ASSESSMENT OF ENVIRONMENTAL EFFECTS OF ELECTRIC VEHICLES

REPORT FOR PROJECT BASED INTERNSHIP

DIGNIQUE TECHLAB

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ACKNOWLEGEMENT

We express our deep sense of gratitude to all almighty for his blessing without which completion of work wouldn’t be possible .Our project wouldn’t have been successful without the assistance and help rendered by each of them. We wish to express our profound sense of gratitude and sincere thanks to our project mentor **Mr Ashish Jha,** who give expert guidance, support, encouragement and valuable suggestion throughout the project work. We also own thanks for fruitful discussions to our friends for their well wishes and all our colleagues who supported in the successful completion of this work.

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ABSTRACT

Under the impression of current discussions on depleting resources and environmental questions, the transportation sector is aware of its responsibility and pushes the development of alternative power train concepts. Especially electric vehicle concepts are investigated, since they decrease the dependency from oil based fuels and reduce local noise and emissions during the vehicle operation. By using renewable energies (e.g. wind power), e-mobility can contribute to a significant reduction of the climate balance of transportation. However, there is only little known about the life cycle impacts of e-mobility and respective vehicle components. Based on the method of life cycle assessment (LCA), this paper gives a first quantification on the environmental profile and relevant indicators of e-mobility.

Chapter 1: Introduction

In the framework of the Fraunhofer System Research for Electro mobility (FSEM), the department life cycle engineering (GaBi) investigates the environmental performance of different electric vehicle (EV) concepts. The main aim of the study is to give a first estimate on the bandwidth of the environmental potential of e-vehicle concepts and to identify the relevant indicators of e-mobility. Based on the outcomes of the study, the demand on further research is evaluated. Within this work, the production and use phase of different electric vehicle concepts, like battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are investigated. For a classification of the environmental performance of the EV concepts, the LCA results are compared to conventional vehicles with combustion engines (CVs). In addition, as a broader market entry of electric vehicles is expected in the next years (e.g. the national roadmap for electric mobility of the German federal government expects around one million electric vehicles on German streets until the year 2020[1]) the study analyses future scenarios to estimate the environmental profile of future concepts and developments. In a first step the scenarios investigate the environmental profile of future developments of the battery systems and the German electricity grid mix.

Chapter 2: Boundary Condition

The data used for this study is based on internal information within the FSEM project, available literature and results from previous studies. For keeping the transparency of results, the components and vehicles are modelled in a hierarchical structure and combined in a system model according to the structure presented in Table 1. The modelling is carried out with support of the LCA software GaBi 4 and its databases [2]. The reference location of the vehicle production and utilisation is Germany. Since the power grid mix (PGM) changes during use phase of the vehicles, a dynamical adjustment of the environmental profile of the power generation according to the lead study of the German federal ministry for the environment [3] has been taken into account. In addition, an alternative scenario is investigated where a straight use of additional installed wind power is assumed. Within the study, exemplified configurations of two battery electric vehicles (BEV) and one plug-in hybrid vehicle (PHEV) are evaluated. The environmental profiles of the CVs and the vehicle platforms are based on the material mix and of comparable vehicles classes [4-6] which have been scaled according to the vehicle and platform mass. The electric motor is based on the material mix of a permanent magnet synchronous motor (PMSM) which is scaled by the weight-to-power ratio [7]. The mass share of magnetic materials has been adjusted according to the average consumption in electric vehicles from around 2 kg, whereas the share of rare earths e.g. neodymium (Nd) or dysprosium (Dy) accounts for up to ~30% in sum [7-9]. The configuration and technical specification of the battery system is based on internal data of the FSEM project. Since there is currently only little information on the LCA of the production of EV batteries and related materials available, assumptions have been made based on from previous studies, available literature and material safety data sheets (MSDS) of Li-Ion battery cells (e.g. [10-14]). The power electronic components (e.g. inverters) are based on existing models of comparable components. At present, there is no information on vehicle or user specific utilisation profiles available. Therefore, the calculation of the energy and fuel consumption of the vehicles is based on the ADAC Eco-Test [15] and NEDC [16] driving cycles. The calculation method is based on a systematic approach developed during the FSEM project [17]. Due to the lack of available data, the impacts of the end of life phase and possible battery recycling concepts are not considered at this stage of the project.

Tab. 1: General boundary conditions

	BEV* (mini-class)	BEV* (compact-class)	PHEV hybrid* (compact-class)
Battery technology	Li-Ion ($LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$)		
Gravimetrical energy density of cells [Wh/kg]	135		
Energy content of battery [kWh]	20	40	14
E-motor PMSM [kW]	43	70	68
Power electronics [kg]	34	35	56
Combustion engine [kW]	-	-	41
Generator [kW]	-	-	41
Car platform and other parts [kg]	736	1,115	1,115
Total mass of EV [kg]	1,037	1,670	1,505
Energy consumption, electrical** [kWh/100 km]	18.7	22.9	20.4
Fuel consumption [l/100 km]***			6,9
Share of electrical mode [%]			80
Lifetime of battery system [years]	8		
Lifetime of other components [years]	12		
Mileage (daily/annual/lifetime) [km]	39/14,300/171,600		

*Exemplified vehicle concepts; **Calculation according to ADAC Eco-Test; ***Emission profile based on HBEFA3.1 [18]

Chapter 3: Results of the production and use phase

The results of the life cycle impact assessment (LCIA) are presented at the example of the global warming potential (GWP) and acidification potential (AP). It shows that due to the additional EV specific components, the share of the production phase of EVs considerably increases compared to the CVs, which is up to around 2 times in the GWP and around 2 to 4 times in the AP. The main contribution is due to the production of the battery system. Depending on the dimensioning in the EV concepts, the battery system causes between 30 and 60% of the GWP and around 50 to 75% of the AP. The assumed battery lifetime of 8 years is lower than the vehicle lifetime of 12 years, which requires a maintenance step during the use phase. Thus, the relevance of the battery system in the vehicle life cycle further increases. Depending on the EV concept and vehicle class, the dimensioning of the battery systems in the vehicles differs (mini-class BEV 20kWh; compact-class BEV 40kWh; compact-class PHEV 14kWh) and therefore the relative share of the battery system in the vehicle life cycle. Depending on the required energy content of the battery system, the additional mass in the vehicle varies between 150 and 450 kg. Since, especially the EV specific components require relatively high amounts of high-tech materials with accordingly high environmental impacts in the raw material extraction and material production, the impacts of these components are considerably higher than the vehicle platform which mainly consist of steel, plastics and light weight metals. The impacts of the battery systems are mainly caused in the extraction and production of the required upstream materials for the cathode production, whereas the impacts of the cobalt production dominate. Also today's PMSM-motors are equipped with rare earths like neodymium and dysprosium, with relatively high impacts in the material production. However, due to the lower mass proportion of the e-motor, the share to the EV production phase is comparatively low.

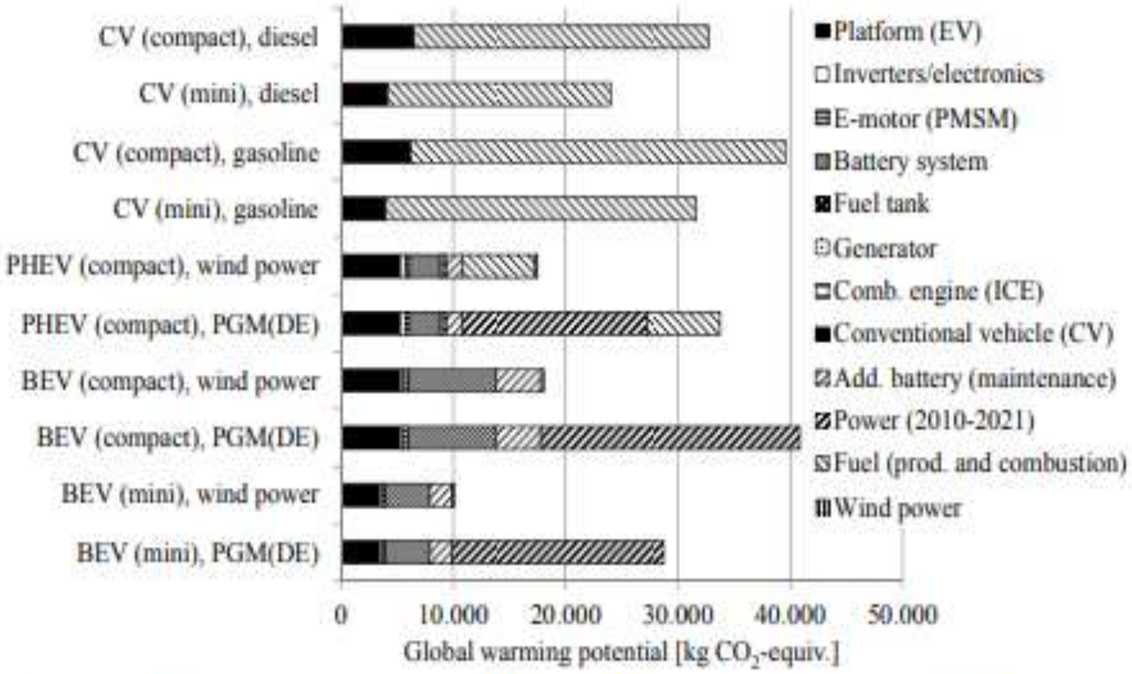

Fig. 1: Global warming potential of the production and use of EVs and CVs

Regarding the use phase, the EVs cause less environmental impacts than the conventional vehicles, which currently describe the environmental benefit. Based on the defined boundary conditions, the impacts of electric vehicle concepts to the GWP are in a comparable range to gasoline vehicles. Diesel vehicles are not reached, yet. In the case that the EVs are solely charged with wind power, significant improvements in the climate balance are achieved compared to the CV. However, this implies that the wind power is provided by additionally installed wind power plants.

Figure 2 presents the results for the AP. Even though the EVs have lower impacts to the AP during the vehicle operation, the higher impacts of the production phase cannot be compensated. Due to the high contribution of the production and maintenance of the battery system, the impacts of the BEV concepts are up to 2 times higher than for comparable CVs. In case of the wind power scenario, the mini-class BEVs reaches a comparable range of the CVs.

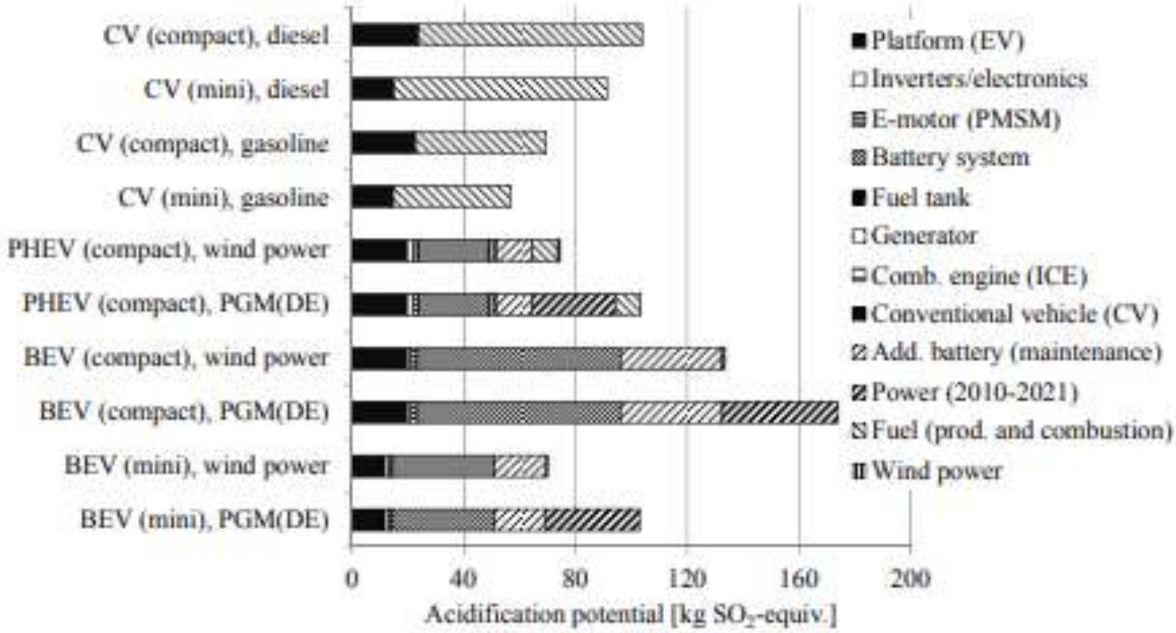

Fig. 2: Acidification potential of the production and use of EVs and CVs

Due to the smaller sized battery system, the contribution of the PHEV to the AP is lower than for the BEVs. Thus, the PHEV results in a range between the CV concepts. By the use of wind power, considerable reductions to CVs are achieved. The results of the impact assessment show that the power generation mix, the battery system and the utilisation profile of the vehicle have a considerable impact on the environmental profile of the vehicle life cycle. Regarding the battery system, the production of the high-tech materials, the lifetime and dimensioning of the battery system are the main indicators. Depending on the chosen driving cycles (NEDC vs. Eco-test) and EV concept, the impacts to the EVs vary between 15-20% in the GWP and 7-10% in the AP. In case of the PHEV, the chosen driving cycle also affects the share of the electrical and combustion driving mode. Depending on the evaluation method, the results vary by around 16%. Since the driving cycles do not necessarily reflect the conditions of realistic utilisation profiles of EV concepts, vehicle and user specific utilisation profiles have to be evaluated in future work to allow a fair comparison to conventional vehicles.

Chapter 4: Scenario Analysis

In contrary to the conventional vehicles with more than a hundred years development, today's alternative power train concepts are in a relatively early development stage. Most EVs battery systems are produced in small scales and have the potential for further improvements. One key aspect for e-mobility is to enable higher driving range with low battery weights. It is expected that the energy density of Li-Ion batteries will increase from currently around 135 Wh/kg to max. 200 Wh/kg in 2020 [19-20]. In long term view, higher energy densities are to be realised with new battery technologies like Li-S or Me-O. Besides the future increase of the energy density of battery cells, it is also expected that lifetime of batteries will be enhanced. Manufacturers target a battery lifetime up to ten years within the next years [21]. In long term view this study assumes that the battery lifetime endures a vehicle life of 12 years. Besides the battery system, improvements are also expected for the e-motor, power electronics and in the vehicle design. As presented above, the power generation mix, the battery system and the use profile for calculating the energy consumption of the vehicle have a considerable impact on the environmental profile of the vehicle life cycle. Hence, the following scenarios concentrate on these aspects by analysing the effects of the future developments of the battery systems and the German power grid mix. The scope of the scenarios is for the years 2010 to 2020. In a second scenario, the dependency of the chosen utilisation profile to the vehicle life cycle is analysed at the example of a mini-class BEV used as a city car. For keeping the comparability of results, a fixed electric driving range of EVs is considered. Therefore, improvements of the batteries result in a lower demand of battery cells and hence a lower impact in the production phase. The fuel consumption and emission profiles of future CVs are based in the scenarios of HBEFA 3.1. The development of the fuel production mix for CVs is not addressed in this study.

4.1 Results of scenario 2020

The results of scenario 2020 show that the improvements of the battery systems, mainly due to the extended battery life time, contribute to a significant reduction of the GWP of the EV life cycle (Figure 3).

In addition, due to a continuous increasing share of regenerative energies in the German power mix (around 58% until 2030), the total impacts of the EV use phase are further reduced. Based on the assumptions of the scenario 2020, all EV concepts show significant improvements against the gasoline CVs and slight improvements against the diesel CVs. However, the significant reductions are still reached by using renewable energies for the battery charging.

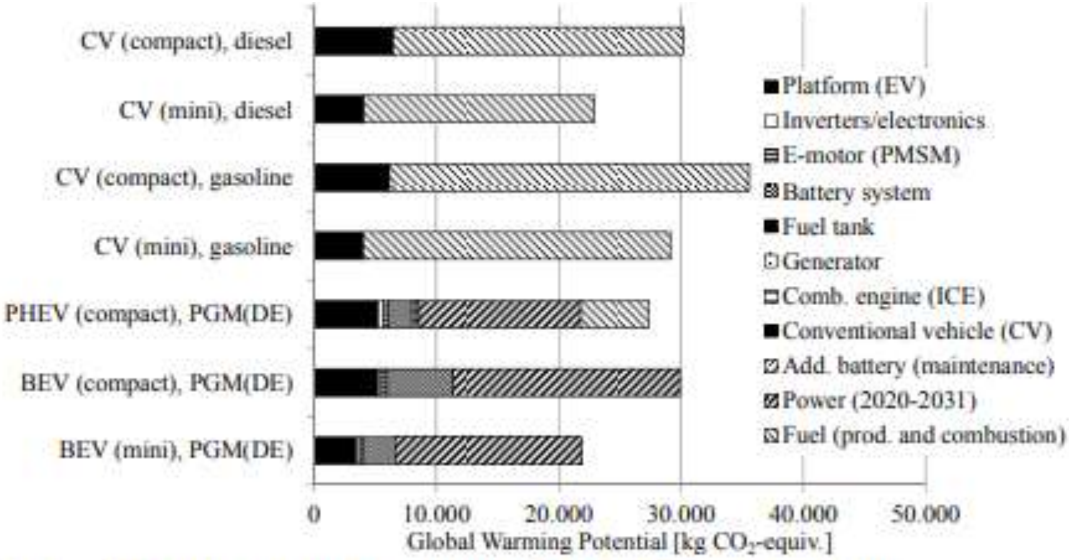

Fig. 3: GWP of the production and use of EVs and CVs (scenario 2020)

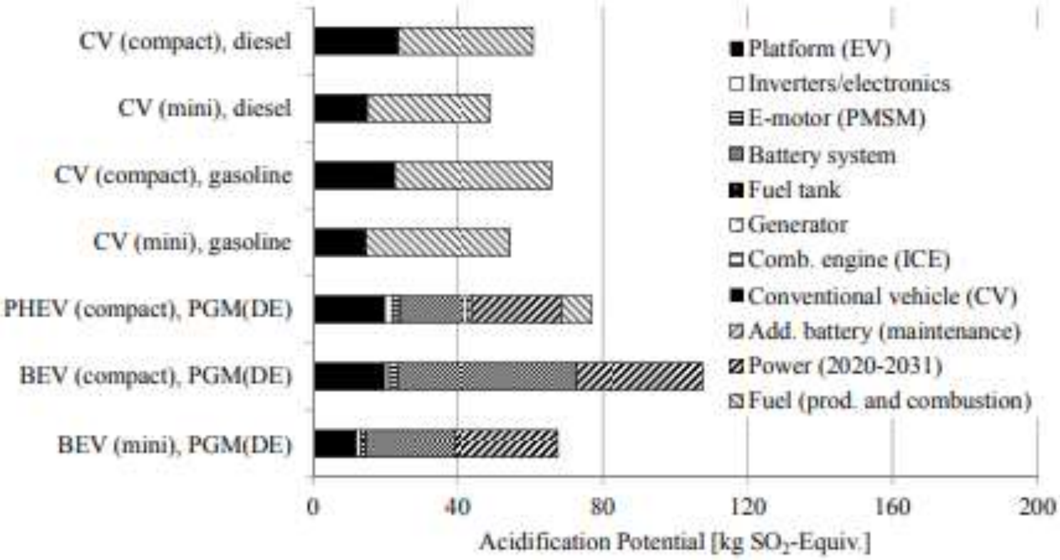

Fig. 4: AP of the production and use of EVs and CVs (scenario 2020)

Figure 4 presents the LCIA results for the AP. Also for the AP, significant improvements are reached by the extension of the battery lifetime and increased energy density, whereas the total contributions of the EV concepts are still considerably higher compared to the CVs. A still open question that has to be addressed in further studies is the evaluation of the future developments of the environmental profiles of used rare high-tech materials. We assume that due to the higher demand, also the environmental impacts of the raw materials extraction and the material production will change.

4.2 Results: User specific utilisation profiles

The calculation of the energy and fuel consumption of the EV concepts is based on the Eco-test and NEDC driving cycles. Due to the defined driving profiles, the driving cycles enable the comparison of the fuel consumption of different vehicles. However, these driving cycles do not necessarily reflect real driving conditions or utilisation profiles of electric vehicles. We rather expect that due to the limited driving range and longer charging times, the utilisation profiles of the EV concepts, especially the BEVs, will differ from the CVs. Furthermore, due to a broader implementation of e-mobility also the mobility itself might change. Thus, based on the following scenarios, the relevance of the defined utilisation profiles to the environmental profile of EV concepts is investigated at the example of a mini-class BEV used as city car. To do this, two cases with varying mileages are evaluated.

Case 1: Mini-class BEV in city use, low mileage

The first case assumes an annual mileage of 8,000 km/year (~21 km/day), e.g. used for shorter trips to work, shopping etc. According to the previous scenarios the considered vehicle lifetime is 12 years, the battery lifetime 8 years. The fuel consumption of the CVs is based on the city cycle of HBEFA 3.1. In contrary to the CVs, where the fuel consumption increases by around 10 to 20%, the energy consumption of the BEV decreases at lower speeds. The calculated energy consumption of the BEV for the city scenario is 0.15 kWh/km. Figure 5 presents the results of the scenarios for the GWP. Due to the lower total mileage of the BEV (96,000 km), the relative share of the production phase increases in the vehicle life cycle. However, the lower energy consumption leads to a GWP of the mini class BEVs which is in a range between the gasoline and diesel vehicles. Based on an increased use of renewable power significant reductions of the GWP could be reached, whereas a straight use of additional wind power would represent the best case scenario. However, we assume that in near- and mid-term, the use phase of the EVs will be in a closer range to the power grid mix scenario. The future improvements of the battery system and a higher share of renewable energies in the power grid mix in scenario 2020 lead to significant reductions compared to the CVs. The break-even to the CVs is then between 40,000 km and 50,000 km.

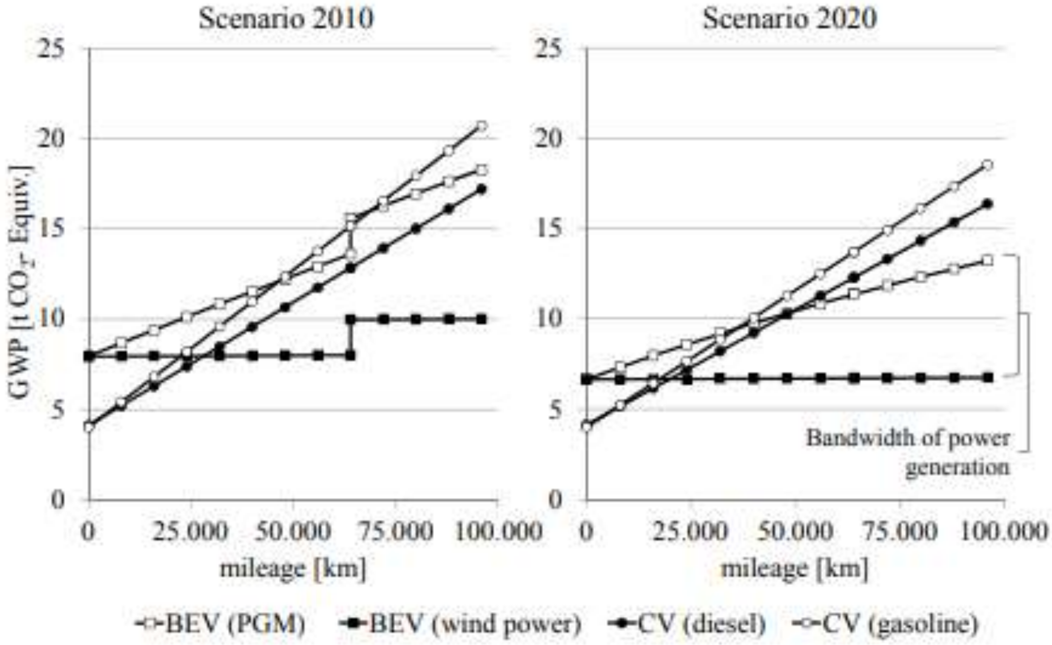

Fig. 5: GWP of a mini-class BEV in city use, low mileage

Case 2: Mini-class BEV in city use, high mileage

The second scenario investigates the case of a city car with a higher utilisation capacity, e.g. a vehicle used in a car sharing fleet. The assumed annual driving distance is 14,300 km (39 km/day). All other parameters remain unchanged. Figure 6 presents the results of the scenario.

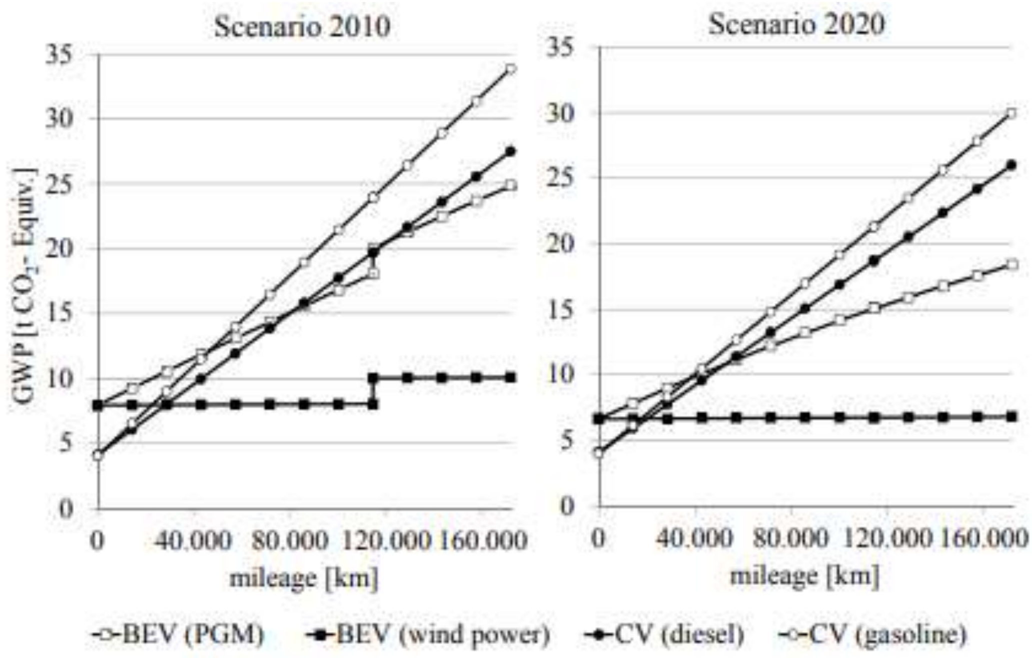

Fig. 6: GWP of a mini-class BEV in city use, high mileage

Due to the higher mileage of the BEV clear improvements are achieved. Even with the use of the power grid mix the impacts to the GWP are considerably below the comparable gasoline CVs and are in a comparable range to the diesel vehicles. The break even to gasoline vehicles is at around 50,000 km and around 125,000 km for the diesel vehicles. The results of the scenario 2020 show that depending on the field of application, the EVs have the potential for a significant reduction of the GWP, compared to the CVs. The investigated scenarios show, that from a today's perspective, the environmental benefits of e-mobility concepts are strongly dependent on the field of use and the assumed vehicle specific utilisation profiles. For a better understanding of e-mobility, more comprehensive and representative data on vehicle specific utilisation profiles are necessary.

Chapter 5: Need for further Research

The results of the assessment of the EV concepts show, that there are still several open questions which have to be addressed in more detail to allow a more reliable evaluation of the environmental profile of e-mobility. Future work has to be done for gaining a better knowledge on the production and upstream processes of the relevant materials (Li, Co, Ni, Mn, Nd, Dy) as well as the future development of the environmental profiles, availability and recycling concepts. Another significant aspect is the future development of components, in terms of technologies, alternative concepts, material use and potential substitutes. Since there is only little information on the environmental profiles of EV battery technologies available, detailed LCA studies have to be carried out in cooperation with battery producers and relevant players in the supply chain and raw material production. Concerning the use phase, there is the need for the investigation of vehicle and user specific utilisation profiles to ensure the representativeness of LCA results and to enable a fair comparison to CVs. These profiles will also provide a basis for the identification of beneficial fields for the application of EV concepts. Furthermore the study showed that there are many variable parameters in the life cycle of EV concepts which can significantly influence the LCA results. Therefore, a common agreed approach for the LCA of e-mobility is required to ensure the comparability and consistency of future LCA studies.

Summary and Conclusion

The paper presented a first quantification of the environmental profile of the production and use phase of different electric vehicle concepts. The results show that the relevant parameters of e-mobility are the used power generation mix, the dimension and lifetime of the battery system as well as the driving profiles and total mileage of the EVs. Due to the use of rare and high-tech materials, the additional components of the EVs lead to an increased relevance of the production phase, whereas the battery system has the main contribution. During the use phase, the EVs cause lower environmental impacts compared to the CVs, which currently represents the environmental benefit of e-mobility. Using the German power mix, the GWP of current EVs are in a comparable range with gasoline vehicles. However, a significant reduction of the GWP is reached when the EVs are charged with additional installed renewable energies, e.g. wind power. Regarding the AP of the EVs, the study showed that the contributions of the EVs are considerably higher than the CVs, whereas also the main impact is due to the production and dimensioning of the battery system. The results of the future scenarios presented that considerable improvements in the EV life cycle can be reached in a long term view. However, the study also shows that there are still many open questions that have to be further addressed for a reliable assessment of e-mobility.

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