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Can battery swapping stations make micro-mobility more environmentally sustainable?

Sebastian Finke[1*], *Nora* Schelte[1], *Semih* Severengiz[1], *Martin* Fortkort[1], and *Ferdinand* Kähler[1]

[1]Sustainable Technologies Laboratory, Bochum University of Applied Sciences, 44801 Bochum, Germany

Abstract. The rapid spread of shared micromobility services e.g. e-scooters raises questions about their ecological impacts. Previous Life Cycle Assessments (LCAs) show that the ecological impacts of shared mobility services vary significantly depending on the sharing mode, the charging concept and the corresponding operating mode. Even though e-scooters could mitigate environmental issues of urban transportation due to their low energy consumption, studies show that service trips for charging and relocation and non-swappable batteries have overall negative environmental impacts. To identify key factors for an environmentally friendly e-scooter sharing infrastructure and operating mode, we conducted a comparative LCA in this study. We developed a method considering a holistic product service system (PSS) of e-scooter sharing including the whole life cycle to cover all environmentally relevant aspects of the sharing operation. In different scenarios, we compared electric stand-up scooters and electric moped scooters for different operational modes. These include free-float, station-based and hybrid sharing. Furthermore, charging methods and the underlying infrastructure with battery swapping stations are varied. The results show that greenhouse gas emissions are the lowest for two scenarios: A free-float sharing mode where batteries are swapped using an e-cargo bike and a hybrid sharing mode using self-service battery swapping stations (BSS).

1 Introduction

Shared mobility has the potential to change the traditional transportation industry in a disruptive way and offers social, economic and environmental benefits [1]. In particular, light electric vehicles (LEVs), which require less energy and resources for production and operation, can be an element in such sustainable mobility concepts [2]. Nevertheless, previous research in the field of LEV sharing shows that several factors like a short lifetime of shared vehicles, charging concepts [5], non-swappable batteries [6] and the charging infrastructure [7] can also have negative environmental impacts. These can, for example, refer to the greenhouse gas (GHG) emissions generated not only in the production phase of batteries [8], but also in the service rides connected with the battery swap for shared vehicles [6]. Existing charging concepts for LEV sharing mostly rely on the so-called milk run, i.e. the entire sharing vehicle or the battery of the vehicle is collected by service vehicles (often

* Corresponding author: sebastian.finke@hs-bochum.de

with a combustion engine), is charged at a central location and then distributed again in the business area.

Battery swapping stations (BSS) can be a solution to the ineffective practice of battery swapping in shared micromobility. Such stations can have several compartments, which contain batteries of different types. These are charged in the station and can be swapped by users for discharged batteries from vehicles. In this way, charging trips by service vehicles can be avoided.

The aim of this paper was to answer the research question: to what extent can battery swapping stations contribute to making micromobility sharing services more environmentally sustainable? To identify the key factors for sustainable infrastructure and operation of shared electric stand-up scooters (SUS) and electric moped scooters (MS), we conducted a comparative Life Cycle Assessment (LCA) in this paper. For this purpose, we applied the LCA methodology to the product-service system (PSS) of light LEV sharing. In addition to the assessment of the environmental impact of the operation modes, the focus was also on conducting an LCA of a battery swapping station as the basis for the analysis. Based on the methodological work, we developed scenarios based on a use case in the German city of Bochum.

2 Methodology

The methodological framework of this research paper is the LCA of different types of sharing service operations. For this purpose, data from previous studies and bills of materials (BoM) from the manufacturers of the technical components in the sharing service were combined. In addition, three providers of sharing services and one industry expert are surveyed using questionnaires and interviews [9-10], as there are hardly any data available for the sharing of electric moped scooters.

The functional unit for the LCA is one passenger-kilometre (pkm), the impact category is the Global Warming Potential over 100 years (GWP100) in kg CO_2 equivalents.

2.1 Goal and Scope definition

The objective of the LCA we conducted in this paper was to analyse different modes of operation of shared LEV. The shared vehicles investigated are electric stand-up scooters with fixed and swappable batteries and electric moped scooters with swappable batteries. Electric moped scooters with fixed batteries are not common and are therefore not examined. The analysis of the two types of shared vehicles allows conclusions about differences in environmental impacts. The investigation into several parameters of the sharing operation allows insights regarding their relevance for the environmental impact of the sharing service and makes it possible to derive recommendations for further improvements. For this purpose, free-floating and station-based sharing offers are investigated as well as a hybrid offer with elements from both systems. Free-floating means that the user can park the vehicles anywhere within the designated service area. A hybrid system of station-based and free-floating means that the user is only approaching a charging station when the battery is below 25% state of charge (SoC). Other parameters include the electricity mix for charging, the type of service vehicles used for charging, maintenance and redistribution of the shared vehicles including the sharing infrastructure such as battery swapping stations (BSS).

2.2 Data sources for the sharing operations and infrastructure

2.2.1 Manufacturing of hardware

For the inventory analysis of the BSS, a BoM is provided by the German company Swobbee GmbH [11]. In addition, the circumstances of the production are surveyed using a questionnaire and an interview [8]. The components and materials are then modelled in the GaBi software [12]. To ensure a high level of quality of the data, all information provided by the manufacturers are considered and, where necessary, supplemented by data from literature. The modelling of the production of the shared vehicles, the batteries as well as the service vehicles is based on models from previous research [13, 14 15]. In the case of data gaps assumptions are made and documented.

2.3 Inventory Data for the Use Phase and End-of-Life

For the use phase, we consider the usage of the electric moped itself, its energy demand as well as service trips for recharging. For the operational phase, we use data from our previous studies [13, 14, 15]. For end-of-life, we assume the scooters to be shredded and no credits are accounted for. The energy consumption for this is 2.7 kWh for the electric stand-up scooters, 15 kWh for the electric moped scooters and 3.7 kWh for the BSS [16]. The lifetimes of the scooters are displayed in Table 1 and the lifetime of the BSS is assumed to be 7.5 years [9].

2.4 Scenarios

Table 1. Overview of the parameters of the scenario analysis

	1	2	3	4	5	6	7
Scenario	**SUS Base Case**	**SUS Green Free-floating**	**SUS Green Station-based**	**MS Base Case**	**MS Green Free-floating**	**MS Green Station-based**	**MS Green Hybrid**
Sharing model	Free-floating	Free-floating	Station-based	Free-floating	Free-floating	Station-based	Hybrid
Weight of vehicle & battery type	19 kg, static battery	28 kg, swap. Battery	28 kg, swap. Battery	102 kg 3 swap. batteries	102 kg 3 swap. batteries	102 kg 3 swap. batteries	102 kg 3 swap. batteries
Lifetime (months)	12	18	18	36	36	36	36
Lifetime (km)	3,800	5,700	5,700	50,000	50,000	50,000	50,000
Charging method	Replacing vehicle	Replacing battery	BSS	Replacing battery	Replacing Battery	BSS	BSS
Number of BSS	0	0	58	0	0	58	22
Charging trips	Diesel van	E-cargo bike	-	Diesel van	E-cargo bike	-	-
Service trips	Diesel van	Electric van	Electric van	Diesel van	Electric van	Electric van	Electric van
Electricity mix	German grid mix	German RE mix	German RE mix	German grid mix	German RE mix	German RE mix	German RE mix

To determine the impact of the operating mode, we set up a total of seven scenarios, three for SUS and four for MS. The parameters and the scenarios are displayed in Table 1.

Each scenario corresponds to either an existing or hypothetical prototypical operating mode. In the base cases, these service trips are completed by service employees collecting the discharged batteries in the business area of the sharing service using vans, recharging them centrally, and then redistributing the charged batteries.

We calculate the environmental impact of the energy demand of the scooters in the base case scenarios one and four using the German grid mix (0.452 kg CO_2e/kWh) [12]. For all other scenarios we assumed a renewable electricity (RE) mix for Germany (0.047 kg CO_2e/kWh) [12]. For the SUS scenarios, we considered whether their battery is fixed or swappable including different scooter lifetimes. For the SUS of an earlier generation with a fixed battery, a service life of 12 months is assumed, while the SUS for scenarios two and three, equipped with a swappable battery, reach a lifetime of 18 months. For the daily distance driven, we assumed 10.2 km [9]. For the MS, the results of the surveys indicate an average rental distance of 18.1 km per vehicle per day and a lifetime of 36 months [9].

For necessary service rides of the sharing providers, we introduced two different parameters: "charging rides" and "service rides". Charging rides refer to the trips for battery swapping, while service rides refer to trips necessary to repair and to redistribute the scooters. Different vehicles such as diesel vans, electric vans or e-cargo bikes can be used for this purpose.

For the service area, we assumed an operation in the city of Bochum in North Rhine-Westphalia, Germany. In the station-based scenarios three and six, we suggest that the BSSs are installed within a maximum of 300 m direct distance from each other in order to keep the user experience for the sharing service as attractive as possible [10]. After removing spots in no parking zones areas such as recreational parks, we calculated a total of 58 BSS within Bochum. In the hybrid scenario, we found that the BSS can be placed within a direct distance of one km from each other since only rides that end with a SoC below 25% need to be approached. Taking this into account, we set the number of BSS for scenario seven to a total of 22.

3 Results

Figure 1 displays the result for the GWP100 in the considered scenarios expressed in g CO_2e per pkm for each life phase of the sharing service.

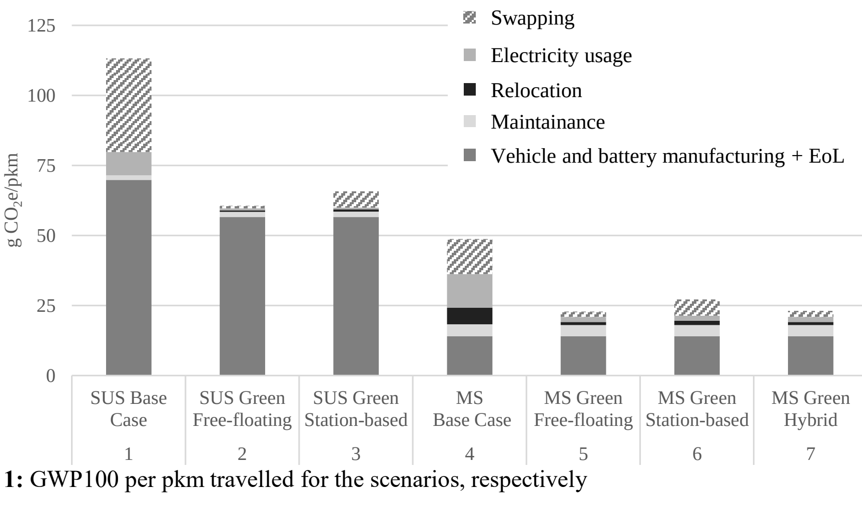

Fig. 1: GWP100 per pkm travelled for the scenarios, respectively

For scenario 1, the GWP100 is 113 g CO_2e./pkm, with a share of 62% from vehicle and battery manufacturing, 7% from electricity usage and 29% from activities related to the battery swapping and 1% from maintenance. A longer lifetime, the usage of renewable energy and the introduction of e-cargo bikes for the battery swapping can decrease GHG emissions by 46% in scenario 2. A similar reduction of 42% can be achieved by the introduction of a station-based sharing service where BSS, located at each station (scenario 3), can substitute the rides for battery swapping. The slightly lower GHG emission savings are due to the emissions occurring during the manufacturing of the BSS.

For the base case of the electric moped scooters (scenario 4) GHG emissions are 49 g CO_2e./pkm, with a share of 29% from vehicle and battery manufacturing, 25% from electricity usage, 26% from activities related to the battery swapping and 21% from relocations and maintenance. The usage of renewable energy and the introduction of e-cargo bikes for the battery swapping can decrease GHG emissions by 53% in scenario 5. Again, a similar reduction of 44% can be achieved in scenario 6 by introducing a station-based sharing service with BSSs. For the hybrid scenario 7 where fewer BSS are installed the GHG reduction compared to the base case is also 53%. For comparison, we determined GHG emissions of a private car to be 192 CO_2e./pkm, a public bus 88 CO_2e./pkm and a subway 78 CO_2e./pkm in a previous study [15].

4 Discussion and conclusion

In this paper, we developed a method considering a holistic PSS of e-scooter sharing including the whole life cycle to cover all environmentally relevant aspects of the sharing operations. We adopted scenarios for the city of Bochum in Germany with a focus on a BSS network in free-float and hybrid scenarios. The results show that GHG emissions for a SUS sharing are the lowest in the free-float scenario 2 where batteries are swapped using e-cargo bikes. For the MS sharing, GHG emissions are the lowest for two scenarios: A free-float sharing mode where batteries are swapped using an e-cargo bike and a hybrid sharing mode using self-service BSSs. Regarding the operation mode, the results of this paper show that BSSs can significantly increase the sustainability of e-scooter sharing systems not in a station based but, in a hybrid setting. In addition, the overall transport volume can be reduced since the batteries are swapped by the user for charging in place, making charging trips for swapping of the entire sharing vehicle or the batteries by the service provider obsolete. Since the e-cargo bikes for battery swapping can significantly reduce GHG emissions, it is crucial to examine the cost of each scenario in a follow-up study.

We did not consider the fleet availability in this LCA study. A low fleet availability can increase the environmental impact of the operation. Therefore, measures that increase fleet availability are beneficial, such as regular maintenance and robust design of shared vehicles. It would also be possible to use software to predict the need for maintenance, as described in projects by Voi Technology [17]. With an increasing level of maintenance, we expect an increase in the e-scooter lifetime leading to a further decrease in GHG emissions [15].
Additionally, a broad survey of substitution rates of other modes of transport by sharing services would allow more well-founded statements about ecological advantages of sharing services compared to other modes of transport.

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