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Life Cycle Assessment of the TIER Mobility e-scooter sharing systems using the TIER V e-scooter

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Abbreviations

GHG	Greenhouse Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LEV	Light Electric Vehicle
NMC	$LiNiMnCoO_2$
PED	Primary Energy Demand
Pkm	Passenger-kilometer

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1. Introduction

According to the International Energy Agency, the transport sector accounts for 24% of global greenhouse gas (GHG) emissions, which caused 8.2 Gt CO_2-eq. emissions in 2018 alone. Passenger road vehicles, including cars, buses, and other two-wheelers, are responsible for about 44% of total transport emissions. Due to rising transport activity, the emissions of road vehicles have continued to rise in recent years, outweighing efficiency gains in vehicle technology. Additionally, the quantity of larger vehicles sold is increasing, which is problematic because they have higher energy demands per passenger transported and occupy more space in already congested cities (IEA, 2020). In light of these challenges, Light electric vehicles (LEV), including stand-up electric scooters, are a promising solution for urban mobility as they require less energy for production and operations as well as less space in comparison to cars (Ewert et al., 2020). Hence, personal LEVs as well as new systems (e.g., LEV sharing services) are emerging in cities worldwide (Heineke et al., 2019; Hyvönen et al., 2016).

Stand-up scooters are driven in a standing position, reach speeds up to 20 km/h in Germany and are therefore especially suitable for transporting individual drivers over short distances. In this study, e-scooter sharing is defined as a service for the shared use of stand-up scooters, where operators enable customers to rent scooters for short-term use directly through a smartphone application. As part of this service, operators maintain, repair, relocate, and charge the e-scooter batteries. The dynamic development of the market of stand-up electric scooter sharing has led to questions about its environmental impact. In particular, the operational logistics of e-scooter sharing services, such as the use of diesel-vans to swap out e-scooter batteries, remains highly questionable

This study uses the Life Cycle Assessment (LCA) methodology to quantify the effect of e-scooter sharing in the impact categories of Global Warming Potential (GWP 100) as well as non-renewable Primary Energy Demand (PED). The study not only covers a product LCA of electric scooters but considers the usage patterns and operation logistics of the sharing service according to TIER Mobility's operational model. Therefore, we develop two different usage scenarios of e-scooter sharing services for the use-case of a European city based on data provided by TIER Mobility as well as existing literature. Our results will help identify the main triggers of negative environmental impacts and advise local authorities, manufacturers, and sharing providers to appropriately reduce these impacts.

2. Methodology: Life Cycle Assessment

Life Cycle Assessments (LCAs) are a methodology of quantifying the environmental impact of technical systems or services throughout their entire life cycle. Consequently, it considers all life phases, including raw material extraction (cradle), production, transport, operations and end-of-life (grave). The LCA of transport modes encompasses the following aspects (Brinkman et al., 2005):

- The manufacturing of the vehicle, its raw materials, and components (Cradle-to-Gate), including the production of the vehicle itself (Gate-to-Gate);
- the 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
- the treatment or recycling of the vehicle and its components to recover raw materials (End-of-Life).

In accordance with the ISO standards 14040/44, the present LCA consists of four phases: Goal and Scope Definition, Life Cycle Inventory, Impact Assessment, and Interpretation (International Organization for Standardization, 2009, 2006).

For the impact assessment, we evaluated the Primary Energy Demand (PED) from non-renewable resources in MJ and the Global Warming Potential (GWP) 100 years in kg CO_2-eq.

The impact category GWP quantifies the global warming potential or greenhouse effect of substances emitted by the analyzed vehicle when equated with effects of CO_2 reflecting heat radiation. GWP is expressed as CO_2-equivalents, (CO_2-eq.) meaning that the effects of the substances are conveyed relatively to the effect of CO_2. The GWP calculation normally considers time horizons of 20, 100, or 500 years for a number of known greenhouse gasses (Danish Ministry of the Environment, 2005). In this study, we consider a time horizon of 100 years (GWP100).

PED quantifies the total energy demanded from nature to produce, use, or dispose of the analyzed product or process by summing up the energy of all required resources (Sala et al., 2016). In this study, we only consider the energy obtained from non-renewable resources.

2.1 Goal and Scope Definition

The goal of this study is to examine the life cycle environmental impact of stand-up e-scooter sharing. The study analyzes TIER Mobility GmbH's TIER V e-scooter, which is shown in Figure 1.

Figure 1: Analyzed TIER V e-scooter.

The system boundaries of the study are shown in Figure 2. It includes impacts caused by the production of primary and secondary materials, component production, transport, use, and end-of-life. The functional unit is one passenger-kilometer (pkm) travelled. We use the CMLmethod in the 2016 version to assess the e-scooter's environmental impact (Centrum voor Milieuwetenschappen Leiden, 2016).

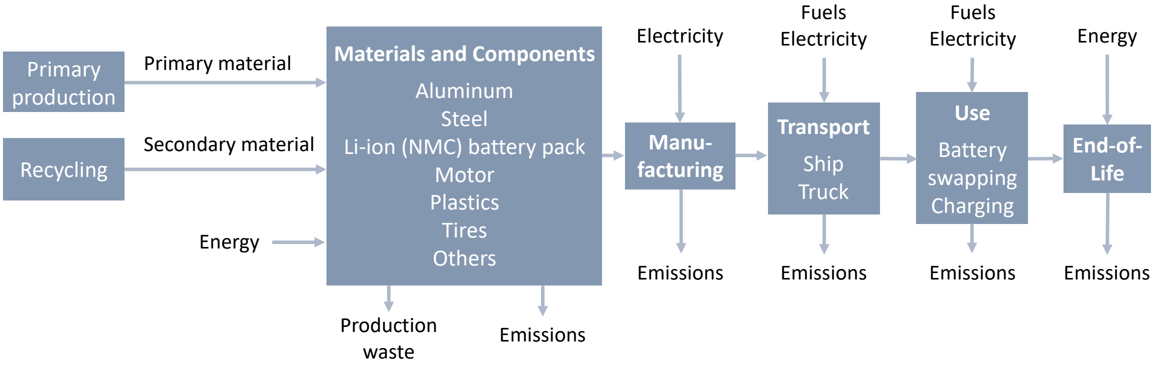

Figure 2: System boundary diagram for the Life Cycle Assessment on shared electric stand-up scooters.

2.2 Inventory data for Manufacturing and Transport phase

The bill of materials (BoM) serves as the data foundation for the inventory analysis of the production of the TIER V e-scooter (Cradle-to-Gate). By dismantling individual components of the e-scooter, we were able to validate the BoM by characterizing and creating an inventory of all components.

First, we created a list of all the e-scooter components and identified the component materials. Each material is matched with its respective emission factor from a dataset of the GaBi software (Sphera Solutions GmbH, 2021b, 2021a). For electronic components, we estimated the proportions of rubber, printed wired circuit boards, and polycarbonate, as it was not possible to break the electronic components down into individual material categories. The product system includes not only the e-scooter itself but also the associated helmet box, which carries the helmet and a hair net. For the aluminum parts, we assumed a 20% composition of secondary aluminum. We did not consider minor components (e.g., stickers, imprints, and paint).

The major materials and components of the e-scooter include aluminum, plastic, iron, battery cells, rubber, copper, and electronics which cumulatively account for 96% of the total e-scooter mass (31.8 kg) as shown in Figure 3.

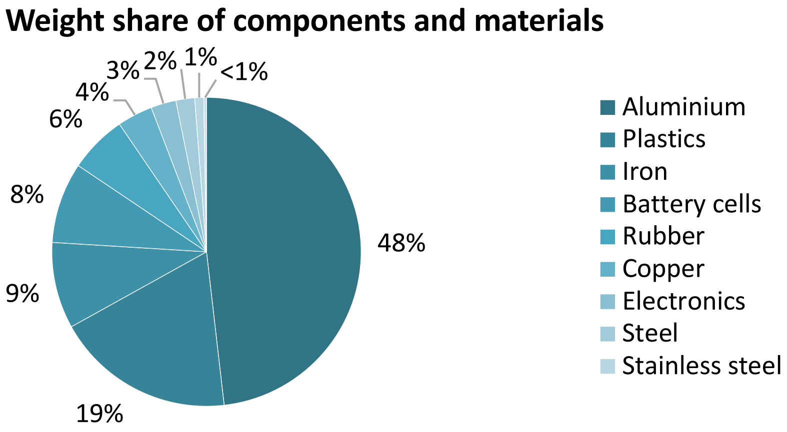

Figure 3: Weight share of the individual components and materials of the TIER V.

The e-scooter was manufactured in China. To model the production impact, we used China's average electricity mix of 0.836 kg CO_2-eq./kWh as the emission factor. The analyzed battery is made of the LiNiMnCoO2 (NMC) cathode material and was also produced in China. We also used a GaBi-dataset to conduct the impact assessment (Stoffregen and Reuter, 2019).

For the transport phase, we assume it took 12,000 km to transport the scooter from the production site to its delivery address in Europe. Based on 2021 corporate logistics data collected by TIER, we assume that 11% of the e-scooters transport phase is completed by container ship, 12% by truck, 72% by rail, and 5% by airplane. The emission factors of the different transport modes are 4 g CO_2- eq./

tkm, 33 g CO_2-eq./ tkm, 15 g CO_2-eq./ tkm, and 941 g CO_2-eq./ tkm, respectively (Sphera Solutions GmbH, 2021a, 2021b).

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

For the usage phase, we consider the use of the e-scooter and its energy demands as well as the emissions from the service trips for recharging and rebalancing the e-scooters. These service trips are completed by service employees with operations vehicles who collect discharged batteries in the business area of the sharing service, recharge them centrally, and then redistribute the batteries. The assumptions and data for the usage phase represent average values for e-scooter sharing services in Europe and are based on data collected by the sharing provider. To evaluate the impact of different operating modes, we defined two scenarios for the usage phase which are shown in Table 1.

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

Parameter		**Scenario 1: green operations**	**Scenario 2: EU average**	**Unit**
Scooter lifetime (in kilometres)		12.000		km
Number of batteries per scooter lifetime		1.35		
Scooter range		53.5		km
Energy demand scooter		0.013		kWh/km
Electricity mix scooter charging		EU wind 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 scooter-kilometer	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

As for the end-of-life stage, the e-scooter is disassembled, sorted into its respective material categories, and then recycled accordingly by the recycling partner. No emission credits are accounted for in the recycling phase. The energy consumption for this phase is 2.7 kWh for shredding (Sphera Solutions GmbH, 2021a, 2021b).

3. Results

Lifecycle greenhouse gas emissions and PED

The results of the LCA show greenhouse gas emissions of 42.8 g CO_2-eq. per passenger-kilometer for the green operations scenario and 46.7 g CO_2-eq/pkm for the EU average scenario (see Figure 4). The 8% difference per pkm between the green operations scenario and the EU average scenario is attributed to differences in the composition of the operations vehicle fleet. The green operations scenario, only has e-vans and e-cargo bikes in their operations vehicle fleet. The EU average scenario represents the global average of the operations vehicle fleet, which is also in the process of transitioning to a fully electric fleet. The same results can be seen for the PED from non-renewable resources. The PED is 0.5 MJ/pkm in the renewable energy scenario and 0.6 MJ/pkm in the EU average scenario, which corresponds to a saving of 9% and is attributable to the same causes.

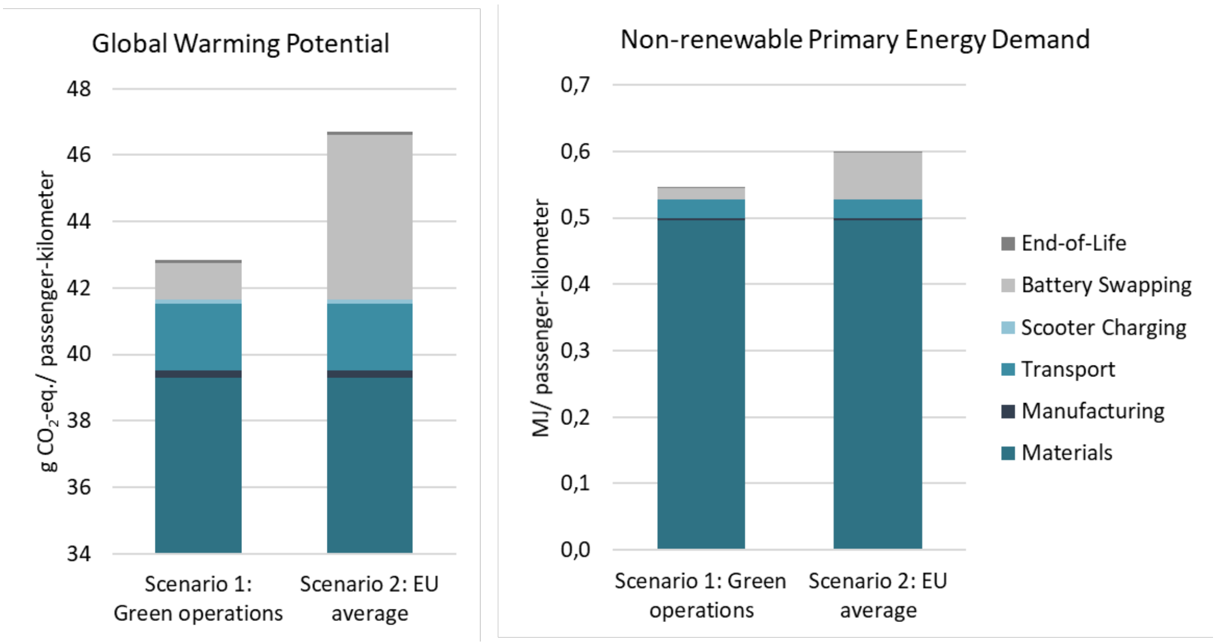

Figure 4: Life cycle environmental impacts for electric stand-up scooters in shared use under alternative scenarios for GWP and non-renewable PED.

Manufacturing and materials make the greatest impact across the lifecycle

The LCA results show manufacturing and materials are the main generators of GWP and PED from non-renewable resources. Specifically, production causes 40 g CO_2-eq/pkm and thus accounts for 93% of the total emissions in the green operations scenario and 90% of the emissions in the EU average scenario. Figure 5 shows the GWP caused by the production of the TIER V e-scooter according to material.

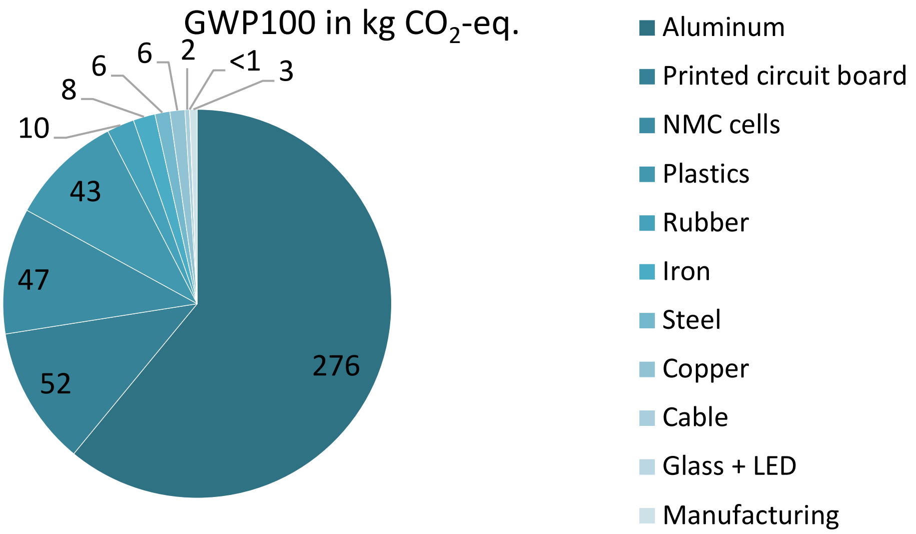

Figure 5: GWP in kg CO_2-eq of the production phase of the TIER V.

Aluminum shares the greatest impact in the production phase; it accounts for 61% of GHG because of the necessity for high energy intensity during its production. Following aluminum are the printed circuit boards (12% of GWP), battery cells (11% of GWP), and plastic parts (10% of GWP).

Figure 6 shows that for the PED, aluminum production is also the largest contributor with 47%, followed by plastic components with 18%, battery cells with 13%, and printed circuit boards with 12%.

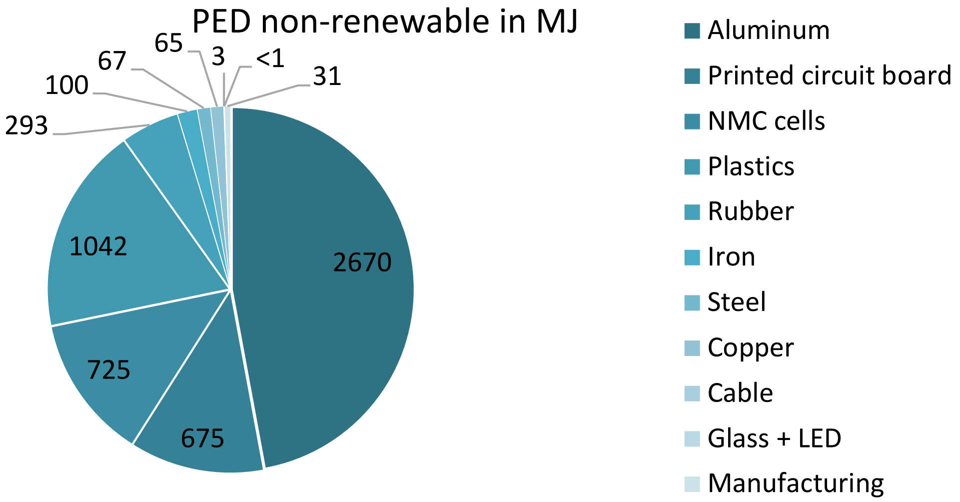

Figure 6: PED in MJ of the production phase of the TIER V e-scooter.

4. Conclusion

In this study, we determined that the GWP of the TIER V e-scooter is 42.8 g CO_2- eq./pkm in the green operations model, 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 average European scenario, in which batteries are swapped with a mixed fleet of diesel vans, e-vans, and e-cargo vans that reflect the composition of TIER's European operations vehicle fleets, results in a GWP of 46.7 g CO_2-eq/pkm. Overall, the GWP is dominated by the e-scooter production phase, especially the production of aluminum parts and battery packs which are key drivers of emission impact and PED. To further decrease the GWP of e-scooters, we recommend focusing on reducing the impact of aluminum as it accounts for a disproportionately high share of production emissions (60%) compared to its weight share (48%). This can be achieved by substituting aluminum with alternative materials, such as secondary aluminum, or through using renewable energies in production. Using renewable energy sources to power battery cell production can further drive down the GWP. Moreover, manufacturers can adapt production materials and e-scooter designs to improve vehicle lifetimes. Doing so would spread out the impact of production over more kilometers travelled. In addition, sharing providers could explore more use-cases for the batteries beyond the lifetime of the vehicle or develop second-life use-cases for batteries to reduce the share of battery production in the e-scooter's GWP. Furthermore, we also recommend optimizing operations by reducing the frequency of battery swaps and performing this service using electric vehicles to further decrease the GWP of the use phase. Finally, it is necessary to further study the impact of modal shifts in order to analyze 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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