

Life cycle assessment of electric vehicles in shuttle traffic - field test results of the project RheinMobil

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Summary

The RheinMobil field test investigated potential ecological benefits of BEVs in cross-border shuttle traffic. For over 2.5 years and 450,000 km, driving profiles, and energy consumption data was collected from seven minivan BEVs used by commuting shift workers. The average TTW energy consumption was 231 Wh/km, significantly higher than the stated NECD value. The LCA results show that under the specific use profiles of RheinMobil the application of BEVs leads to notable benefits in the global warming potential compared to ICEVs, but not in all investigated impact categories, e.g. the acidification potential.

Keywords: Electric vehicles, Life Cycle Assessment (LCA), Environmental analysis, Field test, Shuttle traffic

1 Introduction

Within the last years, the environmental profile of battery electric vehicle (BEV) concepts has been analyzed in several Life Cycle Assessment (LCA) studies and research projects, covering detailed analysis of the complete vehicle life cycle (e.g. [1][2]) as well as focusing on specific fields of use based on empirical data collected in fleet operations (e.g. [3][4]). A literature overview of previous studies discussing BEV emissions and LCA for various countries can be found in [5], which focusses on the empirical time-dependent CO₂ emissions of cross-border commuters. These studies indicate that BEVs with a high lifetime mileage, which are charged with a low emission energy mix, can reduce the environmental impacts. In this line of research, the study at hand presents the LCA of the RheinMobil BEVs, which were deployed in two mobility applications with a distinctively high operating grade.

The project RheinMobil [6] was a long-term cross-border demonstration project, carried out from 2012-2015 between Germany and France to demonstrate the technical, economic and ecological feasibility of BEVs used in company fleets. Two BEV types were deployed. Six electric minivans to commuting shift workers and one compact class EV for business trips during working hours. Over the 2.5 years, the BEVs traveled over 450,000 km. Due to the high degree of utilization with monthly average mileages from 1,500-3,000 km per BEV, the regular use of DC-fast charging was required. Based on the collected empirical powertrain and GPS data as well as the BEV detailed technological specifications this study presents a LCA to quantify the environmental impacts considering material extraction, production, utilization until

recovery, and disposal at the end of life. The results are presented in the example of the commuters and set in contrast to comparable internal combustion engine vehicles (ICEV).

2 Methodology, data, and main assumptions

When calculating the environmental impacts based on a LCA a detailed description of the methodology and data for the production, utilization and recycling phase is required to ensure transparency. In the following chapter, the first part describes the system boundaries, underlying calculations, input data, and main assumptions for the overall LCA assessment approach while the second part focuses on the empirical energy consumption.

2.1 Environmental assessment approach using LCA

The following chapter gives a brief introduction to the methodological approach of quantifying environmental impacts of product life cycles using LCA and summarizes the relevant boundary conditions and made assumptions for the analysis of the RheinMobil use case.

2.1.1 Life Cycle Assessment method

Life Cycle Assessment is a recognized method for the quantification of environmental impacts that occur throughout the life cycle of products, systems or services by using process chain analysis, energy, and mass flow analysis. To ensure the transparency of results, LCA studies are standardized according to ISO 14040 [7] and 14044 [8], which provide a clear framework for the procedure and interpretation of results.

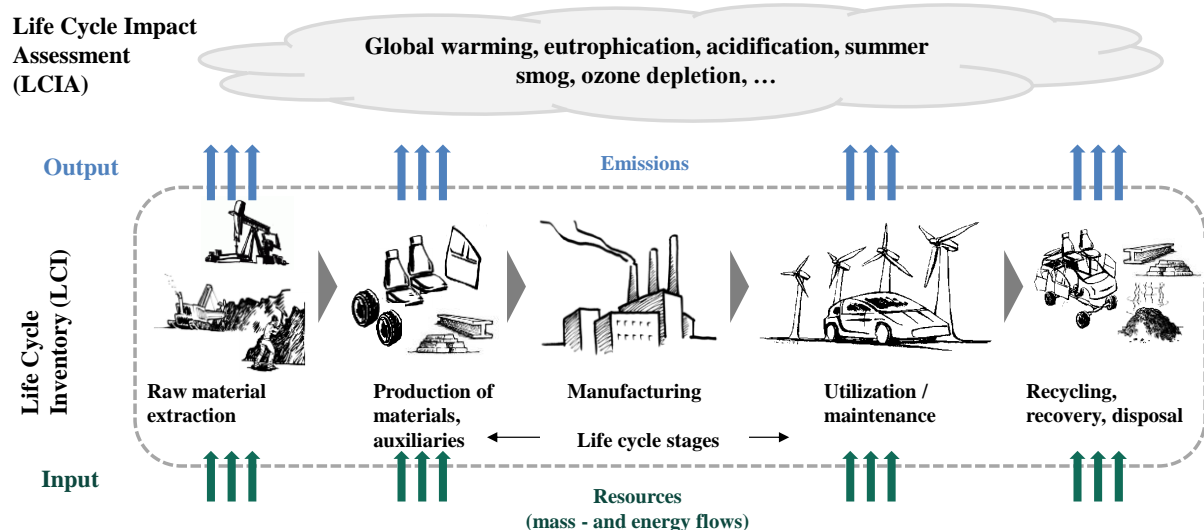


Figure 1: Environmental analysis of product life cycles using LCA

A LCA study accounts for all life cycle stages: from the extraction of raw materials, the processing of materials and auxiliaries, the manufacturing and utilization of the product, until it's recycling, recovery, and disposal at the end of the product life. A LCA study follows four main steps that include the definition of the goal and scope of the study, the definition of the investigated function of the product described by the functional unit, the life cycle inventory (LCI) which includes the collection of all relevant data and information, the life cycle impact assessment (LCIA) where the environmental impacts are calculated and finally the interpretation of results. The calculation of environmental impacts in the LCIA is carried out by two steps. First, all caused emissions in the life cycle are classified according to their contribution to environmental effects, e.g. CO₂ and methane to Global Warming. In the second step, the emissions are summarized and characterized by their impact on environmental effects, using weighting factors and impact categories that are expressed by a reference unit, e.g. Global Warming Potential (GWP), reference unit kg CO₂-equivalent (kg CO₂-equiv.). Using the characterization model of CML2001, NOV16 [9], the factor of CO₂ to GWP is 1; for methane 28.

Since LCA studies require a huge amount of inventory data which result in a high complexity, professional LCA databases are used, that provide all required data and information related to the background system,

e.g. complete process and production chains of used materials or energies, which allow the modelling of the considered product life cycle within a LCA software.

2.1.2 LCA screening model and main assumptions for the RheinMobil LCA

To allow a LCA analysis throughout the whole vehicle life cycles and to ensure a reliable comparison to ICEVs (gasoline and diesel), an internal LCA screening model of IBP was used, that allows the calculation specific vehicle layouts, power train concepts and technologies, which was fed with collected utilization profiles from the fleet operation. The screening model was created within the LCA Software GaBi [10] with access to the complete extent of corresponding LCA databases.

Table 1: Boundary conditions and main assumptions based on empirical RheinMobil data [6]

Boundary conditions and main assumptions for minivans used in operation of commuting shift workers	BEV	ICEV, gasoline	ICEV, diesel	Comment
Production phase				
Vehicle mass [kg]	1,700	1,360	1,400	
Battery system: Technology / Storage capacity [kWh] / Total mass [kg]	Li-Ion (NMC/C) / 24.2 kWh / 250 kg			
Power electronics (inverters, etc.) mass [kg]	35			
Engine performance [kW]	60	81	63	
Engine displacement, combustion engine[l]	-	1.6	1.5	
Utilization				
Vehicle lifetime [a]	12			
Battery life for maintenance scenario [change interval after km traveled]	200,000	-	-	
Average trip distance [km/trip]	~73			
Average monthly mileage [km/month]	~3,000			
Assumed total mileage of base scenario [km/lifetime]	400,000			
Average speed [km/h]	57			
Average energy consumption [kWh/100km]	23.1	-	-	Measured average value in fleet operation
Energy consumption stated by manufacturer (NEDC) [kWh/100 km]	20.0	-	-	Data sheet manufacturer
Additional energy demand due to loss of load	15%	-	-	Measured in fleet operation
Fuel consumption of ICEV [l/100km]	-	8.13*	5.5**	*measured value in field test **assumption, 12% higher than NEDC value (based on measured deviation of gasoline vehicle)
Calculation of tailpipe emission profile based on HBEFA 3.2 [11], EURO 6 standard (vehicles with cylinder capacity from 1,4-2,1 l), calculation of CO ₂ and SO ₂ (fuel: 10 ppm sulfur content) emissions based on fuel consumption values				
<i>Global Warming Potential of electricity generation mix for charging</i>				
German electricity grid mix [g CO ₂ -eq./kWh]	610	-	-	GaBi Database, reference year 2010
French electricity grid mix [g CO ₂ -eq./kWh]	95	-	-	GaBi Database, reference year 2010
RheinMobil-Mix (50% DE / 50% FR) [g CO ₂ -eq./kWh]	352	-	-	calculated
Renewable Energies Mix, Germany [g CO ₂ -eq./kWh]	86	-	-	Assumption based on the German renewable energy mix, 2012
Electricity generation from wind power [g CO ₂ -eq./kWh]	12	-	-	GaBi Database, reference year 2010
End of Life				
Calculation according to cut-off approach according to [12]				

The screening model of the production phase includes the complete production chain of used materials and auxiliaries as well as all relevant production process steps. For simplification, the production of the car body is represented by an average material mix and underlying production processes (such as bending and stamping of steel sheets, cast molding, or injection molding of plastics), whereas the power train specific assemblies and components are represented in more detail to allow a deeper interpretation. To adapt the screening model to the specifications of the investigated vehicles, a comprehensive set of parameters was used that allows the adjustment of single components according to technical properties, dimensioning¹ as well as deeper adjustments of material mixes.

The utilization model considers the energy consumption and occurring emissions during vehicle use and maintenance. It is adjusted according to location-specific boundary conditions (e.g. local energy or

¹ e.g. battery system: Battery technology, cell chemistry, cell type, energy density, total storage capacity, mass of mechanical components and final mass of the battery system

electricity mix) and driving profiles in the investigated field of use. For the calculation of exhaust gas emission of combustion engines, the emission factors of the HBEFA v3.2 [11] are used, providing a comprehensive estimate of exhaust gas emissions, related to the specific drive situations.

The end of life model primarily accounts for the recycling of conventional materials, such as steel, iron, copper or aluminum and thermal recovery of plastics through waste incineration. Due to lack of data, battery recycling scenarios have been investigated but were not accounted for the main analysis. In the framework of this analysis, no credits are given for the recycling or recovery of materials. Table 1 summarizes the main boundary conditions and assumptions for the LCA study.

2.2 Energy model and field-test data collection

The basis for assessing BEV emissions and comparable emission savings during operations is the energy consumption. Previous empirical studies have demonstrated that standardized driving cycles, e.g. the New European Driving Cycle (NEDC) provide no reliable basis for estimating the energy consumption. The real-world consumption is usually higher and dependent on various factors such as driving profiles, driver behavior, battery technology, and the varying use of auxiliaries [13]-[15]. For obvious reasons, these cannot be included in standardized driving cycles but should be considered for a realistic LCA. Therefore, a detailed long-term empirical analysis of the energy consumption was carried out in the project. A detailed description of the empirical data, as well as a corresponding theoretical energy consumption model for the RheinMobil BEVs, can be found in Schücking et al. [16].

The tank-to-wheel (TTW) energy consumption was calculated based on battery and powertrain data. The state of charge (SOC) values at the start and end of the individual trips showed high sensitivities to temperature, load profiles, and other factors. Therefore, they provided no reliable source to assess the energy consumption. Instead, the energy consumption for each trip was calculated based on the constantly measured values of battery current (I^{Bat}) and voltage (U^{Bat}).

$$E_{total}^{Trip} = \left(\sum_{i=Start+1}^{End} \frac{(I_i^{Bat} + I_{i-1}^{Bat})}{2} \times \frac{(U_i^{Bat} + U_{i-1}^{Bat})}{2} \times \Delta t_{i,i-1} \right) \quad (1)$$

$$E_{specific}^{Trip} = \frac{E_{total}^{Trip}}{D^{Trip}} \quad (2)$$

For each data point during the trip the average battery current and voltage the average from it and the previous point was calculated. Both values were multiplied to get the average power demand and again multiplied by the time difference $\Delta t_{i,i-1}$ between the two data points to get the energy consumption (eq. 1). By this way of assessment the energy consumption includes the energy required for propulsion, the energy gained through regenerative braking, and the energy consumed by the auxiliaries. To get the value of the specific energy consumption the total energy consumption per trip was divided by the covered distance measured by GPS as well as an odometer (eq. 2).

The BEVs were equipped with data loggers recording powertrain and GPS data. The powertrain data loggers were connected to the BEV CAN bus system and the battery data came from the BEV battery management system (BMS). While driving the following powertrain and GPS data was recorded with a resolution of 0.05 Hz: date and time, parameters of the high-voltage battery, such as voltage, battery current, medium cell temperature, and SOC, speed and odometer based on axis turning, GPS height, GPS odometer, GPS speed, GPS position latitude and longitude.

3 Results

The results are presented in two parts. In the first part, the empirical energy consumption data of the electric minivans used by the RheinMobil commuters is presented. In the second part, based on the empirical data as well as the other input data and assumptions, the LCIA is conducted and the influences of mileage and energy mix on different impact categories are assessed.

3.1 Empirical energy consumption

The analysis of the long-term specific energy consumption is based on average monthly values. Even though all BEVs were deployed on constant routes the values for the individual trips showed a high variance most likely depending on a combination of different factors such as time of day, the direction of

travel, or current driver. Since these effects are not subject to this study, average values provide sufficient information for the LCA.

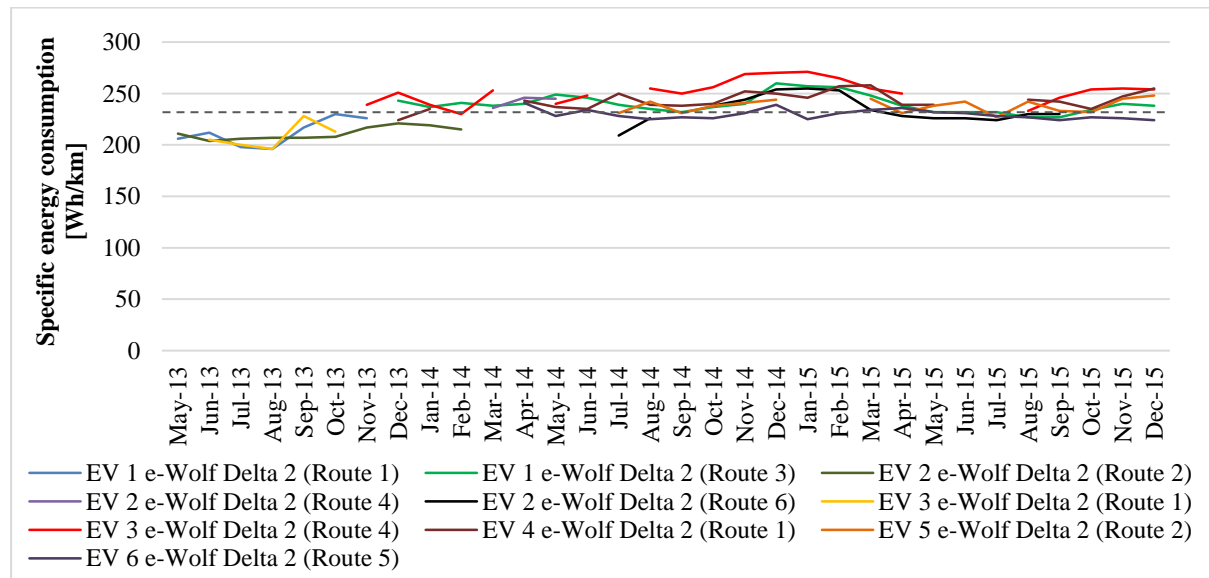


Figure 2: Monthly average specific energy consumption (TTW) of the RheinMobil commuter BEVs

From the empirical data of the monthly average values two differences between the six vehicles and routes can be observed (Fig. 2). Firstly, the energy consumption varies between the routes. This effect can be explained by the different route profiles. For example, Route 4 had the largest share of motorway and accordingly the highest average speed of all commuting routes with 60 km/h. This leads to the highest specific energy consumption due to the additional losses from drag. Secondly, fluctuations on the individual routes throughout the year can be observed. Identifying the main influence factors for this phenomenon is more challenging. In some cases, the route changed for a certain period due to the absence of commuter group members. The most obvious fluctuation can be seen between winter and summer. Between November 2014 and March 2015, Figure 2 shows an increase in specific energy consumption for almost all e-Wolf Delta 2 of around 20 Wh/km. This can be explained by the outside temperature. However, in contrast to other empirical research, the increase cannot directly be explained with additional auxiliary demand, especially for heating the passenger cabin. The heating was done with Biodiesel to avoid this effect. A more detailed analysis revealed that a combination of battery chemistry and BMS was responsible. At lower outside temperatures the average battery cell temperature decreases. This leads to an increase in inner resistance and a decrease in battery efficiency. Additionally, to avoid potentially harmful effects of higher currents at these lower temperatures the BMS also decreased the recuperation power. When breaking, less energy is stored back into the battery but rather lost through mechanical breaking. A more detailed analysis of the empirical results and the influencing factors has been presented by Schücking et al. [16]. Concluding it should be noticed that on annual average the specific energy consumption (TTW) lay at around 231 Wh/km (indicated by the dotted line in Figure 2), which is significantly higher than the NEDC value stated by the manufacturer (Table 1). This value was taken as input for the LCA.

3.2 Life Cycle Impact Assessment

In the following, based on the specific frame conditions of the RheinMobil use case, the LCIA results are primarily presented and discussed for the global warming potential (GWP) and acidification potential (AP). For these impact categories, the relevant technical parameters and influencing factors are presented and discussed for each life cycle stage and in relation to the whole vehicle life cycle. Furthermore, a more detailed view is given for the use phase related parameters since these are of major importance in terms of an environmentally beneficial application of BEVs.

3.2.1 LCIA results, based on the RheinMobil frame conditions

Figure 3 presents the results of the BEV use case of the minivans in use for commuting of shift workers as well as for the comparable minivans with internal combustion engines (gasoline and diesel). The results of the production and use phase are presented separately in more detail. This allows conclusions about the

relevance of single components and influencing factors. The results of the use phase are furthermore presented for two electricity mixes: The mix used in the RheinMobil project (50% DE/50% FR, see Tab.1) and the German electricity mix from renewable energy generation as a scenario. In addition, bandwidths of the use phase impacts related to the measured min. /max. energy consumption of the vehicles is marked.

The results of the production phase show significantly higher impacts of the EV compared to the ICEV, mainly due to the production of the battery system and the extraction and processing of required active material for producing battery cells, in this case, graphite (anode) and Li-NMC (cathode). This can be explained by the fact, that these high-tech materials, on the one hand, represent a significant share in the material mix of the battery systems. On the other hand, these materials have significantly higher environmental impacts in the extraction and processing than conventional materials used in the vehicle production, such as iron-steel, non-ferrous and light weight metals, polymers etc. Hence, the dimensioning and the impacts of the production of the battery system in BEVs have a significant impact on the environmental profile of BEV life cycles. A high potential to reduce these impacts is expected in the implementation of suitable recycling processing and hence to increase the share of secondary material sources in long-term.

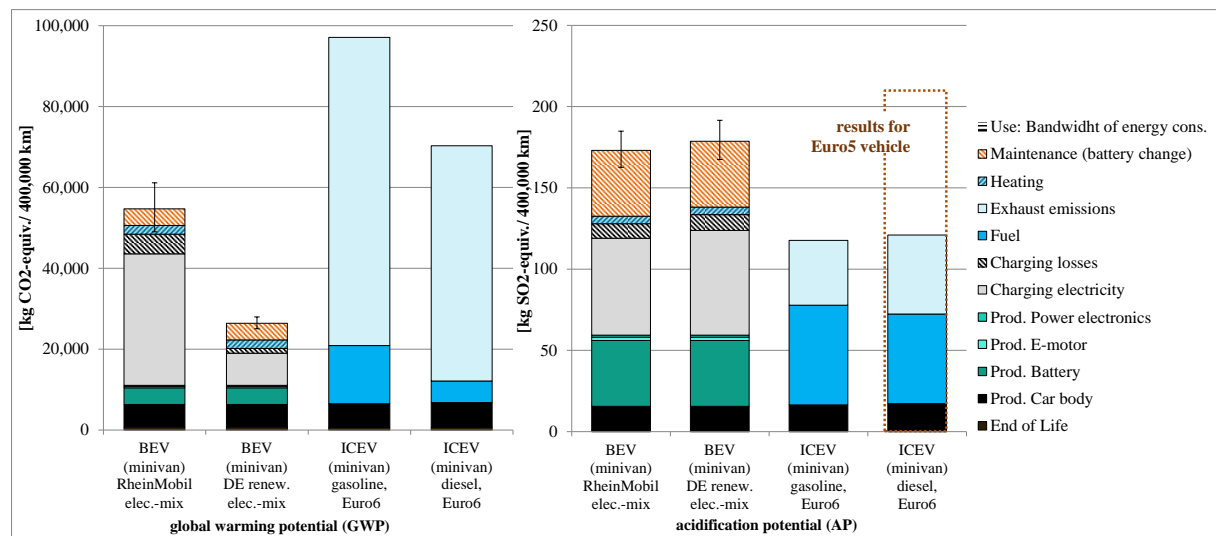


Figure 3: LCIA results of minivan operation in commuter traffic in the use case of the RheinMobil project at the example of the GWP and AP

Furthermore, the results of the GWP show that the higher impact of the BEV production can be compensated by lower impacts during the assumed utilization phase of 400,000 km mileage over 12 years. Main influencing factors of the use phase are the specific energy consumption of the vehicles in the considered use context, the total mileage, the environmental profile of used electricity mix for charging and if required, the maintenance or change of the battery system during the use phase.

Due to the high mileage of the minivans in multi-shift operation, significant improvements can be reached for the GWP compared to the operation of comparable minivans with combustion engines. Based on the boundary conditions of the RheinMobil project, the impacts to the GWP can be reduced by ~15 T CO₂-equiv. (diesel vehicle) and ~42 t CO₂-equiv. (gasoline vehicle). In the case of the renewable energy mix scenario, improvements from ~44 t CO₂-equiv. (diesel vehicle) to ~70 t CO₂-equiv. (gasoline vehicle) are possible, which shows the high potential of electric mobility when using electricity from renewable energy sources. However, to avoid a simple shift of burden in the electricity grid mix, these renewable energies have to be provided from additional installed power plants.

The analysis of impacts to the AP shows, that the relevance of the BEV production phase further increases in relation to the life cycle, mainly due to the production of the battery system and used active materials. Accordingly, the dimensioning, as well as the useful lifetime of the battery, is of high importance, as a change of the battery system would significantly increase the overall life cycle impacts. Based on the given boundary conditions of the RheinMobil use case, the higher impacts to the AP of the BEV production phase cannot be compensated against ICEVs during the vehicle operation. Regarding the lifecycle of the ICEV, the main contribution to the AP is caused in the fuel production routes (mainly due to released SO₂, NO_x and NH₃ emissions during production process chain) and the vehicle operation (Relevant exhaust gas

emissions are NH₃, NO). Furthermore, the impact to the AP of the diesel vehicles is strongly depending on the emission standard of the vehicle, due to stricter limitations of NO_x emission from EURO 5 (180 mg NO_x/km) to EURO 6 (80 mg NO_x/km) [17]. According to HBEFA, the calculated emission factors of NO_x over the investigated driving profile deviate from these limit values (EURO 5: ~500 mg/km, EURO 6 ~174 mg/km). Based on these assumptions the AP of an EURO5 Diesel vehicle is ~ 60% higher compared to an EURO 6 diesel vehicle, market with the dotted line in Fig. 3.

As shown above, the contribution of single components or life cycle stages can significantly vary depending on the investigated impact category. Therefore, to ensure a reliable interpretation, LCA studies need to comprise a full set of relevant impact categories. As it is not possible to discuss all results of investigated impact categories in this paper, the main results are summarized in Table 2 referring to the functional unit of 1 km traveled².

Table 2: LCIA results of investigated vehicles under the use case of the RheinMobil project

Impact category	Acidification potential (AP)	Eutrophication potential (EP)	Global Warming Potential (GWP)	Primary energy demand (non-renewable) (PED)
Reference unit	[kg SO ₂ -equiv./km]	[kg phosphate-equiv./km]	[kg CO ₂ -equiv./km]	[MJPE/km]
Environmental profile of commuting of shift workers				
Assumptions: No change of battery during use phase required; Total mileage 400,000 km				
Electric minivan, RheinMobil electricity mix	3,3E-04	3,0E-05	0,126	2,8
Electric minivan, German (DE) renewable energy mix	3,5E-04	4,5E-05	0,056	0,7
Minivan, gasoline engine	3,0E-04	4,8E-05	0,243	3,2
Minivan, diesel engine	3,0E-04	8,1E-05	0,176	2,4
Environmental profile of commuting of shift workers				
Assumptions: One battery change required during use phase; Total mileage 400,000 km				
Electric minivan, RheinMobil electricity mix	4,3E-04	3,5E-05	0,137	3,0
Electric minivan, RheinMobil electricity mix	4,5E-04	4,9E-05	0,066	0,8

3.2.2 Use phase parameters: The influence of mileage and energy mix

For better understanding the required frame conditions for an environmental beneficial application of BEVs used by commuting shift workers, the following analysis investigates the influence of the use phase related parameters in more detail. To do this, the LCA results are demonstrated at the example of the GWP and AP of the BEVs deployed for commuting shift workers. The GWP (Fig. 4) and AP (Fig. 5) of one BEV and corresponding ICEV over the full vehicle life cycle are presented related to total mileage and used electricity mix for charging as well as break-even points compared to the ICEV.

The higher environmental impacts of BEV production compared to ICEV are represented with the kg CO₂-equiv. offset values at kilometer “0”. As discussed above, the higher impacts of the production have to be compensated during the vehicle’s use phase for gaining an environmental benefit compared to the ICEV. This requires a high operation grade (lifetime mileage) as well as the use of a suitable electricity mix for charging. As Figure 4 shows, based on the boundary conditions and operation profiles of the RheinMobil vehicles and depending on the used electricity mix, break-evens compared to the gasoline ICEV are reached in a range of 25,000 km to 80,000 km and 30,000 km to 75,000 km for the diesel ICEV (whereas no break-even is reached with the German electricity mix).

² Results to the photochemical ozone creation potential are not presented in this paper, due to the character of the CML impact method for nitrogen oxide emissions, which would require more detailed explanation and discussion for better interpretation.

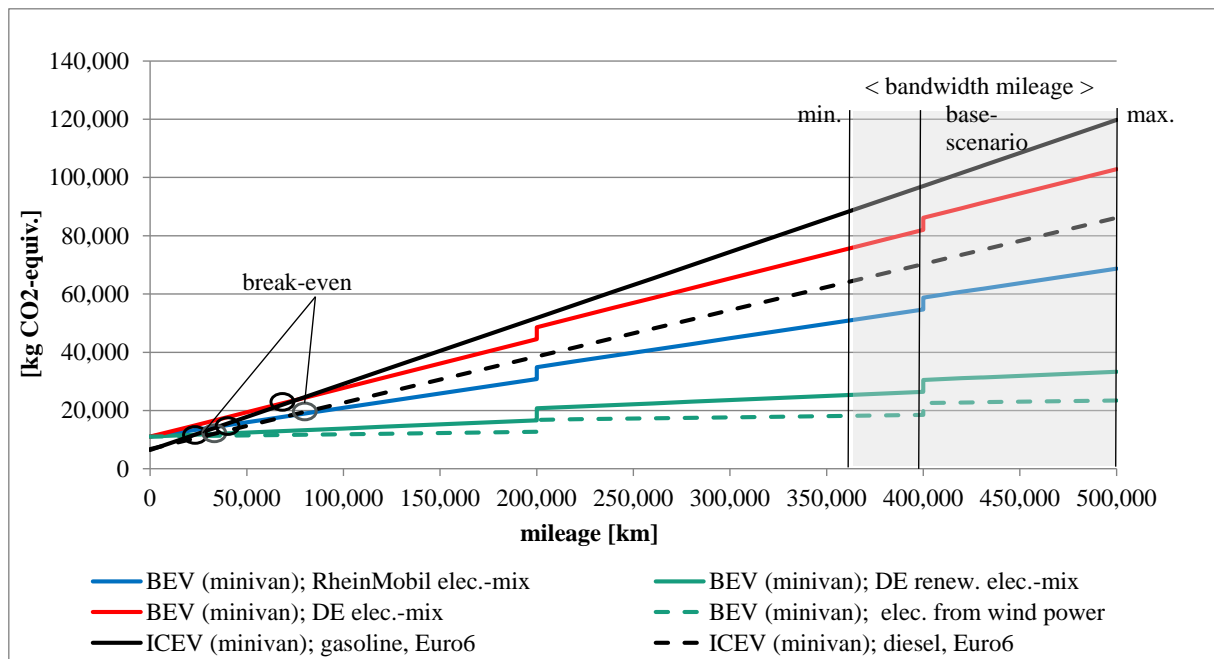


Figure 4: GWP results of the BEV based on the RheinMobil operation profiles and boundary conditions

In the case of AP, the impact of the production phase of the BEV is significantly higher than from the ICEV. If a change of the battery is required during the utilization phase (in this assumption after 200,000 km) the impacts of the BEV further increase to a point where the higher impacts cannot be compensated over the total mileage of 400,000 km. In this investigated case, notable improvements of the AP of the BEV compared to the diesel and gasoline vehicle can only be reached, if no change of the battery system is required during the use phase and electricity from wind power is used for charging the vehicle. Then, the break-even compared to the ICEV would be reached at ~185.000 km. Table 3 summarizes the calculated break-even points of further investigated impact categories as well as for the scenario that assumes a battery change after 200,000 km mileage.

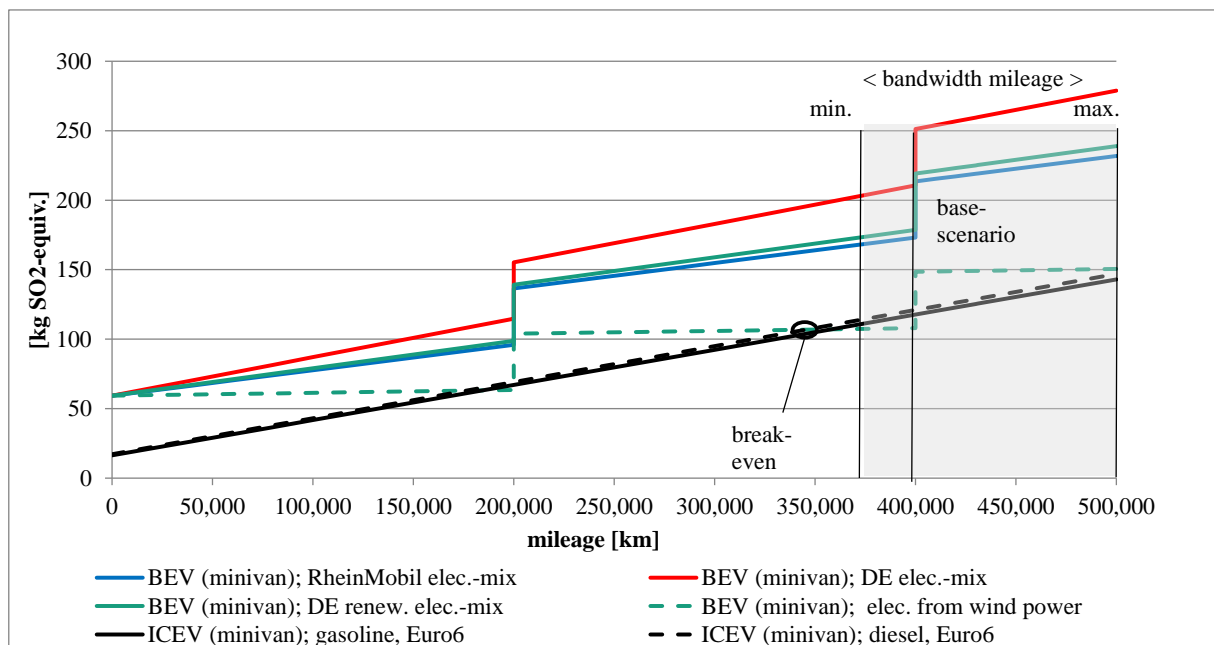


Figure 5: AP results of the BEV based on the RheinMobil operation profiles and boundary conditions

Table 3: Calculated break-even mileage of BEVs to ICEVs for the RheinMobil use case

	Acidification Potential (AP)	Eutrophication Potential (EP)	Global Warming Potential (GWP)	Primary energy demand (non-renewable) (PED)
Break-even against gasoline vehicle (rounded to 5,000 km); [including 1 battery change during use phase]				
Electricity mix „RheinMobil“	-	85,000 km	40,000 km	100,000 km [210,000 km]
German (DE) electricity mix	-	205,000 km [400,000 km]	80,000 km	75,000 km
German (DE) renewable energy mix	-	245,000 km	25,000 km	20,000 km
Electricity from wind power	185,000 km [360,000 km]	45,000 km	25,000 km	20,000 km
Break-even against diesel vehicle (rounded to 5,000 km); [including 1 battery change during use phase]				
Electricity mix „RheinMobil“	-	35,000 km	75,000 km	-
German (DE) electricity mix	-	45,000 km	-	-
German (DE) renewable energy mix	-	45,000 km	35,000 km	30,000 km
Electricity from wind power	175,000 km [340,000 km]	25,000 km	30,000 km	25,000 km

4 Summary and Discussion

The results of the LCA study of the RheinMobil fleet shows, that the operation of BEVs in commuter traffic of shift workers can lead to environmental benefits in comparison to the operation of conventional fuel based vehicles. In particular, environmental benefits have been identified for the impact categories GWP, EP, and PED. However, there are also impact categories, where no improvements to ICEVs can be reached, e.g. in the case of the AP. Main influencing factors to reach these benefits are the tailored dimension of vehicles and energy storage (battery system). BEVs show higher environmental impacts in the production phase than ICEVs, which is mainly due to the comparatively high impacts of the battery production resulting from the extraction and processing of required active materials (anode, cathode) in the battery cells. Currently, these higher impacts of BEVs compared to ICEVs can only be compensated by the lower impacts during the use phase. In this regard, the environmental profile of the used electricity mix for charging the vehicles, as well as the capacity utilization of vehicles, is of major importance.

Based on these results three generalized boundary conditions for ensuring the environmental beneficial application of BEVs in different fields of use can be stated: Firstly, a high utilization (mileage) of vehicles is required to compensate the higher environmental impact during the production phase. Secondly, the long-term supply of charging electricity from additional installed renewable besides already installed renewable power generation of local power grids has to be secured to avoid a shift of burdens. Thirdly, purchasers have to choose tailored vehicle designs according to designated fields of use and individual utilization patterns.

Since the production of the battery system is a relevant driver of environmental impacts of the BEV production phase, significant oversizing of the storage capacity respective of the electrical range should be avoided. Due to the growing variety of BEV/ HEV models and layouts on the market, potential users can choose proper BEVs according to their specific requirements for daily use and boundary conditions. From an environmental (and economic) point of view BEV deployment in mobility applications with moderate individual trips, a high frequency of use as well as the possibility for recharging with a low emission electricity mix between the trips is ideal.

Due to several limitations, generalizing the results and conclusions into a broader context must be done cautiously. The cross-border commuter application, as well as the deployed BEV technology, represents a unique combination. For future research concerning the application, various use profiles could be compared in one study to allow for broader conclusions. Furthermore, the increasing variety of vehicle models and designs, as well as the high influence of boundary conditions during vehicle operation also show that no generalized statements on the environmental performance or benefits against ICEVs can be drawn. Moreover, reliable evaluations of ecological benefits of BEVs rather require detailed analysis taking use case specific and local-dependent boundary conditions into account. Concerning the technology, we are

currently still in an early stage of BEV development. Changes especially in the battery materials, production processes and lifetime will have a major impact on the LCIA results. Also, more detailed information about the recycling phase will become available once the first generations of BEVs are scrapped. Therefore, future research should expand the models by including the newest technical developments and empirical data, to ensure that the introduction of BEVs into the transport sector leads to long-term environmental benefits.

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