications, lacking worldwide precise standard on LCA methodology, whenever you read any outcomes related to LCA EV or ICE emissions, the reader has to go rather deeply to how the LCA was applied by author/s, in which environment, what sort of datasets were used and only after thorough assessment of the author approach, respective results can be used for further decision making.

Keywords: Electric Vehicles, Life Cycle Emissions, LCA Methodology improvements

JEL classification: *F18, L62, L80*

1 Objective of the article

The problematics of environmental impacts evaluation of electric vehicles production and their operation is highly getting momentum as general public often has the possibility to read different, many times contradictory outcomes of several surveys and researches, which are frequently cited in the public medias.

The reason why I have decided to investigate further this problematic is highly pragmatic. If the perception of the future customers to buy electric vehicle is being influenced by information which relates to environmental impact of its purchase and operation, then this information should be based on correct methodology taking into account also updated and trustful inputs.

Policies are being implemented in transport area worldwide to tackle the climate change challenges and policy makers need to have objective assessment tools and methodologies to measure the impact of set targets and action plans.

Objective of this article is to provide the basic overview of respective methodologies, asses them and provide opinion on their future possible evolution. As a side objective of this paper was the identification of possible methodological shortcomings and investigation of their conceptual improvements.

The research approach of this paper is to explore the existing methodologies with regards to researched topic. From methodological perspective, method of analyses and synthesis, including comparison is about to be used. After identification of the respective works, the author will try to derive conceptual outcomes by using methods mentioned above including generalizing his deductions for the particular areas.

2 Methodologies to evaluate emissions in e-mobility industry

The methodologies for assessment of the production of EV, including battery production evolve continuously. Already for decades the professionals and researchers around the globe are defining and finetuning the methodology which should with highest objectivity assess the environmental impacts of EV production and operation.

Some of the research papers and respective methodologies have a focus on life cycle environmental assessment of different types of batteries for EV and Plug in hybrids [1] Within this reference the bottom-up approach of manufacturing process of different types of batteries is the main subject of the research, taking into account the material requirements, processing and energy requirements, transport and infrastructure needs and related emissions for every particular battery component (cathode, electrode, separator, electrolyte, battery management system and other subcomponents) while calculating emissions for production and processing of raw material.

What is the lifecycle approach to emissions? Usually, it covers emissions produced over their “life cycle” of BEV production and usage—from the raw materials to make the car through manufacturing, driving, and disposal or recycling.

Well to Wheel methodology grasp only the fraction of global warming emissions, when compared with life cycle analysis of the production maintenance and disposal of the vehicles. It concentrates on two subparts - energy provision and vehicle efficiency.

Energy provisioning part usually in the Well to Wheel methodology for EV considers emissions which result from extraction of raw materials needed to produce the necessary energy, delivery of these raw material for further processing (e.g. coal) it also includes emissions from burning the fuel in the power plant to generate electricity. Methodology also includes emissions which are associated with transmission and distribution losses.

For comparable gasoline vehicle Well to Wheel methodology covers in energy provisioning part oil extraction emissions, emissions associated with transporting of crude oil to refinery, refining the crude oil to gasoline, delivering the gasoline to gas stations.

For EV and ICE cars vehicle efficiency is considered in determining emissions from combusting the gasoline in the engine, or alternatively consuming the electricity stored in battery to power the electric engine. We should bear in mind that one of the biggest advantages of EV compared to ICE is its higher efficiency, to be followed by possibility to produce the electricity from renewable sources.

The relation between Full life cycle approach and Well to Wheel methodology is described on the picture bellow.

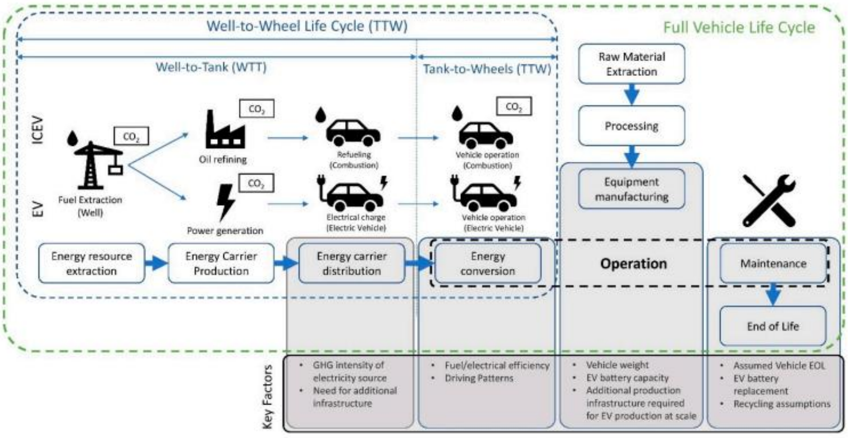


Fig 1. Full life cycle approach and Well to Wheel methodology [2]

For the evaluation of lifecycle emissions, it is important to asses the methodology. There are several studies and research work which compared the recent status of research in this field. The purpose of this article is not to duplicate the comparative process of LCA (life cycle assessment) studies, rather to bring the new insights from methodological point of view.

2.1 LCA methodologies survey & comparison

According to ICCT [3] “Overall, electric vehicles typically have much lower life-cycle greenhouse gas emissions than a typical car in Europe, even when assuming relatively high battery manufacturing emissions. An average electric vehicle in Europe produces 50% less life-cycle greenhouse gases over the first 150,000 kilometers of driving, although the relative benefit varies from 28% to 72%, depending on local electricity production.4 An electric car’s higher manufacturing-phase emissions would be paid back in 2 years of driving with European average grid electricity compared to a typical vehicle. This emissions recovery period is no more than 3 years even in countries with relatively higher-carbon electricity such as in Germany. When comparing to the most efficient internal combustion engine vehicle, a typical electric car in Europe produces 29% less greenhouse gas emissions.”

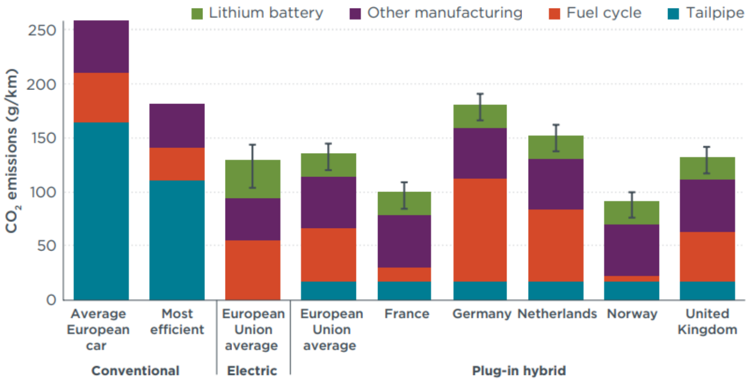
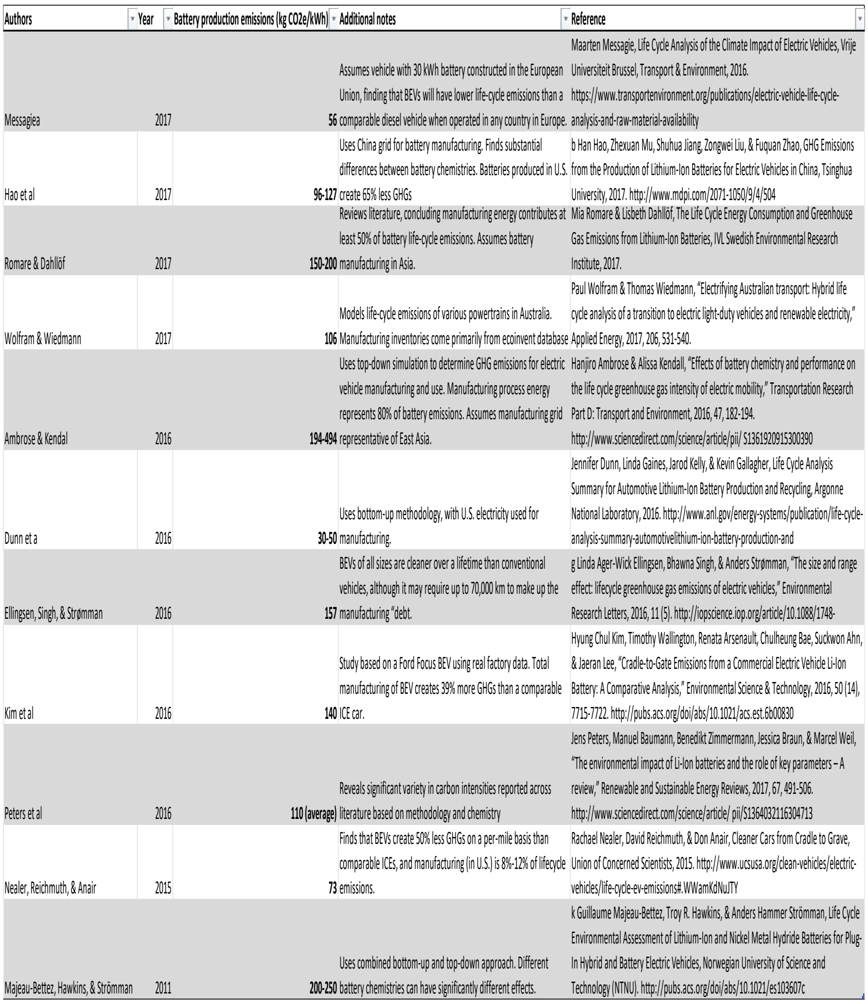


Fig. 2 Comparison of EV, Plug -in hybrid and conventional vehicle LCA emissions [3]

Bellow I will try to point out the few findings which are results from comparing the methodologies and their application, as already identified by the comparative studies.

Excerpt from study bellow shows significant diversity based on used methodology, technology and territory applied for the battery production (just one, still significant element of LCA)

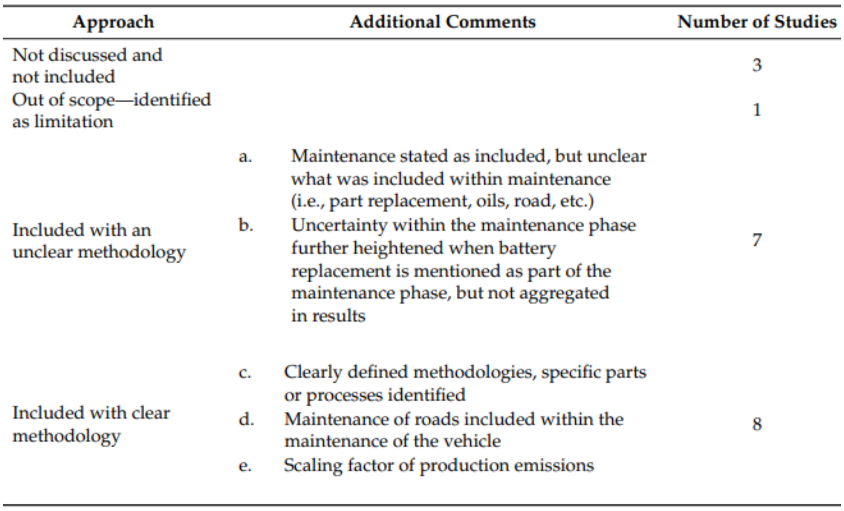
Table. 3 Comparison of LCA studies, according to ICCT [3]



Authors	Year	Battery production emissions (kg CO2e/kWh)	Additional notes	Reference
Messagiea	2017	**56**	Assumes vehicle with 30 kWh battery constructed in the European Union, finding that BEVs will have lower life-cycle emissions than a comparable diesel vehicle when operated in any country in Europe.	Maarten Messagie, Life Cycle Analysis of the Climate Impact of Electric Vehicles, Vrije Universiteit Brussel, Transport & Environment, 2016. https://www.transportenvironment.org/publications/electric-vehicle-life-cycle-analysis-and-raw-material-availability
Hao et al	2017	**96-127**	Uses China grid for battery manufacturing. Finds substantial differences between battery chemistries. Batteries produced in U.S. create 65% less GHGs	b Han Hao, Zhexuan Mu, Shuhua Jiang, Zongwei Liu, & Fuquan Zhao, GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China, Tsinghua University, 2017. http://www.mdpi.com/2071-1050/9/4/504
Romare & Dahllöf	2017	**150-200**	Reviews literature, concluding manufacturing energy contributes at least 50% of battery life-cycle emissions. Assumes battery manufacturing in Asia.	Mia Romare & Lisbeth Dahllöf, The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries, IVL Swedish Environmental Research Institute, 2017.
Wolfram & Wiedmann	2017	**106**	Models life-cycle emissions of various powertrains in Australia. Manufacturing inventories come primarily from ecoinvent database	Paul Wolfram & Thomas Wiedmann, "Electrifying Australian transport: Hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity," Applied Energy, 2017, 206, 531-540.
Ambrose & Kendal	2016	**194-494**	Uses top-down simulation to determine GHG emissions for electric vehicle manufacturing and use. Manufacturing process energy represents 80% of battery emissions. Assumes manufacturing grid representative of East Asia.	Hanjiro Ambrose & Alissa Kendall, "Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility," Transportation Research Part D: Transport and Environment, 2016, 47, 182-194. http://www.sciencedirect.com/science/article/pii/ S1361920915300390
Dunn et a	2016	**30-50**	Uses bottom-up methodology, with U.S. electricity used for manufacturing.	Jennifer Dunn, Linda Gaines, Jarod Kelly, & Kevin Gallagher, Life Cycle Analysis Summary for Automotive Lithium-Ion Battery Production and Recycling, Argonne National Laboratory, 2016. http://www.anl.gov/energy-systems/publication/life-cycle-analysis-summary-automotivelithium-ion-battery-production-and
Ellingsen, Singh, & Strømman	2016	**157**	BEVs of all sizes are cleaner over a lifetime than conventional vehicles, although it may require up to 70,000 km to make up the manufacturing "debt.	g Linda Ager-Wick Ellingsen, Bhawna Singh, & Anders Strømman, "The size and range effect: lifecycle greenhouse gas emissions of electric vehicles," Environmental Research Letters, 2016, 11 (5). http://iopscience.iop.org/article/10.1088/1748-
Kim et al	2016	**140**	Study based on a Ford Focus BEV using real factory data. Total manufacturing of BEV creates 39% more GHGs than a comparable ICE car.	Hyung Chul Kim, Timothy Wallington, Renata Arsenault, Chulheung Bae, Suckwon Ahn, & Jaeran Lee, "Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis," Environmental Science & Technology, 2016, 50 (14), 7715-7722. http://pubs.acs.org/doi/abs/10.1021/acs.est.6b00830
Peters et al	2016	**110 (average)**	Reveals significant variety in carbon intensities reported across literature based on methodology and chemistry	Jens Peters, Manuel Baumann, Benedikt Zimmermann, Jessica Braun, & Marcel Weil, "The environmental impact of Li-Ion batteries and the role of key parameters – A review," Renewable and Sustainable Energy Reviews, 2017, 67, 491-506. http://www.sciencedirect.com/science/article/ pii/S1364032116304713
Nealer, Reichmuth, & Anair	2015	**73**	Finds that BEVs create 50% less GHGs on a per-mile basis than comparable ICEs, and manufacturing (in U.S.) is 8%-12% of lifecycle emissions.	Rachael Nealer, David Reichmuth, & Don Anair, Cleaner Cars from Cradle to Grave, Union of Concerned Scientists, 2015. http://www.ucsusa.org/clean-vehicles/electric-vehicles/life-cycle-ev-emissions#.WWamKdNuJTY
Majeau-Bettez, Hawkins, & Strömman	2011	**200-250**	Uses combined bottom-up and top-down approach. Different battery chemistries can have significantly different effects.	k Guillaume Majeau-Bettez, Troy R. Hawkins, & Anders Hammer Strömman, Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles, Norwegian University of Science and Technology (NTNU). http://pubs.acs.org/doi/abs/10.1021/es103607c

Maintenance is also quite important element where emissions are being produced over vehicle life time, and below table shows, how unclear is the methodology in many LCA emissions studies.

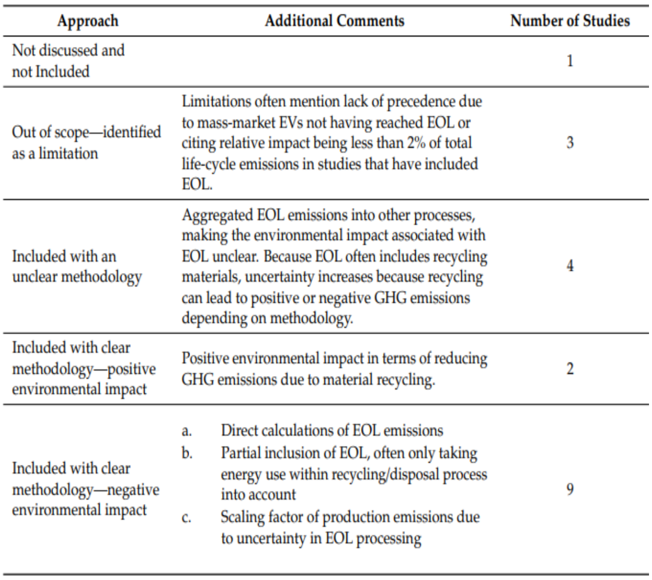
Table. 4 Maintenance within LCA methodology [5]



Approach	Additional Comments	Number of Studies
Not discussed and not included		3
Out of scope—identified as limitation		1
Included with an unclear methodology	a. Maintenance stated as included, but unclear what was included within maintenance (i.e., part replacement, oils, road, etc.) b. Uncertainty within the maintenance phase further heightened when battery replacement is mentioned as part of the maintenance phase, but not aggregated in results	7
Included with clear methodology	c. Clearly defined methodologies, specific parts or processes identified d. Maintenance of roads included within the maintenance of the vehicle e. Scaling factor of production emissions	8

The similar applies also to calculating end of the lifetime vehicle emissions as compared within the same study [6].

Tab. 5 End of lifetime within LCA methodologies [6]



Approach	Additional Comments	Number of Studies
Not discussed and not Included		1
Out of scope—identified as a limitation	Limitations often mention lack of precedence due to mass-market EVs not having reached EOL or citing relative impact being less than 2% of total life-cycle emissions in studies that have included EOL.	3
Included with an unclear methodology	Aggregated EOL emissions into other processes, making the environmental impact associated with EOL unclear. Because EOL often includes recycling materials, uncertainty increases because recycling can lead to positive or negative GHG emissions depending on methodology.	4
Included with clear methodology—positive environmental impact	Positive environmental impact in terms of reducing GHG emissions due to material recycling.	2
Included with clear methodology—negative environmental impact	a. Direct calculations of EOL emissions b. Partial inclusion of EOL, often only taking energy use within recycling/disposal process into account c. Scaling factor of production emissions due to uncertainty in EOL processing	9

3 Outcomes and discussion

There are however several methodological issues, which should be emphasized and which concerns the majority of concerned studies. The purpose of this paper is not to generate a new study focused on calculating emissions for EV production and use, rather to critically assess used methodology and identify possible shortcomings and to provide recommendations from methodological point of view.

3.1 Comparative period/life span of vehicles

The different studies (including those mentioned in this paper) take certain amount of mileage/km driven when comparing the lifetime emissions of EV´s and combustion engine propelled cars. It should be recognized that lifetime of car produced after year 2000 is in general is longer, and there are very many evidences that recent lifespan of car approaches 200,000 miles (320,000 km), [8] Rather dramatical increase of lifespan (compared to previously recognized standard 150 000 miles) is caused by mix of factors like better longevity materials used, better diagnostic technology, supervision and control systems, tighter tolerances, antic- corrosion coating and others.

Moreover, electric vehicles produced recently are expected to have longer lifespan– reaching 300 000 miles or even longer [8] 1 000 000 miles (even though, there are very few evidences in reality nowadays).

We can conclude that usage of the EV is associated with environmental benefits with regards to emissions produced when compared with ICE car which is even more highlighted when we compere these benefits over longer lifespan. 150 000 km lifespan assumption often used in different studies is simply short and detrimental to the EV´s.

3.2 Battery second life

EV have another comparative advantage when compared with ICE propelled cars. The battery, when reaching 70-80 % of their initial capacity, was considered to not be suitable any more for it ´s original usage in EV.

We should take into consideration, that driving range and hence battery capacity of EV´s is continuously rising, so it is quite probable that lower share (cca. 50%) of original battery capacity will still be suitable for propelling an electric engine/s in EV. Obviously, battery capacity deteriorating curve, charging and usage patterns, battery chemistry and other factors will influence whether original battery in EV will still be suitable for driving purposes, or it potentially will serve for secondary purpose – battery second life.

Increasing battery capacity which we can see over last decade of EV production is happening in high speed, or rather in multiples (EV produced 2012 has a battery capacity of cca. 24kWH, recently in 2022 you can easily find EV models with capacity of battery from 60 kWh -100 kWh.

Bigger battery capacity allows for higher mileage of range, but it also influences lifespan of EV´s. (since it provides higher allowance for battery degradation, which will be still sufficient for driving purpose). On the other side, increased battery capacity, taking into account the degradation after primary use (EV purpose) improves the prerequisites for most business cases in the battery second life.

Second life of the battery can result in saving of additional emissions throughout its usage in many applications. One of the most frequent and representative use case for second life of the EV battery is storage of electricity for households or commercial purposes. Storage for electricity allows more extensive integration of renewables, which provides for structural change in electricity generation leading to low carbon economy and thus lower emissions.

It is foreseen that second life battery can lasts up to or even more than 10 years, utilizing in this period up to 60% [10] of the original battery capacity.

Therefore, from methodological point of view, saved emissions which are a consequence of second life battery usage (e.g. storage of battery) should be incorporated in comparison with ICE alternative.

3.3 Recycling of the batteries

As the battery is very important element, which production from virgin raw material causes significant emissions) one of the ways forwards is recycling of the batteries from EV in order to reduce emissions and increase energy efficiency.

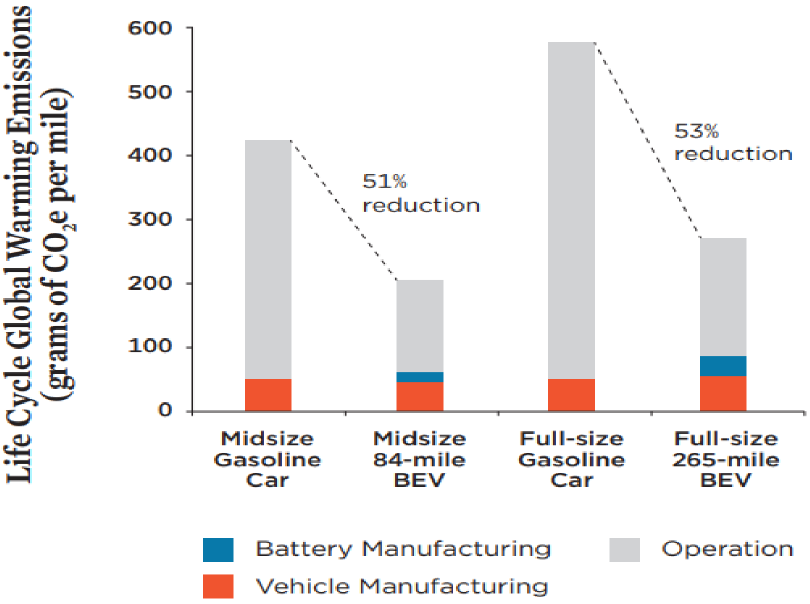


Fig. 5 Battery impact within LCA [7]

Recycling of the EV batteries is still in rather in early stage, as the whole industry is very young and there are very few companies / use cases which on European market which specialize in this field. The recycling processes and legislation are under way and research is continuously ongoing. Recently we recognize two main technological process of pyrometallurgy and hydrometallurgy [7], but obviously due to the lacking batteries which have reached the end of lifespan (and which were built for EV´s, later had their second life) calculating the effects of recycling would be rather theoretical exercise.

Recycling is also energy demanding process which generate own emissions but is more efficient compared to obtaining virgin raw materials with respect of mainly cobalt, lithium, nickel and manganese.

Therefore, from methodological point of view, recycling effects should be taken into account when calculating emissions from battery production, as this will be the case for future EV production. Recent status (where very few materials entering battery production lines come from recycled sources) is rather reflecting very early stage of EV battery productions.

3.4 Mining equipment, Crude oil pipeline, Refineries, Gas stations network versus Energy generation and charging stations network

If we have the ambition to cover all emissions which are generated during the production, use and recycling of ICE and EV, we should not underestimate the whole supply chain which serves to deliver electric energy to EV or products from oil to ICE (lubricants, diesel, gasoline).

To cover also these emissions in methodology the ICE car emissions should include lifecycle emissions from mining equipment construction, operation and disposal, lifecycle emissions from crude oil pipeline construction, operation and disposal, also lifecycle emissions from refineries construction, their operation and disposal and last but not least lifecycle emissions covering construction of gas station network, their operation and disposal including supply chain logistics of oil products.

One can argue, that crude oil products are not only used in transport (and thus consumed by ICE vehicles) but we use crude oil products also in the agriculture (e.g. fertilizers) very many industry, chemical and consumer applications (from different polymers products, asphalt, pharmaceuticals to heating substances). In order to reflect other that transport usages, only portion of above-mentioned lifecycle emissions related to transport (¾)should be considered.

On the EV side, parallel approach should be applied (which in fact with regards to energy generation for EV and Battery production and EV usage is the case in majority of methodologies). EV lifecycle emissions should incorporate allocated proportion of Chargers production, their operation (idle time electricity consumption, charging effectivity) and disposal.

Even in the subtitle there is missing electricity transmission and distribution networks, which is happening by purpose. From methodology point of view, only emissions attributable to lifecycle of EV should be taken into account, whereas there needs to be direct causal effect. Transmissions and distribution networks were built long time before recent uptake of e-mobility. They were designed to distribute to final customers electric energy with certain qualitative characteristics, while vast majority of their services/outputs is satisfying other than EV´s needs, therefore we can neglect emissions associated with their design, operation and disposal. In case of very prudent approach, allocation of emissions regarding the operation and disposal according to volume of electric energy transmitted and distributed to e-mobility industry compared to total energy might be considered.

3.5 Emissions from maintenance services

It is well recognized fact that service interventions and maintenance in case of EV are less frequent and simpler compared to ICE vehicle. This result form construction and design simplicity of EV (when compared to ICE vehicle). In particular engine problems and maintenance is much simpler (for EV hardly any), there is no DPF filter or EGR vent in EV, no tail pipe, brakes in EV have much longer lifespan due to regenerative braking, there are no engine oils and related filters to be regularly changed in EV´s, EV has no transmission gear which has to serviced.

Emissions as the result of spare parts production and service centers running should be incorporated in the methodology to assess overall EV lifetime emissions, benefitting from lower need for spare parts (compared to ICE) and less services centers (as a consequence of simpler and less time demanding maintenance needs).

3.6 Electricity gets greener/non static approach

In many methodologies, usually fix assumptions are taken into calculations and modeling of lifetime emissions. This is however simplification, which for longer lifespan of EV is not reflecting reality. Implementation of renewables into energy mix is not a short process, on the other side from perspective of 10 – 20 years there are significant changes on energy generation and distribution market observable. Tendencies to integrate low or zero carbon sources into energy generation sources are evident and rather differs regionally in the pace and structure.

Therefore, methodologies to cover emissions should rather model the evolution of energy mix in given region, taking into account rising proportion of renewable sources of energy over time, when defining lifetime emissions of EV.

Conclusions

Excerpt from studies related to LCA of EV emissions shows significant diversity based on used methodology, technology and territory applied mainly for the battery production.

The purpose of this paper is not to generate a new study focused on calculating emissions for EV production and use, rather to critically assess used methodologies and identify possible shortcomings and provide recommendations from methodological point of view.

We can conclude that usage of the EV is associated with environmental benefits with regards to emissions produced when compared with ICE car, which is even more highlighted when we compere these benefits over longer lifespan. 150 000 km lifespan assumption often used in different studies is simply short and detrimental to the EV´s.

From methodological point of view, saved emissions which are a consequence of second life battery usage (e.g. storage of battery) should be incorporated in comparison with ICE alternative. This element is still missing in many studies, that elaborate on this topic.

If we have the ambition to cover all emissions which are generated during the production, use and recycling of ICE and EV, we should not underestimate the whole supply chain which serves to deliver electric energy to EV or products from oil to ICE (lubricants, diesel, gasoline).To cover also these emissions in methodology the ICE car emissions should include lifecycle emissions from mining equipment construction, operation and disposal, lifecycle emissions from crude oil pipeline construction, operation and disposal, also lifecycle emissions from refineries construction, their operation and disposal and last but not least lifecycle emissions covering construction of gas station network, their operation and disposal including supply chain logistics of oil products

In LCA methodologies covering emissions should rather the evolution of energy mix in given region be taken into account thus reflecting rising proportion of renewable sources of energy over time, compared to standardly used fixed assumptions.

Emissions as the result of spare parts production and service centers running should be incorporated in the methodology to assess overall EV lifetime emissions, benefitting from lower need for spare parts (compared to ICE) and less services centers (as a consequence of simpler and less time demanding maintenance needs).

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