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Study

Environmental Impact of Electric Scooter Sharing

Life Cycle Assessment of the TIER Mobility VI e-Scooter

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Abbreviations

CO_2-eq.	Carbon dioxide equivalents
GHG	Greenhouse gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LEV	Light Electric Vehicles
pkm	passenger-kilometre
tkm	tonne-kilometre

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1. Introduction

According to the International Energy Agency (IEA, 2021), the transport sector produces 37% of global energy-related greenhouse gas (GHG) emissions - passenger transport being responsible for a share of 44%. While this calls for increased efforts in decarbonising mobility, we also see an increase in transport activity and vehicle size. Emissions of road vehicles have continued to rise in recent years, outweighing efficiency gains in vehicle technology (IEA, 2021).

Considering these challenges, Light Electric Vehicles (LEVs), including stand-up electric scooters, are a promising solution for urban mobility: they require less energy for production and operations as well as less space in comparison to cars (Ewert et al., 2020). Hence, personal LEVs and new systems (e.g., LEV sharing services) are emerging in cities worldwide (Heineke et al., 2019; Hyvönen et al., 2016). Despite these advantages, it is necessary to constantly monitor the potential contribution of LEVs to climate-friendly mobility - from a holistic life cycle perspective. Although a number of studies on greenhouse gas (GHG) emissions from e-scooter sharing are already available (Chester, 2019; Hollingsworth et al., 2019; Moreau et al., 2020; Severengiz et al., 2020; Kazmaier et al., 2020; de Bortoli, 2021; Deutsche Energie-Agentur GmbH - German Energy Agency (dena), 2021; Gebhardt et al., 2021; Ishaq et al., 2022)), new developments in the design, vehicle and service operations should be assessed.

This study conducts a Life Cycle Assessment (LCA) of the new e-scooter model from TIER Mobility, the TIER VI. The goal is to quantify the vehicle's impact in the impact category Global Warming Potential (GWP). Based on primary data from TIER Mobility, the study covers the e-scooter's production as well as usage patterns and operations logistics of the sharing service. The study compares a European grey scenario of TIER's sharing system operations to a green scenario; the main differentiating factors are the service vehicle types and the electricity mix for e-scooter charging. The results can be used to inform operators and manufacturers decision-making on the sustainable design of an e-scooter model.

2. Methodology: Life Cycle Assessment

The methodology of a Life Cycle Assessment (LCA) quantifies the environmental impact of technical systems or services throughout their entire life cycle. Therefore, it includes all product life phases, from raw material extraction (cradle), over production, transport and lifetime usage to end-of-life (grave) as illustrated in Figure 1.

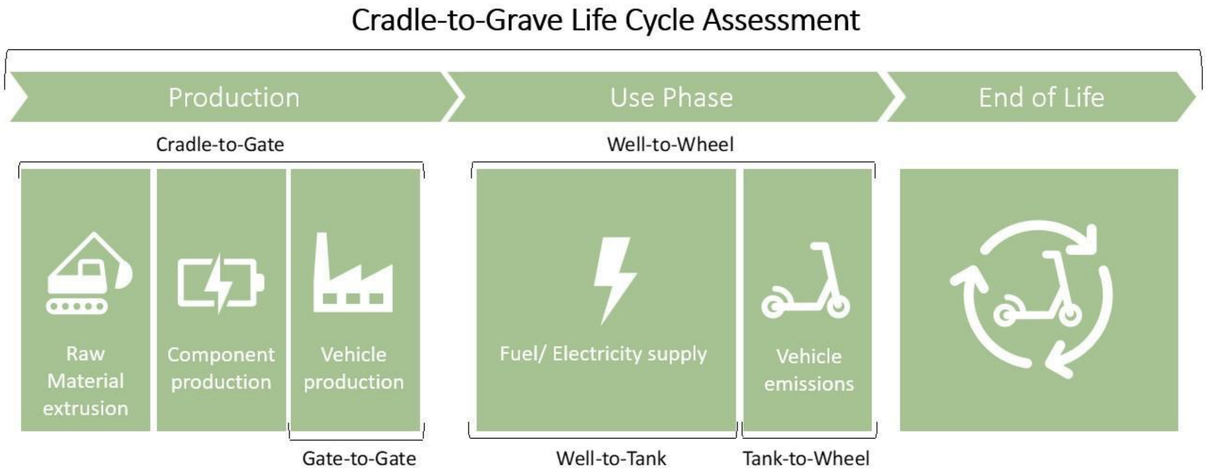

Figure 1: Product life phases considered in Cradle-to-Grave Life Cycle Assessment.

According to Brinkman et al. (2005), LCAs of transport modes include:

- vehicle production, incl. raw materials and components (Cradle-to-Gate), and vehicle assembly (Gate-to-Gate)
- use phase of the vehicle (Well-to-Wheel), including the generation provision of the drive energy (Well-to-Tank) and the conversion into kinetic energy to operate of the vehicle (Tank-to-Wheel); and
- treatment or recycling of the vehicle and its components to recover raw materials (End-of-Life).

The present LCA is conducted in four phases, in accordance with the ISO standards 14040/44: 1) Goal and Scope Definition, 2) Life Cycle Inventory, 3) Impact Assessment and 4) Interpretation (International Organization for Standardization, 2009, 2006).

For the impact assessment, we evaluated the GWP 100 in kg CO_2-eq. GWP calculates the potential effect of substances emitted by the analysed product system that contribute to global warming, when equated with the effects of CO_2 reflecting heat radiation. GWP is expressed as CO_2-equivalents (CO_2-eq.); the effects of the substances are conveyed relative to the effect of CO_2. The calculation of GWP can consider different time horizons (20, 100, or 500 years) in which the known GHGs have a different effect on global warming as derived from the IPCC Second Assessment Report (Houghton et al., 1996). In this study, we consider a time horizon of 100 years (GWP 100).

2.1 Goal and Scope Definition

The goal of this study is to examine the life cycle environmental impact of a sharing service using a stand-up e-scooter. The study analyses the TIER VI e-scooter model, which is shown in Figure 2.

Figure 2: E-scooter model analysed: TIER VI e-scooter.

The system boundaries of the study are illustrated in Figure 3. It includes impacts caused by the production of primary and secondary materials, component production, vehicle manufacturing, transport, use and end-of-life. The functional unit is one passenger-kilometre (pkm) travelled. We use the IPCC 2021 AR6 method to assess the e-scooter's environmental impact (Forster et al., 2021).

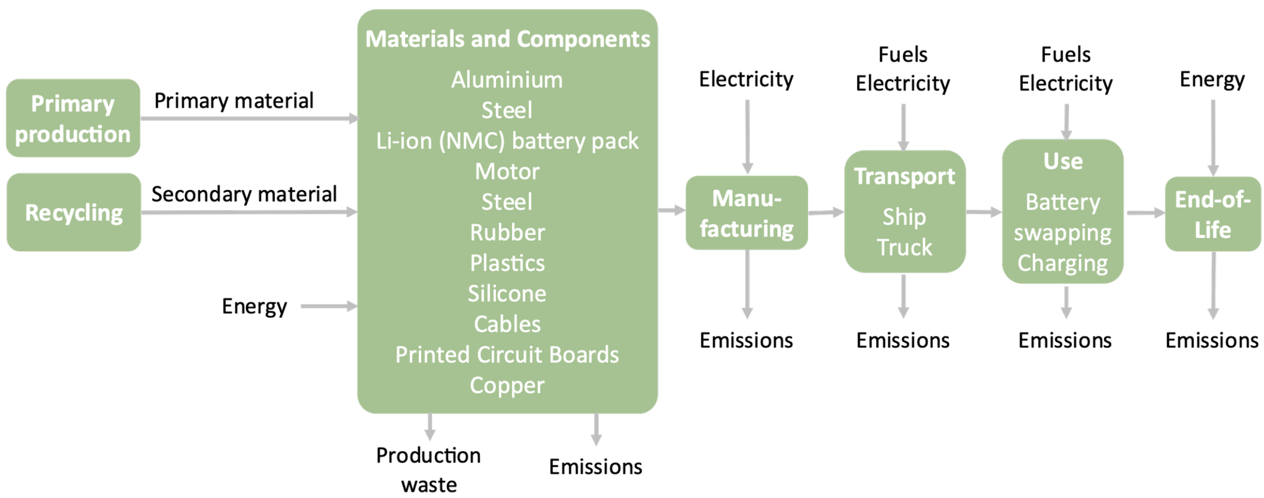

Figure 3: System boundaries for the Life Cycle Assessment on shared e-scooters.

2.2 Inventory Data for Production, Transport and End-of-Life: Product Carbon Footprint

The main data source for the life cycle inventory of production was a bill of materials (BoM). The BoM was obtained by completely disassembling the e-scooter provided by TIER Mobility, weighing the components individually and assigning corresponding material properties and manufacturing processes. In addition, the product data sheet, listing all details on materials in aggregated form, was used. Afterwards, each material was matched with its respective GHG emission factor from a dataset of the GaBi software (Sphera Solutions GmbH, 2022a, 2022b). For the printed circuit boards (PCB), an individual assessment was carried out: the components of all PCBs were determined and then remodelled in the software. A list of the components is provided in the Appendix. Paint and engravings were not included in the assessment.

Figure 4: Disassembling the e-scooter.

The materials and components of the e-scooter include aluminium, battery cells, the motor, steel plastics, PCBs with electrical components, rubber, silicone (as sealing material for electronics), cables and copper. The total mass of the e-scooter is 31.6 kg. The weights of the individual materials and components can be found in Figure 5.

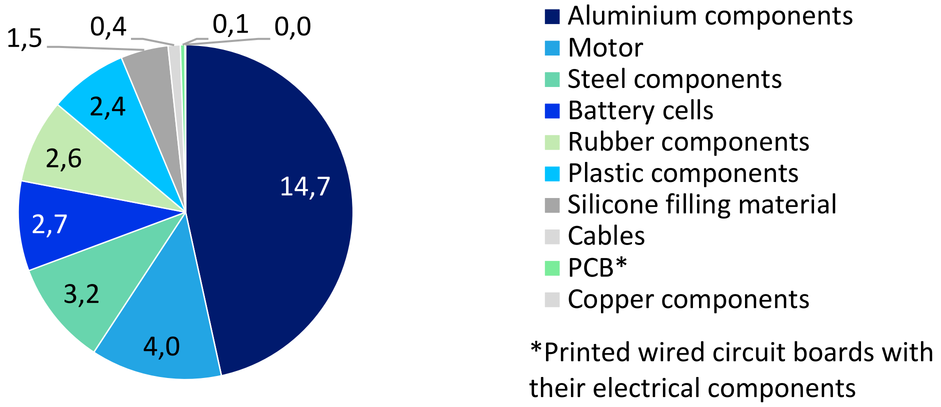

Figure 5: Weight share of the e-scooters' individual components and materials in kg.

Aluminium accounts for the largest share of weight with 46.6% of the e-scooter's total mass. The motor, mostly composed of steel (45%), copper (30%), aluminium (20%) and magnet (5%), has the second largest share with a weight of 4 kg, followed by non-motor steel with 3.2 kg. Battery cells, rubber and plastics each account for around 2.5 kg, followed by silicone as a filling material for electronics with 1.5 kg. The smallest components by weight are cables with 374 g, the PCBs with electrical components at around 138 g and non-motor copper with 20 g.

The e-scooter is manufactured in China, which requires 2,4 kWh of electrical energy per scooter based on the Chinese grid mix. For the transport phase, we assumed the following:

- 336 km via truck for transportation of the vehicle from the manufacturing site in China to the harbour.
- 22,126 km shipping from the Port in China to the Port of Rotterdam.
- 914 km via truck for the average distribution distance per e-scooter from the Port of Rotterdam to cities in Europe (weighted average distance provided by TIER Mobility).

The GWP factors of the different transport modes are 59.8 g CO_2- eq./tkm for trucks and 4.35 g CO_2-eq./tkm for container ships respectively.

For the end-of-life stage, the e-scooter is disassembled, sorted into its respective material categories and then recycled accordingly by TIER Mobility's recycling partner. No emission credits are accounted for in the recycling phase.

2.3 Methodology and Data for the Sharing Service Operations

For the usage phase, we consider the electricity demand of the e-scooter as well as the energy demand of service trips for recharging and rebalancing of e-scooters. The e-scooter's electricity demand was calculated based on the real-life e-scooter range and battery capacity. The resulting GWP is calculated based on the electricity mix used for charging and its emission factor per kilowatt-hour (kWh).

The service trips are done by employees which use different service vehicles such as diesel vans, electric vans and cargo bikes, to a) collect discharged batteries in the business area of the sharing service, b) recharge them centrally and c) then redistribute the batteries. The GWP of the service trips is calculated according to equation 1:

$$GWP_{service\ trips} = s_{service\ vehicle} \cdot GWP_{service\ vehicle} \tag{1}$$

where $s_{service\ vehicle}$ is the average distance of the service vehicles per kilometre travelled by the e-scooter and $GWP_{service\ vehicle}$ the emission factors of the service vehicle per kilometre travelled. The average distance of the service vehicles is calculated according to equation 2:

$$s_{service\ vehicle} = \frac{s_{d,service\ vehicles}}{s_{d,e-scooter}} \tag{2}$$

in which $s_{d,service\ vehicles}$ is the average daily distance of service vehicles and $s_{d,e-scooter}$ the average daily distance of e-scooters.

Parameter		**Green scenario**	**Grey scenario**	**Unit**
E-scooter lifetime (in kilometre)		12.000		km
Number of batteries per e-scooter lifetime		1.35		
E-scooter range		55		km
Energy demand e-scooter		0.012		kWh/km
Electricity mix e-scooter charging		EU wind mix	EU grid mix	
Method of energy supply		Battery swapping		
Share of service-vehicles	Diesel van	0%	57%	
	Electric van	43%	27%	
	Cargo bike	57%	16%	
Distance of service-vehicle per e- scooter-kilometre	Diesel van	0	18.2	m
	Electric van	13.7	8.6	m
	Cargo bike	6.3	1.8	m
Emission factor service vehicle	Diesel van	0.236		kg CO_2-eq./km
	Electric van	0.064		kg CO_2-eq./km
	Cargo bike	0.034		kg CO_2-eq./km

Table 1: Parameter specifications for the usage phase of the e-scooter within a sharing service.

Furthermore, we assumed an e-scooter lifetime of 12,000 km - in line with the data provided by the sharing provider - in order to calculate energy demand over lifetime and to relate all resulting emissions from production, transport and use phase to the functional unit ‘one kilometre travelled’. In addition, we considered the production and use of 1.35 batteries per e-scooter lifetime.

To assess and compare different operating modes, we developed and analysed two scenarios. Scenario 1, termed the ‘Green scenario’, considers the use of electricity from wind power plants for e-scooter charging and a higher share of electric vans and cargo bikes for service trips. Scenario 2, termed the ‘Grey scenario’, represents a scenario in which the EU grid mix is used for charging e-scooters and diesel vans account for 57% of service trips. Details on the assumptions of scenario 1 and 2 can be found in Table 1.

3 Results

The results of the LCA show GHG emissions of 39.5 g CO_2-eq. per passenger-kilometre in the Green scenario compared to 47.6 g CO_2-eq/pkm in the Grey scenario (see Figure 6). The difference between the green scenario and the grey scenario is attributed to differences in the composition of the operations vehicle fleet and the electricity used for charging. For the Green scenario, it was assumed that the operations fleet was composed of e-vans and e-cargo bikes only. The Grey scenario represents the European average of TIER Mobility's operations vehicle fleet. E-scooter production accounts for most emissions with 94% in the Green and 78% in the Grey scenario. Vehicle charging and operations emissions also have a significant impact on the GWP. This can be mitigated by charging the battery with renewable energy as well as using electrical vehicles to service the fleet.

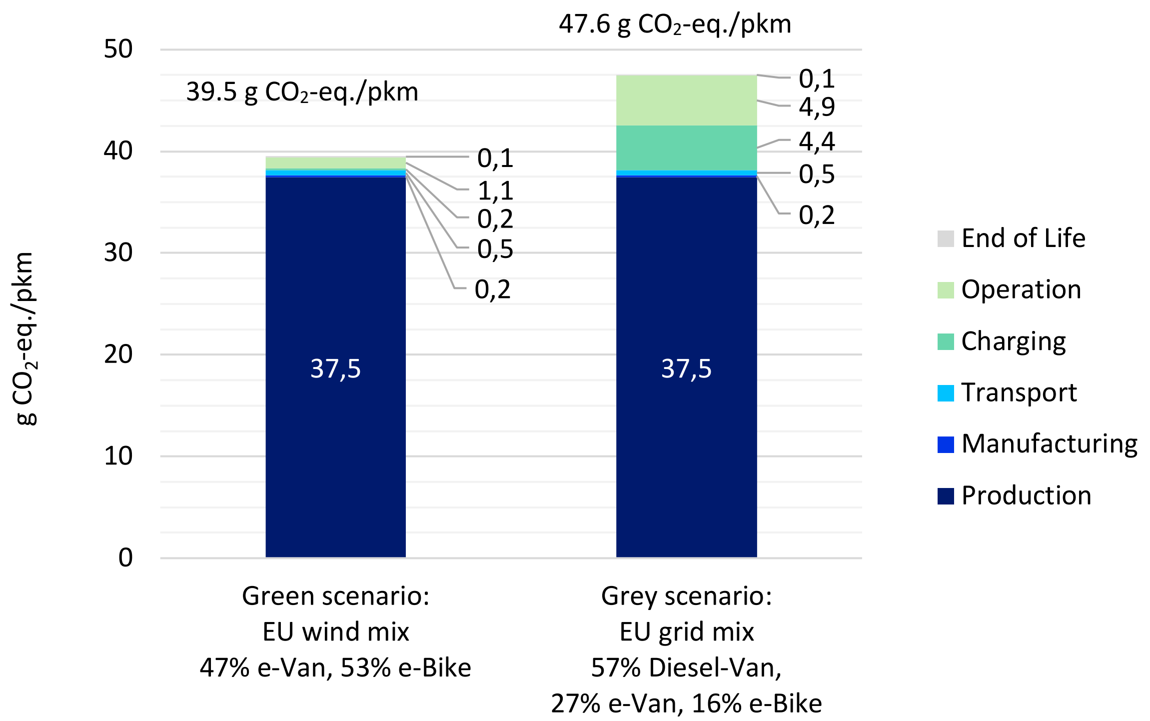

Figure 6: Life cycle environmental impacts for stand-up e-scooters in shared use under alternative scenarios for Global Warming Potential.

3.1 Hotspot: E-scooter production

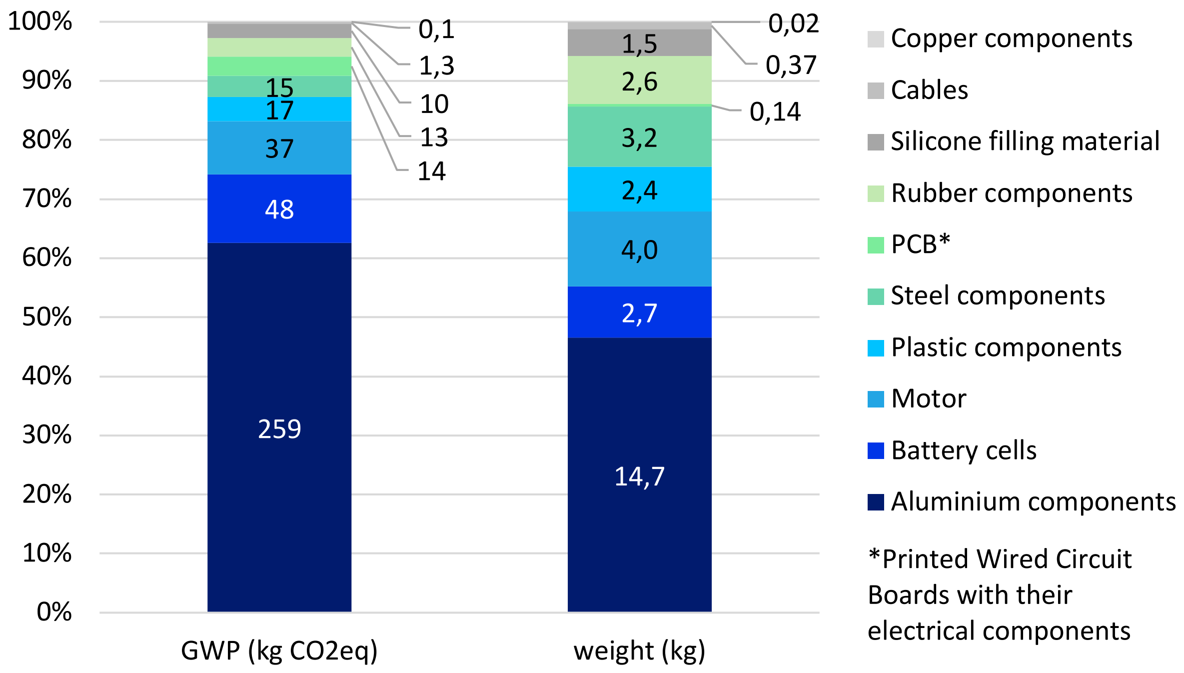

Figure 7: Comparison weight and Global Warming Potential in kg CO_2-eq of the production phase of the TIER VI e-scooter.

Since most emissions are generated during the production of an e-scooter, emissions of this phase are broken down in Figure 7 and set in relation to their weight. Aluminium is responsible for 63% of the GHG emissions during production with a weight share of 47%. The battery cells cause 12% of the GHG emissions at 9% of the total weight. Compared to their weight, the PCBs with electrical components account for the largest share of GHG emissions, but in total they are only responsible for about 3% of the production GHG emissions.

4 Conclusion

This study determined the GWP of the TIER VI e-scooter in shared use. In the Green scenario, in which the e-scooters are charged by wind power and the batteries are swapped with an all-electric operations fleet (i.e., e-cargo bikes and e-vans), the GWP results in 39.5 g CO_2-eq./pkm. The Grey scenario results in a GWP of 47.6 g CO_2-eq/pkm. This scenario assumes a mixed operations vehicle fleet of diesel vans, e-vans and e-cargo vans and charging with the average electricity mix for Europe. Overall, the GWP of the e-scooter is dominated by the production phase. In the production phase, aluminium has the highest impact on GWP, despite a significant share of secondary aluminium in the vehicle.

To further decrease the GWP of e-scooters, we recommend focusing on the *design of aluminium parts* as they account for a disproportionately high share of production emissions (63%) in comparison to their share in the e-scooter's weight (47%). It could be beneficial to further substitute primary aluminium with alternative materials, such as secondary aluminium or steel. Another measure could be the implementation of lightweight design, especially for aluminium parts as their weight share correlates with their environmental impact. Furthermore, it is recommended to use renewable energy in the e-scooters energy-intense production phase. Using renewable energy sources to power battery cell production can further decrease the GWP of the production phase. On the other hand, plastic parts do not have a significant impact on the e-scooter's GWP and are therefore not a major leverage point for emission reduction.

The second important action field is *design for durability*. Manufacturers should adapt production materials and e-scooter designs to improve vehicle lifetime. In doing so, the environmental impacts of production would be distributed over more kilometres travelled during the e-scooter lifetime. This field of action may also be addressed by the e-scooter operator by promoting a high frequency of use of the e-scooters and transferring them to other applications after use in the sharing service.

These recommendations pay into measures considering *end-of-life-strategies*. TIER Mobility has already established partnerships to enhance battery lifetime through battery repairs and recycling both batteries and vehicles. Sharing providers could explore more use-cases for the batteries beyond the e-scooter's lifetime or develop second-life use-cases for batteries to reduce the share of battery production in the e-scooter's GWP. To enhance second-use, it is indispensable to consider reparability and universal applicability already in the battery design.

Furthermore, we recommend optimising *operations* by reducing the frequency of battery swaps and performing this service using electric vehicles to further decrease the GWP of e-scooter sharing.

5 Outlook

The model used to calculate the GHG emissions of the sharing service is designed in a way that allows important core parameters to be adapted. Thus, different cities and regions can be modelled and compared in future studies. However, further studies should take a deeper look into the environmental impacts of spare part demand and maintenance. Moreover, the study quality and objectivity could be improved by gathering more independent data on e-scooter lifetime and usage frequency.

Finally, it is necessary to further study the impact of modal shifts to analyse the impact of e-scooter sharing on the broader urban transportation system and compare the environmental impact of e-scooters with alternative transport modes.

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