Optimizing the charging schedule of Battery Electric Vehicles to mitigate environmental impacts

1 Introduction and Structure

The energy sector and the transport sector were the largest and third-largest emitters of greenhouse gases (GHG) in Germany in 2020 (Umweltbundesamt 2021). To reduce the emissions in the energy sector, it is forecasted that future electricity generation will be based on fluctuating renewable energy sources (Baumann et al. 2019). Both wind and solar energy are dependent on the local meteorological conditions. Consequently, with the expansion of renewable energies, the electricity market is increasingly determined by dynamic parameters that can hardly be influenced. In the transport sector, battery electric vehicles (BEVs) have great potential for reducing GHG emissions (Marmiroli et al. 2018). Detailed life cycle assessments (LCAs) for the environmental impacts of BEVs compared to internal combustion engine vehicles already exist. Those assessments indicate that the climate change impact of a BEV is lower than that of an internal combustion engine vehicle, with the use phase presenting a large emission reduction potential (Bauer et al. 2015; Marmiroli et al. 2018). The main determinators of emissions in the use phase are the emissions attributed to the charging electricity, which can vary depending on the energy system configuration (Marmiroli et al. 2018). Marmiroli et al. (2018) analyzed 44 LCA studies examining the environmental impacts of electrified vehicles, with the global warming impact varying from 27.5 g CO_2-eq/km to 326 g CO_2-eq/km compared to an internal combustion engine with 308 g CO_2-eq/km (Girardi et al. 2015). The authors found that 70% of the variability in the results is attributed to differences in the chosen electricity generation scenario. Furthermore, Cox et al. (2018) claim electricity generation is the largest source of uncertainty in the environmental assessment of BEVs. Against this background, several further studies investigate the influence of different electricity generation scenarios (Ehrenberger et al. 2019; Filote et al. 2020; Kawamoto et al. 2019; Malandrino et al. 2020; Mendoza Beltran et al. 2018) and compare the electricity generation of different countries or evaluate future electricity generation scenarios in contrast to current electricity generation. They examine the composition of electricity generation based on mean values for the temporal and geographical references considered. However, due to the expansion of energy conversion technologies based on fluctuating renewable energy sources, the LCA results of BEVs will also be increasingly dependent on the time of charging. The current use of average, static electricity market data to draw up an LCA (Kiss et al. 2020; Munné-Collado et al. 2019; Nordelöf et al.

2014) will increase the existing uncertainty (Cox et al. 2018; Marmiroli et al. 2018). To respond to the new requirements of increasing fluctuations, a suitable method is needed that considers the composition of the purchased electricity in a time-differentiated manner.

Facing the influence of fluctuating electricity generation, several studies use an hourly defined electricity supply when it comes to the environmental assessment of BEVs. Baumann et al. (2019) provide an approach that addresses the operational composition of electricity generation and show that the climate change impact of a BEV depends primarily on the charging time selected. Rovelli et al. (Rovelli et al. 2021) investigate based on an hourly defined model how the BEV’s interdependence with the electricity grid influences BEV environmental impacts. Having studied an hourly defined model of electricity generation in Hungary, Kiss et al. (Kiss et al. 2020) point out that the variability of the environmental impacts of electricity generation on a daily and seasonal basis increases with the rising share of renewable energy sources. Rupp et al. (Rupp et al. 2019) apply different charging scenarios to determine how charging time influences the global warming impact of electrified city buses. Based on a quarter-hourly defined carbon footprint of electricity generation, the authors highlight how charging time affects the global warming impact compared to a combustion engine bus. Rangaraju et al. (Rangaraju et al. 2015) perform a case study with five BEVs charged according to peak or off-peak charging profiles and conclude that off-peak charging reduces the environmental impact of BEVs, based on hourly defined electricity assessment. The chosen electricity mix is, however, characterized by a predominant share of nuclear energy. Consequently, the results cannot be transferred to regional electricity mixes with high shares of fluctuating energy sources, or to an electricity generation scenario after nuclear phase-out. All mentioned studies highlight the charging time’s influence on the final environmental impact of a BEV. Nevertheless, no study applied hourly optimized charging profiles based on real-world whereabouts profiles and hourly assessed electricity generation. The research question of this paper is thus: *How can the BEV charging profiles’ mitigation potential on environmental impacts be quantified and optimized*?

To answer the research question, we develop a mixed-integer linear programming (MILP) model based on hourly defined environmental impacts of the electricity generation mix and representative user behavior in Germany. In this manner, the uncertainty of using yearly mean values is overcome. To face the uncertainty of future electricity generation, the approach is applied to prospective electricity generation scenarios for 2025, 2030, and 2050. A goal of the study is hence to calculate optimized charging schedules to minimize environmental impacts. Studies examining the environmental impact of a BEV imply that the electric energy supply for charging the battery in the use phase and the production of the battery is the main contributor to the BEV's global warming impact, and the vehicle body causes a minor impact (Bauer et al. 2015; Baumann et al. 2019; Cox et al. 2018; Marmiroli et al. 2018; Nordelöf et al. 2014). Since it can be assumed that due to a longer life time and reduced production emissions, the contribution of battery production to the environmental impacts of the BEV will decrease in the future (Hoekstra 2019), the question of whether a BEV has a lower global warming impact than an internal combustion engine vehicle depends significantly on the global warming impact of the fluctuating electricity generation itself, that provides the charging energy in the use phase (Cox et al. 2018; Lombardi et al. 2017; Marmiroli et al. 2018; Mendoza Beltran et al. 2018; Petrauskienė et al. 2020). In this study, we therefore concentrate on modeling the charging energy, and exclude the production and end-of-life phase of the BEV and battery from the modeling.

In this study the focus is on the potential of mitigating GHG emissions, as it is the focus of many studies analyzing the environmental impacts of BEVs (Marmiroli et al. 2018). However, the optimization is also performed for the remaining 15 environmental impact categories to provide the basis for a holistic decision process. Since many of the environmental impact categories are presumably in a conflicting relationship with each other, there is potentially no solution for holistically minimizing the environmental impacts of a charging profile. To determine a solution in multi-criteria decision making (MCDM) as it is in the context of independent environmental impact categories, a variety of approaches have been applied in the context of electricity generation (Kügemann/Polatidis 2020; Lee/Chang 2018; Martín-Gamboa et al. 2017). Furthermore, Kägi et al. (2016) and Zanghelini et al. (2018) point out a growing interest in linking LCA with MCDM. Another approach is to use either directly aggregated endpoint categories that deal with areas of protection (human health, ecosystems, and resources availability) or a fully aggregated single score. The use of aggregated indicators is controversially discussed, as the grouping into three areas of protection or a single score increases the degree of uncertainty of the results and is afflicted by a subjective weighting (Kägi et al. 2016; Kalbar et al. 2017). Furthermore, in an aggregated assessment of the charging profile, the results cannot be attributed to the contributions of individual impact indicators. Since the weighting cannot be done objectively, the ISO 14040/44 standards refer to the use of only the midpoint impact assessment indicators (Kägi et al. 2016).

Instead of focusing on a method that minimizes the overarching environmental impacts, which could lead to ambiguous results, we aim to analyze the competing impact categories by minimizing the environmental impacts of a charging profile. Accordingly, the optimized profiles are evaluated regarding all other impact categories to measure the deviation between the environmental objectives when it comes to minimizing the environmental impact of charging a BEV. With this approach, this study aims to add a holistic perspective on conflicting and non-conflicting impact categories to the debate about the environmental impacts of BEVs and electricity generation in general.

2 Literaturverzeichnis

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