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Comparative life cycle assessment of mid-sized electric, diesel, and gasoline passenger vehicles

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Summary

This article provides an updated evaluation of environmental performance of battery electric vehicles with respect to technological progress as well as battery and vehicle size from a cradle-to-grave perspective. The life cycle impacts of the D-segment electric vehicle are compared to those of similarly sized conventional gasoline and diesel vehicles. The environmental performance is assessed across seven environmental impact categories, and the electric vehicle is found to offer both environmental benefits and disadvantages compared to the conventional vehicles; these environmental trade-offs are primarily found in connection with battery production as well as electricity mix used for charging.

Keywords: LCA (Life Cycle Assessment), environment, BEV (battery electric vehicle), lithium battery, sustainability

1 Introduction

While battery electric vehicles (BEVs) convey zero tailpipe emissions during operation, their overall life cycle environmental performance is more complicated and unclear, particularly when impacts other than global warming potential (GWP) are considered [1]. Upstream emissions, particularly pertaining to battery production, have been indicated as a source of high environmental concern that may compromise the overall life cycle environmental benefit of BEVs compared to conventional internal combustion engine vehicles (ICEVs) [1], [2]. Thus, a holistic systems perspective is required to quantify and compare the environmental impacts of BEVs to that of ICEVs.

Life cycle assessment (LCA) offers the best available framework for assessing life cycle environmental impacts of products and services [3] and is widely used to estimate the environmental impacts of passenger vehicles by different actors, including the automobile industry [4], [5]. Generally, comparative LCA studies performed both by researchers as well as the automobile industry find that BEVs offer reduced greenhouse gas (GHG) emissions compared to similarly sized conventional vehicles [6], [7]. However, much is still unknown about the overall environmental performance of BEVs as most LCA studies consider only smaller vehicles or limit the environmental impact assessment to solely consider GHG emissions [8]. As such, the environmental performance of larger BEVs with higher capacity battery packs is still not well established. To fill this knowledge gap, the current study aims to assess the environmental performance of a D-segment BEV and compare its environmental footprint with that of similarly sized diesel and gasoline vehicles.

2 Method

The primary goal of this study was to assess the environmental performance of a D-segment BEV across multiple environmental impact categories and compare its impact to that of similarly sized ICEVs using LCA. A secondary goal was to evaluate the environmental effects of varying the battery size and varying the number of battery replacements. The functional unit was set to "the use of a vehicle per km", where emissions were estimated based on a total mileage of 250 000 km. The main intended audience of this study are private and public consumers as well as policy and decision makers.

2.1 System boundaries

A process-based attributional and comparative approach was used to estimate the cradle-to-grave environmental impact potentials of the vehicles. As such, the analysis was based on average data, unless otherwise specified. The analysis considers the complete life cycle consisting of both the vehicle equipment life cycle and the energy carrier life cycle – also known as a Well-to-Wheels (WTW) analysis, as shown in Figure 1.

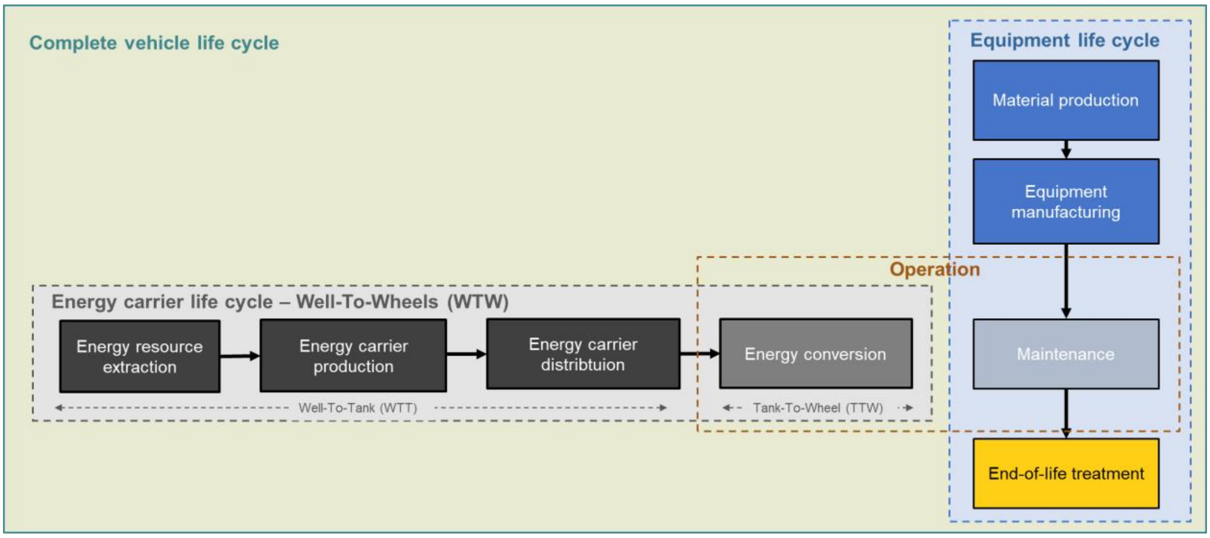

Figure 1: Complete life cycle of vehicles (after Nordelöf et al.[9])

The foreground system consists of both original inventory data as well as inventory data from preceding LCA studies. Original inventory data were compiled for the production of the Li-ion battery packs. The latest *ecoinvent* database version (3.8 released in 2021) was used as background system [10].

The cradle-to-gate inventories reflect what can be considered common production practice for current European manufacturers; Li-ion traction batteries are produced in South Korea, while vehicle production and assembly take place in Germany. For both battery and vehicle materials and processes, global average market mix data were assumed. As such, background data generally represent global averages, or European averages where global averages were unavailable. For end-of-life (EOL) treatment, disassembly and material recycling were considered. It was assumed that the vehicles and battery packs are disassembled and recycled somewhere in Europe (i.e., European average data were used).

Transport of materials and subcomponents were modeled using generic background data and added to the foreground by specifying the distances and transport modes between the suppliers and vehicle assembly and recycling sites. Transport of the battery from South Korea to Germany was included, while transport from the vehicle factory to market was excluded for all three vehicle technologies.

2.2 Inventory data

The LCA considers a BEV with an 80 kWh battery pack, and similarly sized diesel and gasoline vehicles to act as a comparative benchmark. Cradle-to-grave inventories were compiled for each of the vehicles. The inventory data for production, use, and EOL as well as the sensitivity analyses are described in the text below.

For production (cradle-to-gate) of the vehicles, we relied on preceding and on-going LCA studies as well as *ecoinvent 3.8* process data. Aside from the battery, electric powertrain components were based on preceding LCA studies [11]–[16]. The Li-ion battery inventory relied on a modular cradle-to-gate inventory compiled in connection with on-going electromobility research under the MoZEES research center. The cathode material $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC-622) was assumed in combination with a graphite anode for the battery. The 80 kWh battery pack weighs 520 kg. *Ecoinvent* process data were used for extraction and production of materials. For both the electric and conventional vehicles, the glider was based on *ecoinvent* process data. Similarly, the internal combustion engine for the conventional vehicles were also based on *ecoinvent*.

The average energy use over a year was assumed to be 23.2 kWh/100 km for the BEV, 6.7 l/100 km for the diesel vehicle, and 8.3 l/100 km for the gasoline vehicle. The total electricity use for the BEV was estimated based on real-world operational electricity use data and charging efficiency. We estimated the operational electricity use based on data from a study examining energy efficiency trade-offs in small to large electric vehicles [17]. When we plot the reported real-world operational electricity use as function of curb weight of the BEVs examined in the study, we find that there is a correlation between operational electricity use and curb weight, as seen in Figure 2.

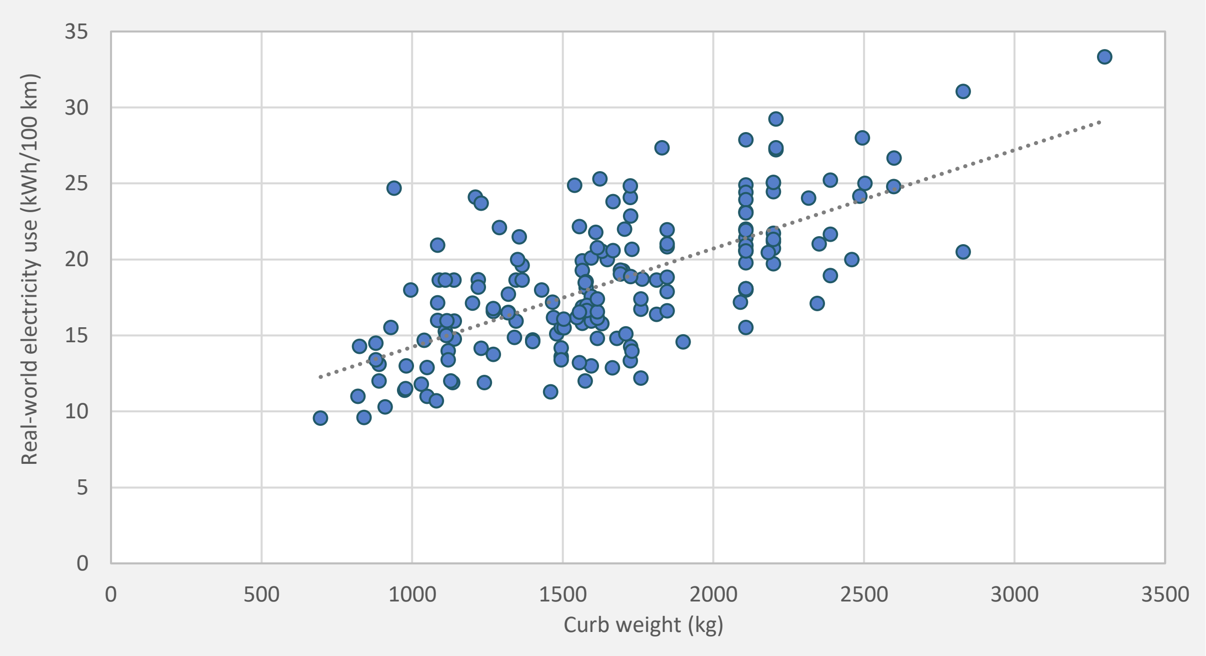

Figure 2: Real-world electricity use as function of curb weight, based on data reported by Weiss et al. [17]

The correlation between the reported real-world electricity use and the curb weight given by the dotted trendline is provided by Equation 1.

$$E_{BEV} = 0.0065 * x + 7.7584 \quad (1)$$

Where E_{BEV} is electricity use expressed in terms of kWh/100km and x denotes the curb weight in kg. For the BEV modelled in the study with a curb weight of 2130 kg, the operational electricity use with no losses in charger and battery was estimated to be 21.6 kWh/100 km. Charger and battery efficiencies were assumed to be 98% and 95%, respectively, resulting in an overall charging efficiency of 93% and giving overall electricity use of 23.2 kWh/100 km. The fuel uses of the ICEVs were set loosely based on WLTP fuel use data reported for the most selling D-segment models (i.e., VW Passat, Audi A4, Mercedes-Benz C-class, and BMW 3-series). The total estimated electricity use of the BEV as well as ICEV fuel use and vehicle curb weights are provided in Table: 1.

Table: 1 Vehicle curb weight and energy use

	Electric	Diesel	Gasoline
Curb weight (kg)	2130	1670	1590
Electricity use (kWh/100km)	23.2		
Fuel use (l/100km)		6.7	8.3

The WTW environmental impacts of the BEV were assessed using three different average market mixes: Norwegian (26 g CO_2-eq/kWh), European (381 g CO_2-eq/kWh), and Global (731 g CO_2-eq/kWh). Average production in Europe was assumed for both diesel and gasoline fuels. Generation and transmission of electricity and production and combustion of fuels were based on *ecoinvent* process data.

Vehicle maintenance was based on the *ecoinvent* process. EOL modelling was performed in accordance with the cut-off approach. The cut-off method allocates no burden to the recycled materials (i.e., downstream products) and instead, raw material input upstream of component and vehicle production has a recycled content [18]. EOL treatment covered vehicle disassembly, waste handling treatment, and hydrometallurgical treatment of Li-ion battery packs. Disassembly and waste handling were modeled using *ecoinvent* processes. The hydrometallurgical treatment of Li-ion batteries at EOL was based on a preceding LCA study that provides aggregated primary industry data for recycling of Li-ion batteries [19].

In addition to the main analysis described above, two sensitivity analyses regarding the battery pack were conducted for the BEV. The first sensitivity analysis considered both a smaller battery pack of 60 kWh weighing 393 kg and a larger battery pack of 100 kWh weighing 647 kg. Using Equation (1) and the overall charging efficiency of 93%, electricity use was estimated to be 22.4 kWh/100 km for the 60 kWh BEV and 24.2 kWh/100 km for the 100 kWh BEV. The second sensitivity analysis considered the need for replacing battery modules. While the main analysis assumed that the battery lasts the lifetime of the vehicle, the sensitivity analysis assumed that all battery modules would be swapped once during the vehicle lifetime.

2.3 Impact calculation

To assess the environmental performance, we considered seven mid-point impact categories that are particularly relevant for passenger vehicles. The considered impact categories were global warming potential (GWP), freshwater ecotoxicity potential (FETP), stratospheric ozone depletion potential (ODP), freshwater eutrophication potential (FEP), terrestrial acidification potential (TAP), fine particulate matter formation potential (PMFP), and human carcinogenic toxicity potential (HTP). Impacts were calculated using the ReCiPe characterization method from a hierarchical perspective using the openLCA software. Characterization methods are best estimates of the potential environmental impact of emissions to the environment along the life cycle of a product and are based on models of cause-effect chains from point of emission to impact on a chosen impact category [20].

3 Life cycle impact results

This section presents the life cycle environmental impacts of the electric, diesel, and gasoline vehicles. Sub-section 3.1 presents results expressed in terms of GWP while sub-section 3.2 presents other life cycle environmental impact potentials.

3.1 Global warming potential

Figure 3 presents the life cycle GWP of the three vehicle alternatives with the contribution towards total emissions from vehicle production denoted by blue, from the energy carrier (WTW) by grey, from maintenance by blue-grey, and from EOL treatment by yellow. Emissions are reported in terms of g CO_2-equivalents per kilometer driven (g CO_2-eq/km) and are based on a total mileage of 250 000 km.

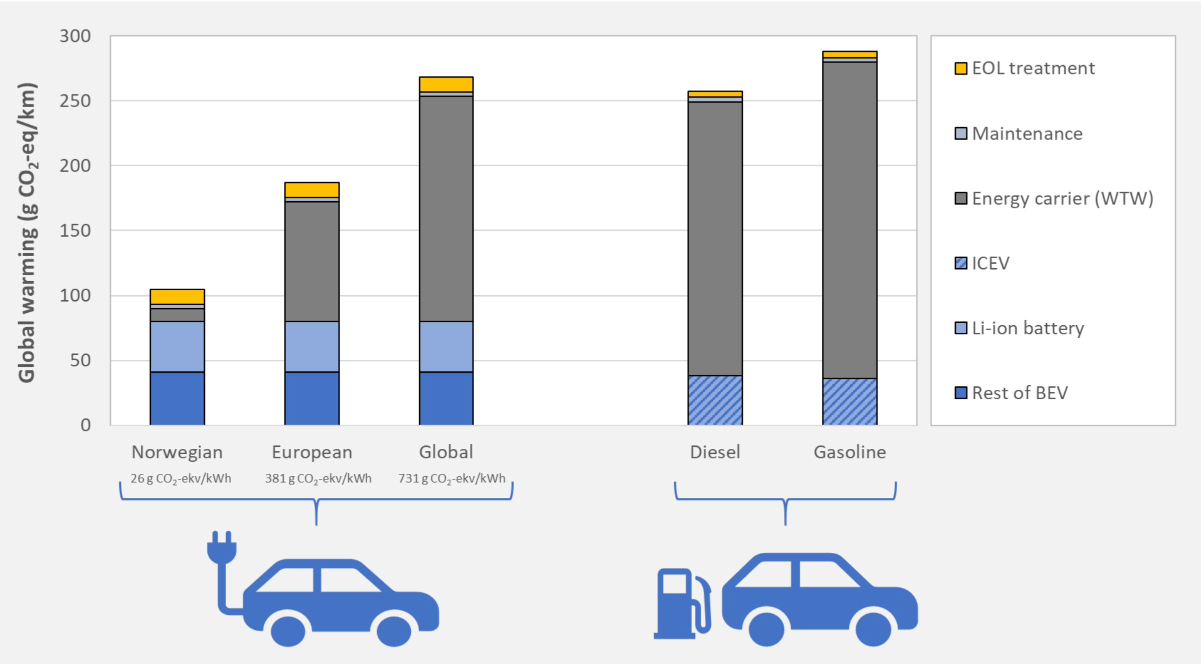

Figure 3: Life cycle greenhouse gas emissions of battery electric (left) and conventional (right) passenger vehicles based on a 250 000 km operating phase

Expectedly, the GHG emission performance of the BEV depends significantly on the electricity mix. With a low carbon electricity mix the BEV offers significantly lower life cycle emissions compared to both ICEVs, but a higher carbon electricity mix may result in comparative life cycle GHG emissions to the ICEVs. We find that the relative contributions towards total life cycle emissions differ significantly between the BEV and ICEVs, but that relative contributions also vary within the BEV category depending on the charging electricity mix utilized. The BEV has higher production emissions than ICEVs, primarily due to the Li-ion battery, where about 70% of the production emissions stem from battery cells deriving mostly from the cathode active material. Based on a total mileage of 250 000 km, the BEV offers a GHG emissions reduction compared to the ICEVs when charged with the average Norwegian and European electricity mixes while the Global average results in similar emissions as the ICEVs. Maintenance emissions contribute very little to overall emissions for both BEVs and ICEVs. The BEV has higher EOL emissions than the ICEVs due to the energy intensive hydrometallurgical treatment of the Li-ion batteries; this electricity use in the treatment process is the highest contributor to battery recycling emissions. When we compare GHG emission contributions for the BEV to that of the ICEVs, we generally find that there is a shift from WTW emissions to equipment life cycle emissions as the BEV has considerably higher emissions from production as well as EOL treatment than the conventional vehicles.

3.2 Other environmental impact potentials

To obtain a holistic perspective of the environmental performance of the three vehicle technologies, we consider six additional environmental impact potentials including FETP, ODP, FEP, TAP, PMFP, and HTP. Figure 4 presents the relative environmental performance of the vehicles and the contribution shares to impact potentials.

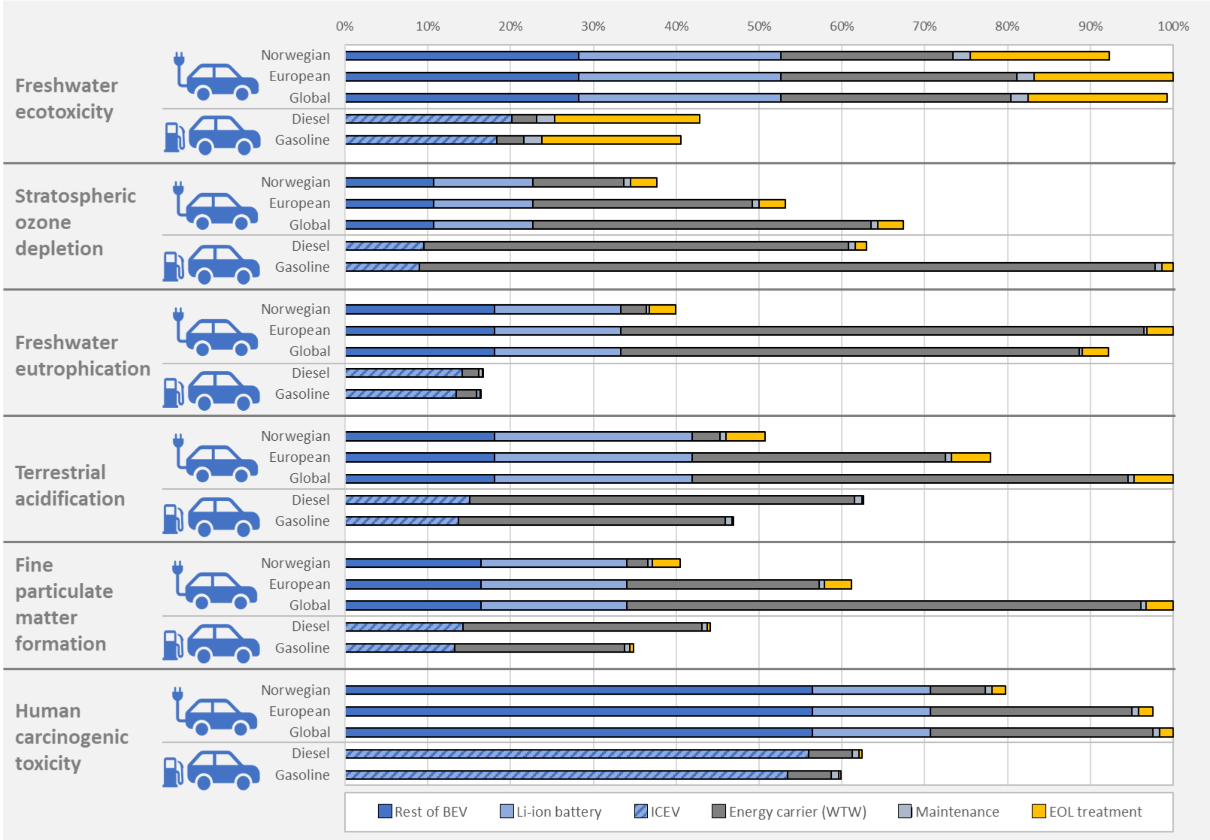

Figure 4: Life cycle environmental impacts of electric and diesel and gasoline passenger vehicles

When comparing the environmental performance of the BEV against the ICEVs across a wide range of environmental impact categories, we find that it offers somewhat limited benefits. As for GWP, the relative environmental performance of the BEV often depends on whether the WTW impacts are low enough to compensate for the higher impacts deriving from production. In contrast to GWP results, we find that the BEV may in fact have a higher environmental load compared to the ICEVs regardless of electricity mix as the production impacts impose too high of a constraint and to some extent because the WTW impacts may also be prohibitively high. Across the six impact categories considered in Figure 4, the high production impact of the BEV pertaining to battery production particularly relates to metals used in the active cathode material (NMC-622) and the anode current collector (Cu), where especially sulfidic tailings from mining are associated with high impact.

3.3 Sensitivity analyses

In the sensitivity analyses, we assessed alternative battery sizes of 60 kWh and 100 kWh for the BEV as well as implementation of a battery swap that involve replacement of all battery modules. Figure 5 reports the GWP results (g CO_2-eq/km) as a function of carbon intensity of the charging electricity (g CO_2-eq/kWh). In the figure, solid lines denote results from the baseline analysis (results of the ICEVs are straight lines as these results are not affected by the carbon intensity of the charging electricity), while dashed lines denote the battery size sensitivity analysis and the dotted line denotes the battery swap sensitivity analysis.

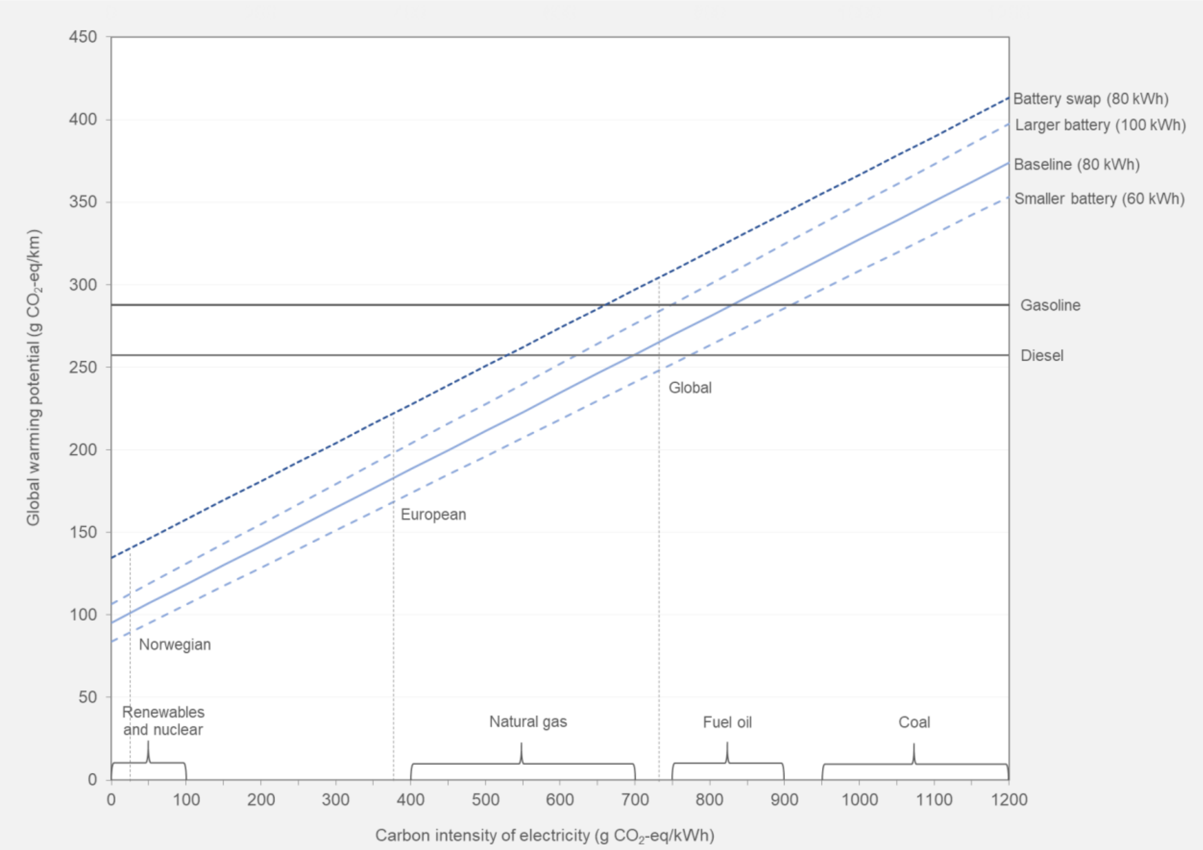

Figure 5: Sensitivity analyses considering battery size and replacement as a function of electricity carbon intensity

Lowering battery demand, whether it is in terms of battery capacity or avoiding replacement, is found to be highly beneficial for the BEV. The more carbon intensive the electricity mix is, the more important the battery size becomes as battery weight affects the electricity use during driving; the GHG emission differences between the BEV with the largest and smallest battery packs are 23, 30, and 36 g CO_2-eq/km when using an average Norwegian, European, and Global electricity mix, respectively. If swapping all battery modules becomes necessary, BEV GHG emissions increase by 39 g CO_2-eq/km, which places stricter carbon intensity requirements on the charging electricity for the BEV to outperform the ICEVs in terms of GWP. This is a conservative scenario as it is technically feasible to only replace the battery modules that are faulty, rather than all the modules/cells. As for the sensitivity analysis considering battery size, we see again that the carbon intensity is an important factor towards determining GWP benefits of BEVs versus ICEVs.

4 Discussion and conclusion

The goal of the study was to evaluate the environmental performance of a D-segment BEV and compare its performance to that of equally sized ICEVs. To this end, we assessed an 80 kWh BEV using different electricity mixes and compared its environmental impact potentials against that of diesel and gasoline vehicles across seven impact categories.

Generally, we found that a change from a conventional to an electric powertrain results in problem shifting between life cycle stages as well as impact categories. This problem shifting is mainly due to battery production and charging energy, with the magnitude depending on the impact category and electricity mix selected. In terms of climate emissions, the problem shifting can greatly benefit the BEV depending on the electricity mix used for charging, but for other impact categories the higher production impacts and effects from changing the energy carrier to electricity may limit the opportunity to provide wider environmental benefits.

Through the sensitivity analysis considering battery size, we found that consumer choice in battery size significantly influences the life cycle GHG emissions of the BEV and that the choice has a larger consequence in areas with more carbon intensive electricity mixes. This finding indicates that climate conscious consumers can affect the climate footprint of their vehicle beyond how much they drive the vehicle, as the chosen battery size affects resulting impacts deriving from production, use, and EOL treatment. Nonetheless, the carbon intensity of the electricity mix has an overridingly large effect on lifecycle impacts compared to these consumer choices, and efforts made to green global electricity mixes will likely reduce the regional differences over time.

Although efforts were made to model the technologies and their performance as objectively and realistically as possible, the presented results should be viewed as indicative rather than a definite answer of environmental performance. For example, LCA studies considering Li-ion battery technologies and materials report that environmental impacts may vary significantly depending on supply chains differences such as regional variations and production technologies [21]–[23]. As such, one must expect that battery production impacts vary and differ from results reported here. Uncertainty regarding battery lifetime was assessed in a sensitivity analysis showing the effect a replacement of all battery modules would have on life cycle GHG emissions. Another important source of uncertainty and variability pertains to the assumed energy use of the vehicles; we aimed to model average electricity and fuel use that we deemed representative for D-segment vehicles, but we would like to point out that there are differences in energy use between vehicles within the same size segment – not just between vehicle brands but also within vehicle models.

From an environmental perspective, our results suggest that policy makers can indirectly improve environmental performance of BEVs through policies pertaining to greening the electricity sector, which affects both battery production (in battery producing countries) and charging as well as legislating battery recycling that ensures recovery of high impact and critical battery materials. Vehicle manufacturers may address these issues by shifting battery cell production to areas that reduce the negative environmental impacts of this part of the BEV production, and enable replacement of faulty modules or cells rather than complete battery packs. Since battery production is a main source of impacts for the BEV, increased use of recycled battery materials or components may offer an opportunity to improve the environmental performance of BEVs. As such, closing battery materials loops through a high degree of battery recycling for reuse in batteries is highly beneficial. Because BEV technology, and particularly battery technology, as well as electricity generation are developing, it is important to assess the environmental impacts of BEVs regularly. This is both to ensure that the development is progressing in an environmentally desirable direction and to allow policy makers to identify strategic measures to obtain impact reductions, since these may change over time.

Acknowledgments

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Presenter Biography

Linda Ager-Wick Ellingsen is a senior researcher at the Institute of Transport Economics with a doctorate in industrial ecology focusing on LCA of Li-ion traction batteries. She has worked extensively with LCA on battery, energy, and transport technologies. Her work includes LCA of Li-ion traction batteries for land transport (light- and heavy-duty vehicles) and marine applications (supply vessels, express boats, and tank ships). In addition, she has also worked with novel battery chemistries, such as silicon anodes and Al-ion batteries for energy storage applications.

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