

Life Cycle Assessment on the Mobility Service E-Scooter Sharing

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Abstract—E-scooters are controversially discussed as a new mobility alternative for cities. The rapid growth of the shared use e-scooter market has raised questions about environmental sustainability and public benefits in many cities worldwide. The high dynamics of the market and insufficient public data available about the concrete business processes of shared e-scooters are making clear statements about the ecological effects difficult. The paper aims to conduct a life cycle assessment using Berlin as an example for shared e-scooters. Based on different operating scenarios, the ecological potentials of e-scooters should be assessed in a more differentiated way. The results show how product lifetimes, swappable batteries, alternative collection logistics and charging concepts influence the greenhouse balance compared to alternative means of transport.

Keywords—e-scooter sharing, e-mobility, e-scooter, energy supply system, environmental impact, life cycle assessment, mobility services, Sharing economy, sustainability, urban mobility

I. INTRODUCTION

Sharing concepts with light electric vehicles are spreading in major cities around the world. E-scooters, in particular, are at the forefront of public interest and are being controversially discussed as a new mobility alternative. The term e-scooter is not used uniformly. In particular, a distinction must be made between stand-up electric scooters and electric motor scooters.

Stand-up scooters are driven in a standing position, reach lower speeds (up to 20 km/h in Germany) and are therefore especially designed for transporting individual drivers over short distances in the urban environment. While e-scooters have been in use for years in the USA or China, for example, they have only been approved for use on German roads in Germany since the German Regulation on Electric Small Vehicles (eKfV) came into force in June 2019. Since then, around 35,000 e-scooters have been available in sharing services in German cities [1].

This rapid development led to many questions about the benefits of e-scooters and their environmental impact. The dockless sharing of e-scooters is touted as the last mile solution, as a supplement to local public transport and as an alternative to private car traffic. Compared to alternative means of transport, they are supposed to reduce traffic volume, reduce congestion and represent an ecologically advantageous mode of transport [2]. Although e-scooters have no direct tailpipe emissions, full life-cycle impact assessment is necessary to understand their environmental impact properly. In this study, we use the methodology of Life Cycle Assessment (LCA) to quantify the total global impact of shared electric scooters on the environmental impact

categories Global Warming Potential (GWP 100) and non-renewable Primary Energy Demand (PED). The aim of this study is in particular to analyse the production of a new type of e-scooter model with swappable battery and to consider the influence of a swappable battery on the use phase of the e-scooter. The introduction of new e-scooter models with swappable batteries will result in new usage patterns. By analysing the production and use phase of e-scooter sharing, it is possible to identify the main triggers for negative environmental impacts, to make recommendations for local authorities, policies or practices that would reduce these impacts and compare the overall impacts with other modes of transport.

II. RELEVANCE FOR PRACTICE

Although numerous life cycle analyses for vehicles [3, 4] and even sharing services [5, 6] are available, the environmental impact of e-scooter sharing has so far been studied only to a limited extent. Due to earlier market launch, this discussion has started in the US before. Chester shows important results of an LCA on shared dockless e-scooters. Findings are based on several assumptions with a wide variety of different scenarios. In the baseline scenario, Chester shows that manufacturing and materials cause most life-cycle CO₂eq. emissions, followed by collection and distribution and charging of the scooter, for a total of 200 g CO₂eq./ kilometre. By increasing the distance travelled over the life cycle of the e-scooter from 1200 to 6000 kilometres, emissions could be reduced to a total of 57 g CO₂eq./ kilometre [7].

In their recent work, which was conducted with parameters specific to the determining factors of Raleigh, North Carolina, Hollingsworth et al. found out that the global warming impacts associated with shared e-scooters are dominated by materials, manufacturing and automotive use for e-scooter collection for charging [8]. The authors pointed out that extending scooter lifetime, reducing collection and distribution distance, using more efficient vehicles, and less frequent charging strategies can significantly reduce environmental impacts. Potentials of swappable batteries and the use of electric e-cargo bicycles for battery and vehicle collection, which are more and more used in many cities in Europe, were not part of investigations in the study.

But shared e-scooters are a new phenomenon. The use of sharing services in the transport sector in general could minimise total CO₂-emissions, fuel consumption, traffic volume and congestion [6]. Furthermore, sharing services can be an integral part of an intermodal mobility concept. According to the German Federal Ministry of Transport,

intermodal mobility can have a positive impact on the environment by linking services of public transport to car sharing in terms of location, payment and tariffs [9]. Ecological impacts are associated with substitution of transport mode as much car passenger-kilometres can be substituted by e-scooters, as much emissions can be reduced.

Substitution rates of fuel-based motorized vehicles by e scooters differ a lot between the USA and Europe. Based on different survey results from Portland [10] (34% of locals, 48% of tourists), San Francisco [11] (41%) and Paris [12] (8%) we see huge differences. Different determining factors in cities, poor data availability and high uncertainties show that further investigations are needed to finally judge on environmental impacts of shared e-scooters.

A further study of a German think tank provides policy recommendations for local governments [13]. Municipalities should encourage e-scooter sharing providers to use swappable battery systems and e-cargo bikes for collection and deployment operations to reduce environmental impacts. The German Environment Agency is also recommending swappable batteries and point out that ecological benefits would only occur if cars and motorcycles are substituted, and no further fuel-based vehicles are needed. A lifetime of scooters is another important issues for improvements [14]. First, e-scooter sharing providers like Tier Mobility and Circ already use swappable battery systems and aim to use mainly e-cargo bikes for deployment [15, 16]. Spin, another e-scooter sharing provider, has also been experimenting with station-based charging stations in US cities to limit the number of trips to collect and charge scooters. Combined with power supply from solar panels, emissions could be further decreased [2].

III. RESEARCH DESIGN

Following the ISO standard, the present LCA is structured as follows: Goal and Scope definition, inventory balance, impact assessment and interpretation. The system boundaries are shown in Fig. 1. The study includes material and component production, manufacturing, transport, use and charging. Due to the poor database, maintenance and repair were only considered to a limited extent. The functional unit is one passenger-kilometre travelled. The base case for the daily use, collection and charging of the e-scooters was defined through interviews with e-scooter companies. The city of Berlin was used as an example of the market situation. A bill of material (BoM) was used to collect data for the inventory analysis of the production of the e-scooters. Individual components were also disassembled.

The inventory modelling was done with the program "Ganzheitliche Bilanzierung - GaBi" from thinkstep AG [17].

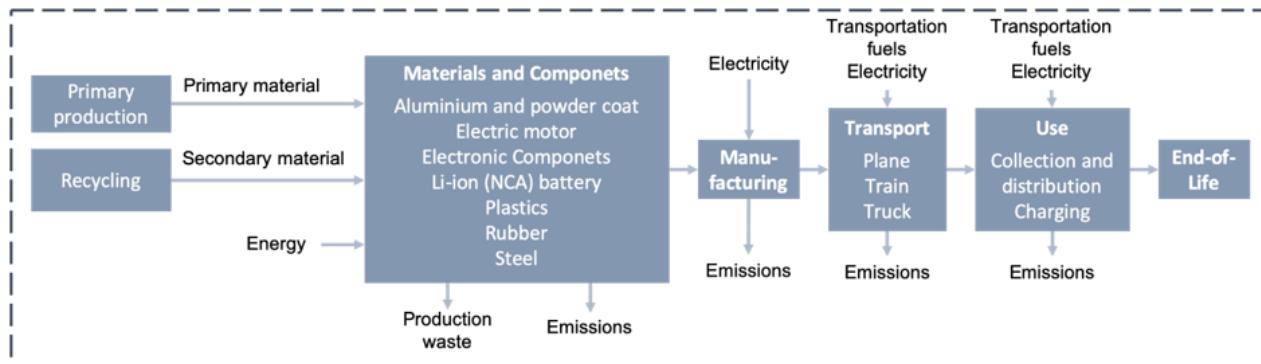


Fig. 1. System boundary diagram for a life cycle assessment on shared electric scooters.

The CML method in the updated version of January 2016 is used as the method of impact assessment. This method is based on the international standard of the Centre voor Milieuwetenschappen (CML) in Leiden (NL) [18].

A. Manufacturing

The major materials and components of the e-scooter include aluminium components (45%), a lithium-ion battery pack (16%), an electric motor (14%), rubber (7%) and plastic parts (7%) which in total account for 89 % of the total scooter mass as shown in Fig. 2.

The lithium-ion battery has a cathode material LiNiCoAlO_2 (NCA), as indicated by the battery manufacturer. A GaBi-dataset is used for the inventory analysis and the impact assessment of the NCA-battery cells [19]. The energy consumption for manufacturing the scooter and assembling the battery is assumed to be 3.9 kWh based on interviews with scooter-sharing providers. We consider recycling content for aluminium: The base case assumes a recycling content of 24% for aluminium, which corresponds to the average Chinese aluminium in 2017 [20].

B. Transportation to Germany

The majority of scooter manufacturers are located in the Zhejiang and Guangdong province. The rounded total mass of the e-scooter is 28 kg. Based on the statement of the e-scooter sharing service providers, it is assumed that the e-scooter is transported on the rail (estimated 10500 km), resulting in 290 ton-km transport via rail, per scooter.

C. Use Phase

The environmental impact of the use phase depends on various factors: the daily distance travelled, the electricity grid mix used for charging and the method of charging. The assumptions made for the use phase are based on the statements of e-scooter sharing providers. In the base case, an e-scooter travels an average distance of 10,2 km per day. With a current lifetime of 24 months, this results in an average distance of 7500 km over the entire life-cycle. However, this does not consider scooter downtime for maintenance and repairs. The sharing provider states that 0.5% of scooters are collected daily for repairs. More research is needed on how long the scooters are in repair and how many total breakdowns there are in order to estimate a more realistic lifetime. The e-scooters have a range of 30 km with a battery capacity of 0.46 kWh. This results in energy consumption of 0.02 kWh per km or 115 kWh over the entire lifetime. In the base scenario, the environmental impacts of electricity demand are modelled according to the country-specific conditions of the German electricity mix of 2016.

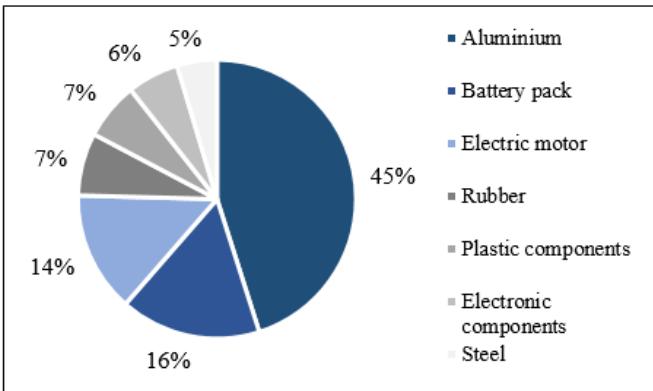


Fig. 2. Share of materials/ components of an e-scooter

The Global Warming Potential is 0.568 kg CO₂eq. Per kWh of electricity [17]. In the base case, it is assumed that the e-scooters have a swappable battery. The batteries are swapped with vans (diesel, Euro 4, 3.5 t) [17]. The van has a GWP over its entire life-cycle of 337 g CO₂eq. per km [17]. According to the service provider, one van can serve 200 scooters per day. Each day, 70 batteries are swapped using a van. The vans also collect e-scooters (0.5% of all scooters per day) for repair. In total, one van drives a distance of 50 km per day, meaning it travels 0.25 km per e-scooter per day or 183 km over the lifetime of an e-scooter. As the e-scooters are continued to be used while the batteries are charging, it is assumed that 1.5 batteries are required per e-scooter.

D. End-of-Life

For End-of-Life the e-scooter is shredded. No credits are given for this. The energy consumption for this is 2.7 kWh. [17].

E. Scenarios

E-scooter sharing is a relatively new business. Therefore, there is hardly any reliable data on the lifetime of e-scooters, and the methods for charging the e-scooters also differ greatly. To take these uncertainties into account, different scenarios for the use phase were created. In addition to the base case, we examine three scenarios relating to the battery or e-scooter collection for charging, one scenario related to e-scooter lifetime and one scenario related to the electricity grid mix used to charge the scooters. Table 1 shows the parameters that were varied within the sensitivity analysis, and thus their influence on the environmental impact of e-scooter sharing was tested.

1) Scenario 1: Shorter lifetime

The e-scooter sharing provider TIER state that their scooter is particularly robust, which is shown, for example, by its high weight, and that it, therefore, has a particularly long lifetime of 24 months [15]. In previous studies, a shorter lifetime of 6-24 months is assumed [8]. As there are many reports of vandalism against shared e-scooters, it is more likely that they have a shorter lifetime [21]. In this study, we test a scenario with a shorter lifetime of 6 months.

2) Scenario 2: Not-swappable Battery

If the e-scooter has no swappable battery, the whole scooter with the battery is collected and charged. This method of charging was common practice until recently. It can be assumed that a van can serve fewer scooters with this method, as the scooters take up more space in the van than the batteries. According to the service provider, a van can transport 40 scooters per day for charging. This means that one van can

serve 100 scooters, travelling a distance of 100 km/day. In total, in this scenario, a van travels 1.00 km per e-scooter per day or 730 km over the life-cycle of an e-scooter. In this scenario, only one battery per scooter is required.

3) Scenario 3: Battery Swapping with E-vans

Some surveyed e-scooter sharing service providers use electrified vans for battery exchange. It is assumed to be a van of a Chinese manufacturer with a LiFePO₄ battery [23]. The production of the battery and the van and the transport to Germany was modelled using the software "GaBi - Ganzheitliche Bilanzierung" [17, 23]. Based on a lifetime of the van of 150,000 km [24], the production was included in the environmental impact assessment of the battery exchange with the e-van. As with the diesel van, it is assumed that a van travels 0.25 km per e-scooter per day or 183 km over the lifetime of an e-scooter. The e-vans have a range of 160 km with a battery capacity of 56 kWh [22]. This results in energy consumption of 0.35 kWh per km or 63.875 kWh over the entire lifetime of the e-scooter. In the base scenario, the environmental impact of electricity demand is modelled according to the country-specific conditions of the German electricity mix [17]. The result of the modelling is a GWP over the entire life-cycle of the e-van of 64 g CO₂eq./ km.

4) Scenario 4: Battery Swapping with E-cargo Bikes

Some e-scooter sharing service provider claims to use electrified cargo bikes to change batteries in future. Currently, cargo bikes with a capacity of 20 - 40 batteries are being tested. However, since the cargo bike can only cover shorter distances (range of approx. 30 km) and due to safety and weight restrictions, it can serve fewer e-scooters than a van. It is assumed that a cargo bike can serve 100 scooters per day. In total, a cargo bike travels 0.33 km per e-scooter per day or 219 km over the lifetime of an e-scooter. The production of an e-cargo bike and its battery was modelled using the software "GaBi - Ganzheitliche Bilanzierung" [17, 25]. The assumptions regarding the components of a cargo bike and the energy required for production are based on a study by Leutenberger et al. [26]. It is assumed that the cargo bike is produced in Germany. The battery was modelled as a battery with LiNiMnCoO₂ cells with a capacity of 1.4 kWh. With a range of 30 km, the energy demand is 0.046 kWh per kilometre or 10.074 kWh over the entire life-cycle of the e-scooter. Based on a lifetime of the e-cargo bike of 15,000 km [26], the production was included in the environmental impact assessment of the battery exchange with the e-cargo bike. The result of the modelling is a GWP over the entire life-cycle of the e-cargo bike of 34 g CO₂eq./ km. Electrified vans are also used in this scenario to collect broken e-scooters for repair. According to the sharing provider, one van that travels 50 km per day is sufficient to collect the broken scooters (daily 0.5% of all scooters).

5) Scenario 5: Transportation by Plane

The surveyed e-scooter sharing service providers claim their e-scooters are transported by train from China to Germany. In order to examine the influence of transport on the environmental impact of e-scooter sharing, in this scenario, transport by air is assumed. The transport is modelled using the corresponding process of the Software GaBi (Cargo plane, 65 t payload) [17] over a distance of 7500 km, resulting in 208 ton-km transport via plane, per scooter.

TABLE I. PARAMETER OF THE SCENARIO ANALYSIS

	Base Case	Shorter Lifetime	Not-Swappable Battery	E-vans	E-cargo Bikes	Transport by Plane	Solar power
Energy demand per km [kWh]	0.015						
Average distance per day [km]	10.2						
Lifetime e-scooter [month]	24	6	24	24	24	24	24
Battery type	swappable	swappable	not-swappable	swappable	swappable	swappable	swappable
Energy demand per lifetime [kWh]	115	29	115	115	115	115	115
Average distance per lifetime [km]	7500	1900	7500	7500	7500	7500	7500
Vehicle for collecting broken Scooters	diesel-van	diesel-van	diesel-van	e-van	e-van	diesel-van	diesel-van
Vehicle for battery swapping	diesel-van	diesel-van	diesel-van (e-van	e-cargo bike	diesel-van	diesel-van
Distance per van and day [km]	50	50	100	50	50	50	50
Served e-scooters per van and day [#]	200	200	100	200	-	200	200
Distance per van, scooter and day [km]	0.25	0.25	1.00	0.25	0.03	0.25	0.25
Distance per cargo bike and day [km]	-	-	-	-	30	-	-
Served e-scooters per cargo bike and day [#]	-	-	-	-	100	-	-
Distance per cargo bike, scooter and day [km]	-	-	-	-	0.33	-	-
Electricity grid mix for charging of e-scooters	German mix, 0.568 kg CO ₂ eq./ kWh [60]						Solar power, 0.0806 kg CO ₂ eq./ kWh [71]
Transport of the e-scooter to Germany	Train					Plane	Train
Number of batteries per scooter	1.5	1.5	1.0	1.5	1.5	1.5	1.5

6) Scenario 6: Solar Power

The environmental impact of the electricity mix used to charge the e-scooters has a strong influence on the life cycle assessment of the use phase. To evaluate this effect, it is assumed in this scenario that the e-scooters are charged with solar power. In this scenario, the environmental impacts of electricity demand are modelled according to the country-specific conditions of German electricity from photovoltaic. The GWP is 0.0806 kg CO₂eq. per kWh of electricity [17].

IV. MAIN FINDINGS

Fig. 3 shows the life cycle environmental impacts per passenger-kilometre travelled for each scenario. In the base case, the average GWP is 77 g CO₂eq./passenger-kilometre, with 63% from materials and manufacturing, 1% from transportation and 35% from the use phase. In the use phase, 11% of the GWP comes from electricity for charging the batteries, 13% from collecting the batteries and e-scooters with a diesel van and 4% from the battery for swapping (1.5 batteries per scooter).

A shorter lifetime can greatly increase the environmental impact of e-scooter sharing. With a lifetime of 6 instead of 24 months (scenario 1), the GWP increases by 21% to 237 g CO₂eq./passenger-kilometre, with a far higher share of production of 82 %. Alternative approaches to charge the e-scooters can greatly reduce or increase the adverse environmental impacts. If no swappable batteries are used, resulting in an average distance of 1 km per e-scooter per day for the van to collect and charge (scenario 2), the GWP will increase by 56% to 121 g CO₂eq./passenger-kilometre. The use phase then accounts for 58% of this environmental impact. The use of electrified vans for collection (scenario 3) results in a 12% reduction. Using electrified cargo bikes to collect the batteries and e-vans to collect broken e-scooters (scenario 4)

could yield a net reduction in GWP of 17%. If the e-scooters were charged with solar power, the GWP impact could be reduced by 14%. If the e-scooters were transported by air from China to Germany, it would increase by 20%. Fig. 4 shows the Global Warming Potential of the production of an e-scooter. Per 1 kg weight of the e-scooter, the GWP is 13 kg CO₂eq. The production of the aluminium components accounts for 65% of this, the battery for 12% and the motor and the electronic components for 6% each. In order to better understand the environmental impact of e-scooter sharing, it is necessary to compare it with alternative modes of transport. As shown in Fig. 5, it becomes clear, that e-scooter sharing in a best-case scenario has a lower environmental impact than private cars, electrified mopeds and public transport buses, but performs worse than trams, electrified bikes and bicycles. In the worst-case scenario, e-scooters have the worst environmental impact of all modes of transport. To evaluate these results, it is necessary to consider which modes of transport are likely to be substituted by e-scooter sharing. Hollingsworth et al. surveyed e-scooter drivers to find out which means of transport they would have used if the e-scooter sharing had not been available. 7% of users reported that they would not have taken the trip; otherwise, 49% would have biked or walked, 34% would have used a private passenger cars or ride-share service, and 11% would have taken a public bus [8] The research institute 6t-research determines a substitution rate of 8% for private passenger cars. The substitution rate of footpaths by electric scooters is thus over 44 % and for public transport approx. 30 % [12].

The sensitivity analysis shows that the GWP is most sensitive to the scooter lifetime and the distance driven for collection. A low scooter lifetime shows very high global warming impacts driven from the manufacturing and materials burdens, which are spread across a smaller number

of passenger-miles travelled over the e-scooter lifetime. Therefore, it is clear that the production is an important parameter to influence the environmental impact of e-scooter sharing, but this study did not include a sensitivity analysis of production. Another important parameter is the distance travelled to collect batteries or scooters per distance travelled with the scooter. Especially the use of swappable batteries reduces the collection distance enormously. Also, densely populated urban areas can allow a higher density of e-scooters and lower collection distances per scooter. Another result of the sensitivity analysis is that differences in the grid emissions of the electricity used to charge the scooter cause only small changes in the overall results. While this study was conducted with parameters specific to Berlin, Germany, the results can be interpreted and used for a wide range of locations.

V. LESSONS LEARNED

E-scooters may be an effective solution to urban congestion and last-mile problem, but they do not necessarily reduce the environmental impacts of the transportation system. This study demonstrates that there is the potential for e-scooters to increase life cycle emissions relative to the transportation modes that they displace. In the worst-case scenario, the GWP per passenger-kilometre of e-scooter sharing could be higher than all other modes of transport, including private cars. In this study, we found that the GWP associated with the use of shared e-scooters are dominated by the manufacturing phase, especially the production of aluminium parts.

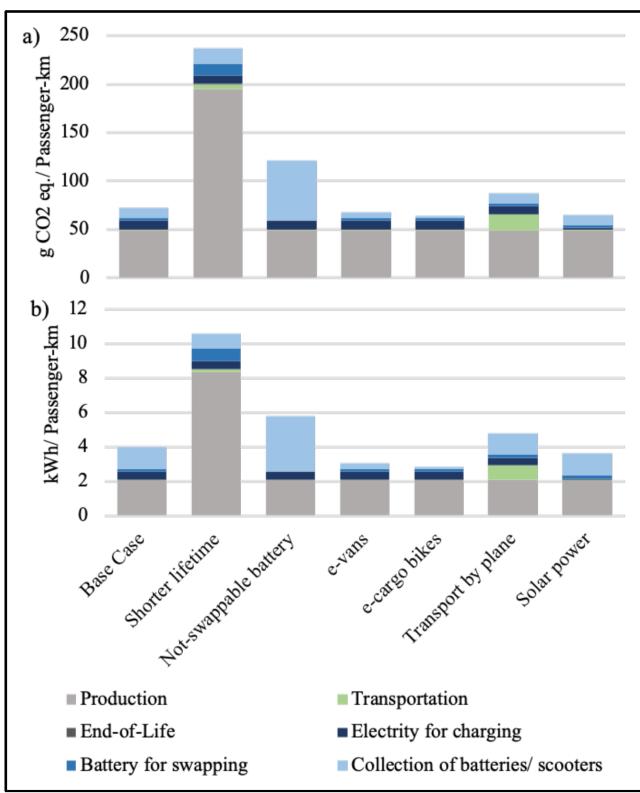


Fig. 3. Life cycle environmental impacts for shared electric scooters under Base Case and alternative scenarios for a) global warming potential and b) non-renewable primary energy demand.

In addition to production, the lifetime of the scooters, the distances to collect the batteries or scooters, the type of collection vehicle and the electricity mix for charging the scooters are important influencing factors. If non-swappable

batteries are used, and the entire scooter is collected for charging, every 10th trip travelled with the e-scooter is accompanied by a trip of the collection vehicle. However, it is important not to replace all e-scooters with new scooter models immediately, but only at the end of the scooter's lifetime, as the lifetime has the highest influence on the environmental impact. It would also be a possibility to extend the lifetime by selling the scooter in private ownership.

There are effective measures for cities and decision-makers to work towards integrating e-scooter sharing into urban transport in an environmentally friendly way. By limiting the business area of the sharing service to the inner-city area, the density of scooters increases, and the distances of battery/ scooter collection trips are reduced. By offering a joint service of e-scooter sharing and local public transport, cities could promote e-scooter sharing as a complement rather than a substitute for the more environmentally friendly public transport. Additionally, cities could enforce anti-vandalism policies to reduce e-scooter mistreatment, which can result in short lifetimes (and thus high manufacturing impacts per passenger-kilometre travelled).

The scooter-sharing providers can take important measures to reduce the environmental impact as well. First of all, it may make sense to produce vehicles with a lower share of aluminium, as the aluminium components account for a share of 65% of the GWP of the production of the e-scooter. The manufacturer is recommended to use "green" aluminium, with a high recycling rate and renewable energies in the production. Previous studies have analysed a much lighter scooter (approx. 17 kg), with the result that the GWP of scooter production is only half as high, at 178 kg CO₂eq. per scooter [8]. On the other hand, the lighter scooter is supposed to have a shorter lifetime, which compensates the lower environmental impact of the production regarding the impact per passenger-kilometre. In addition, the sharing providers should use electrified vehicles to collect the scooters and batteries, switch to scooter models with swappable batteries and charge their vehicles with electricity from renewable energy sources. In the future, it is also feasible to set up a battery charging infrastructure consisting of battery charging and swapping stations, which would enable the user to change and charge the battery himself, so that collection trips are eliminated.

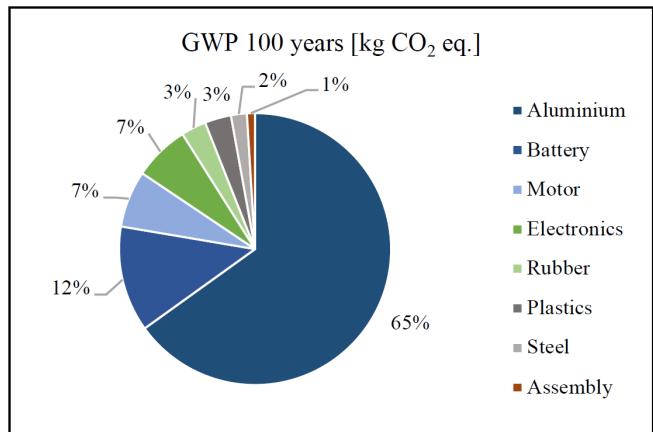


Fig. 4. Global warming potential of the production of an e-scooter.

The results of this study are comparable to previous studies. Hollingsworth et al. determined a GWP of 88 g CO₂eq./ passenger-kilometre for a lifetime of 24 months and

281 g CO₂eq./ passenger-kilometre for a lifetime of 6 months [8]. The values determined in this study are 17% lower. These deviations are due to the assumption of shorter distances for collecting the batteries.

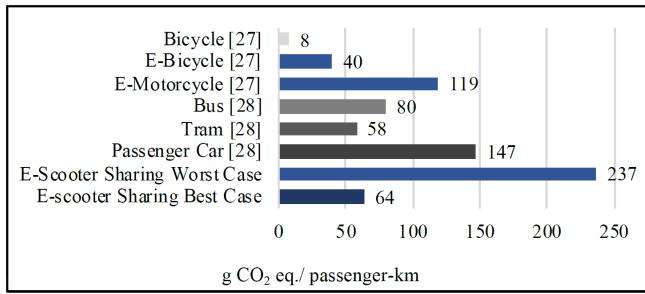


Fig. 5. Comparison of the global warming of e-scooter sharing to alternative modes of transport

Cities and e-scooter sharing service providers can use this study to explore the life cycle impacts of e-scooter sharing. Through further research on usage patterns and operating systems in e-scooter sharing services, it will be possible in future to make even more precise statements on the environmental impact over the life-cycle. Further studies should also examine the influence of aluminium components on the environmental impact and potential measures to reduce the impact, such as relocation of production, a higher proportion of secondary aluminium and a lower proportion of aluminium components in scooters. The claim that e-scooter sharing will benefit the environment should be viewed with scepticism unless longer product life, environmentally friendly production of e-scooters and efficient collection and charging of e-scooters are achieved.

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