Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2024, Volume 12, Issue 2, 1120508

Original Research Article

Life Cycle Assessment of Shared Dockless Stand-up E-scooters in Sweden

Kristina M. Holmgren[1], **Elin Einarson Lindvall**[2], **Joakim Rosell**[1]*
[1]Mobility and Systems, RISE Research Institutes of Sweden, Gothenburg, Sweden
e-mail:kristina.holmgren@ri.se
[2]Department of System Transition and Service Innovation, RISE Research Institutes of Sweden, Gothenburg, Sweden
e-mail: elin.einarson.lindvall@ri.se

Cite as: Holmgren, K., Einarson Lindvall, E., Rosell, J., Life Cycle Assessment of Shared Dockless Stand-up E-scooters in Sweden, J.sustain. dev. energy water environ. syst., 12(2), 1120508, 2024, DOI: https://doi.org/10.13044/j.sdewes.d12.0508

ABSTRACT

Shared stand-up e-scooters have been used in Sweden since 2018. Both models in use and policies applied in different cities have evolved rapidly. This study aimed to examine the environmental impacts of shared stand-up e-scooters in Sweden and identify the key factors that impact the resource and energy efficiency of these e-scooters. The findings can help e-scooter providers and cities reduce the environmental impacts of shared e-scooter services. A comparative life cycle assessment was conducted on two main cases: Case 1 corresponds to first-generation shared e-scooter models that dominated the Swedish market from 2018 to 2020, while Case 2 corresponds to a significantly heavier e-scooter model introduced in Sweden from 2020 onwards. The results show that the production of e-scooters is part of the life cycle and has the largest contribution to the environmental impacts for both e-scooter models.

KEYWORDS

Shared e-scooters, Dockless e-scooters, Life cycle assessment, Climate change, Urban transport, Micromobility.

INTRODUCTION

Shared stand-up e-scooters (ESs) were introduced in Swedish cities in August 2018 [1]. The shared ESs can be rented by the minute and are localised and unlocked using a smart app. The dockless scooters can be picked up and dropped off anywhere within a designated service area and do not need a fixed station or a dock. Just as in other countries, the rapid increase of shared dockless stand-up ESs in Swedish cities has triggered a demand for new regulations regarding the offering of rental and use of these vehicles. The public's main concerns regarding the ESs have been parking, safety issues, and environmental impacts [2].

There are previous studies of the environmental impact of shared stand-up ESs from a life cycle perspective; a review of those studies is given in [3]. The earliest study is from the U.S. [4], but there are more recent studies that have performed life cycle assessments (LCA) for European conditions, such as [5] in the case of Berlin, [6] for the case of Paris and [7] for the case of Brussels. Some of these LCA studies compare the environmental impacts to the impacts of alternative modes of transport or even analyse the impact based on what transport modes the e-scooter service replaces [6]. The earlier studies evaluate the first-generation shared ESs that were put on the market, not designed for intensive use and, therefore, had short

---

[*] Corresponding author

lifetimes of 6−24 months [4], 12 months [6] and 7.5 months [7]. The results of the studies of the first-generation shared ESs show that their climate impact is generally higher than the modes of transport they replace, and the main reasons for that are the low utilisation rates and short lifetimes [3]. These two factors determine the lifetime mileage of the ESs, which is significant in determining its environmental impact. The studies evaluating later-generation ESs show lower environmental impacts than first-generation models, but their impacts are still higher than most of the transport modes they replace. For the German setting analysed by [5], the worst case of shared e-scooters had a higher climate impact than personal cars, whereas the best case showed a lower climate impact than public transport buses but higher than trams. The introduction of shared e-scooters in the Paris transport system, analysed by [8], resulted in increased emissions of GHG since many of the replaced trips were from modes with lower climate impacts, such as metro and RER (Regional Express Network). According to [9], the first and newer generation shared e-scooters have lower climate impact than cars (personal, shared or taxis) but higher impacts than shared e-bikes, mopeds, or buses. The authors of [10] conclude that private e-scooters emit less CO_2 than the transport modes they replace, whereas shared e-scooters emit more CO_2 than those they replace.

Studies of the utilisation rate of e-scooters show a significant variation between different European cities [11]. The companies providing the ESSS are aware of the sustainability issues (all three aspects, environmental, economic, and social) of their services and have been working to improve them. The ES designs and functionality have rapidly developed since the first-generation ES was made for private use. Subsequent models have been developed specifically for shared use and made more robust [8]. The more recent models are also modular, making them easier to repair (more parts that can be replaced easily), and the batteries are swappable, reducing the need for vehicles to collect and charge and increasing the time that the ES is available for hire. Another significant difference with the more recent models is the weight. The weight has more than doubled compared to the first models of ES used in the shared services, significantly increasing the environmental burden from the scooter's production. However, the increased robustness also increases the ES lifetime and, hence, the ES's lifetime mileage, which implies a potential to reduce the environmental impact per travelled kilometre.

- We hypothesise that redesigning the ES and doubling its weight will improve the lifetime mileage and reduce the environmental impact per kilometre travelled.
- We hypothesise that the largest contributor to the environmental impact of the shared ES in Sweden is the production phase of the ES.

To the authors' knowledge, no life cycle assessment studies of shared ES use data reflecting their use in Swedish cities. Furthermore, only a limited number of studies evaluate the more recent models that have been put on the market. By identifying the factors that most contribute to the environmental impact and resource use of shared ESs in Sweden, policymakers and ESSS companies can better understand how to reduce these impacts. This information can also help identify important parameters that must be monitored for regulatory purposes or for achieving environmental targets. The two hypotheses are investigated by conducting a comparative attributional LCA for two cases of ES.

In parallel with the development of the ESs, policies and regulations have been developed in the cities and municipalities where Electric Scooter Sharing Services (ESSS) are offered. In Sweden, ESs are subject to the same traffic rules as conventional bikes, and municipalities have used other legislation and regulations to manage the use and parking of ESs. In some cities, the number of active ESSS companies and the number of offered ESs have been restricted to minimise the problems citizens perceive, such as too many ESs taking up public space or not being parked properly. Additionally, many cities have introduced designated areas or geofencing for parking the ESs. Many other policies have been applied or suggested to minimise perceived problems. New policies and regulations can result in changes in the utilisation rate, design of vehicles, and other factors which can impact the environmental burden of the ESs.

MATERIALS AND METHODS

Life Cycle Assessment is a standardised methodology used to analyse the environmental impact of products and systems. Following the LCA standard, ISO 14044 [12], the Life Cycle Assessment is performed by *Goal and Scope Definition*, *Life Cycle Inventory Analysis*, *Impact Assessment,* and *Interpretation*. This study also conducted a review process, as suggested in the ISO 14044. The scientific literature has widely used LCA for electric vehicles [13].

The product life cycle is divided into three phases: production, use and end-of-life. The system boundaries and processes specific to the shared ES system investigated in this study are shown in Figure 1. The following processes are included in each of the life cycle phases:

- The production phase includes raw material acquisition, recycling of materials (such as the production of materials from raw materials and the production of complex materials), production of components, and manufacturing of the ES. Some of the materials used in the production of the ES are recycled materials.
- The transport phase includes the transportation of the ES from the manufacturing site (China) to the site where it is used (Sweden).
- The use phase includes charging (including upstream emissions from the production of electricity and losses from the distribution network and in the ES); collection and redistribution (including vehicles used for the collecting batteries and/or ES for charging and maintenance and redistribution), and repairs (including the environmental impacts of the production of spare parts).
- The end-of-life phase includes handling the ES at the end of its life. The environmental impact of recycling materials is not included in the end-of-life phase, as it is allocated to the next product (note that some incoming materials in the production phase are assumed to be recycled materials). However, incineration and landfilling are included processes.

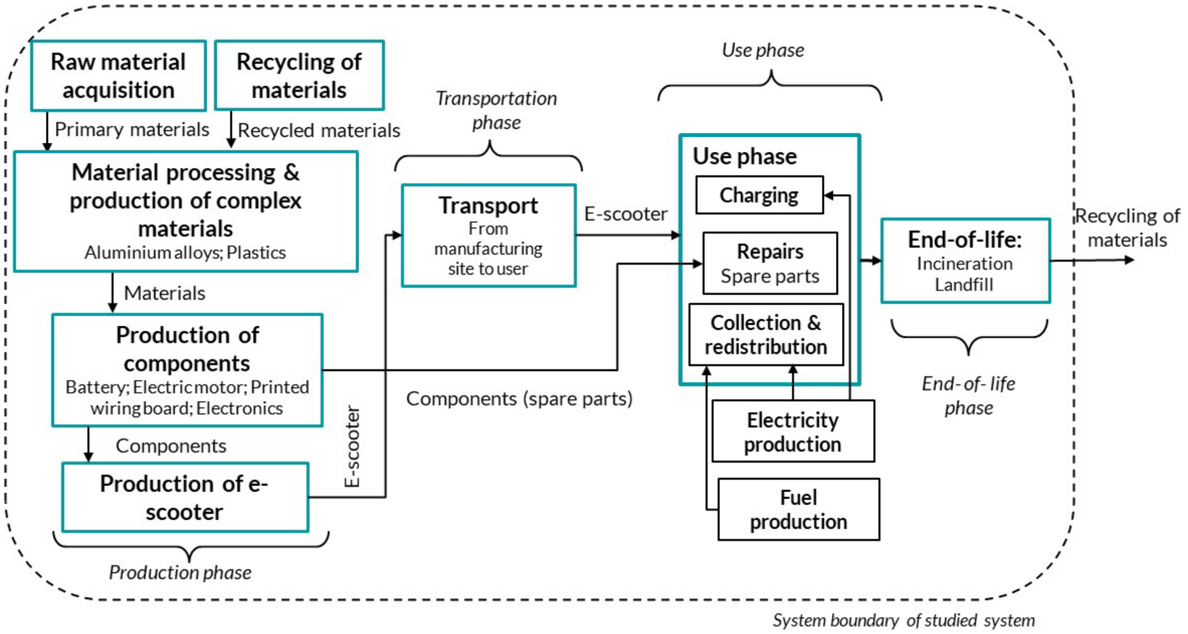

Figure 1. System boundary of the shared ES life cycle; in repairs, the upstream emissions of the raw material acquisition and production of spare parts are included; note that electricity and fuels are used in many of the processes but are not specifically pointed out in the figure

Goal and scope definition

The objective of the study is to understand the environmental burden and the energy and resource utilisation of shared stand-up ESs in Swedish cities, as well as to understand which factors have the largest impact on the resource and energy efficiency of these ESs.

Table 1. Description of the main characteristics of the two analysed cases

	Case 1	Case 2
Bill of materials (BoM)	Based on average values from two previous studies ([4] and [7]); total mass 15.2 kg	Based on data from e-scooter providers in the Swedish market; total mass 32.2 kg
Material extraction	Secondary data Ecoinvent 3.8 database based on BoM.	
Manufacturing	Process steps from Ecoinvent 3.8 considered – the same amount of energy/resources needed per kg of material. Input: electricity, natural gas, and oil (based on data from ES companies). Production in China (ES) and Korea (battery); the environmental impact of electricity is based on national electricity production data for the respective country.	
Transportation	Transportation by boat and truck from China to Sweden − scaled by mass/weight of ES.	
Use pattern	Lower utilisation rate due to unavailability during sharing. Longer distances for collection due to collecting the entire ES.	Data collection on use phase from this project; trip length and number of trips per day from ESSS companies.
Collection & redistribution	The vehicle fleet includes diesel and electric vans.	Cargo bikes are used in the fleet for battery swapping, and vans (diesel and electric) are used for collection and redistribution.
Battery size/ energy use	0.344 kWh battery at full charge, 0.017 kWh/km; non-swappable battery.	0.733 kWh battery at full charge, 0.016 kWh/km, swappable battery
Lifetime mileage of ES	1760 km/lifetime (1.9 km/trip; 1.3 trips/day, 2 yr) in base case. [a]	8640 km/lifetime (1.9 km/trip, 2.5 trips/day, 5 yr) in base case. [a].
End-of-life	Based on recycling rates according to Stena Recycling (from ESSS providers).	

[a] For both cases, sensitivity analysis was performed for different levels of lifetime mileage

The performed study is a comparative attributional LCA. Two main cases are analysed: Case 1 corresponds to the first-generation ES model that dominated the Swedish market during 2018−2020, which has a low weight and a short lifetime mileage and does not have a swappable battery, and Case 2 corresponds to a significantly heavier ES that was introduced in Sweden from 2020 onwards with a swappable battery and with different scenarios for the lifetime mileage. The functional unit used in this study is the passenger kilometre (pkm). The system boundaries of the ES life cycle in this study, which include the production, the transport of the ES from the manufacturer to the user, the use phase, and the end-of-life phase, are shown in **Figure 1**.

The Environmental Footprint method 3.0 is used for the impact assessment [14]. The included environmental impact categories are:

- Climate change, indicated by radiative forcing as global warming potential, measured in g CO_2 eq. (summarised by GWP_{100} factors according to IPCC 2013 baselines [15]).

- Resource use, minerals, and metals indicated by abiotic depletion potential (ADP) for minerals and metals measured in mg Sb eq. (Antimony equivalents).
- Total energy demand or cumulative energy demand, measured in MJ of the higher heating value of fuels.
- Photochemical ozone formation, indicated by tropospheric ozone concentration increase, measured in g NMVOC eq. (Non-Methane Volatile Organic Compound equivalent).

Table 1 presents the main characteristics and data used for the two cases. More details are given in the following sections and the Appendix. The results should be used to identify which parts of the lifecycle contribute most to the ES's resource use and environmental impact and answer the two hypotheses in the introduction.

Life cycle inventory analysis

Data on the ES models from two ESSS companies active in the Swedish market, along with estimates for their operational parameters (such as collection, storage, and redistribution) were complemented by data and estimates from previous studies from the Ecoinvent 3.8 library (cut-off by classification) were used in the study. Estimates for the use phase (such as trip distance and energy use) are based on data from the ESSS companies and our estimates using a dataset from ESSS' in Sweden that included over 2.6 million trips of shared ESs in Stockholm and Gothenburg during parts of 2019–2021. For each trip, the dataset provided: ESSS operator, unique ES-id, start and end time, state-of-charge, and location coordinates (latitude and longitude). Analyses from the dataset are presented in [16].

Resource extraction and manufacturing

The bill of materials (BoM) for Case 1 ES, with the exemption of the battery, is based on average values from two previous studies, [4] and [7]. The environmental impact of the battery is based on the model from [17]. The mass of the battery was assumed to be proportional to its capacity, with an energy density of 106 Wh/kg. The capacity of the Case 2 battery is double that of the Case 1 battery.

The BoM for Case 2 ES is mainly based on average values provided by two ESSS companies; see **Figure 2** and **Table A1** in the Appendix. The total mass of the ES is 15.5 kg and 32.2 kg for Case 1 and Case 2, respectively. The variation in plastic content between the datasets obtained from the two companies was resolved by assuming, as previously suggested, that all plastic parts consist of either ABS or PVC [7].

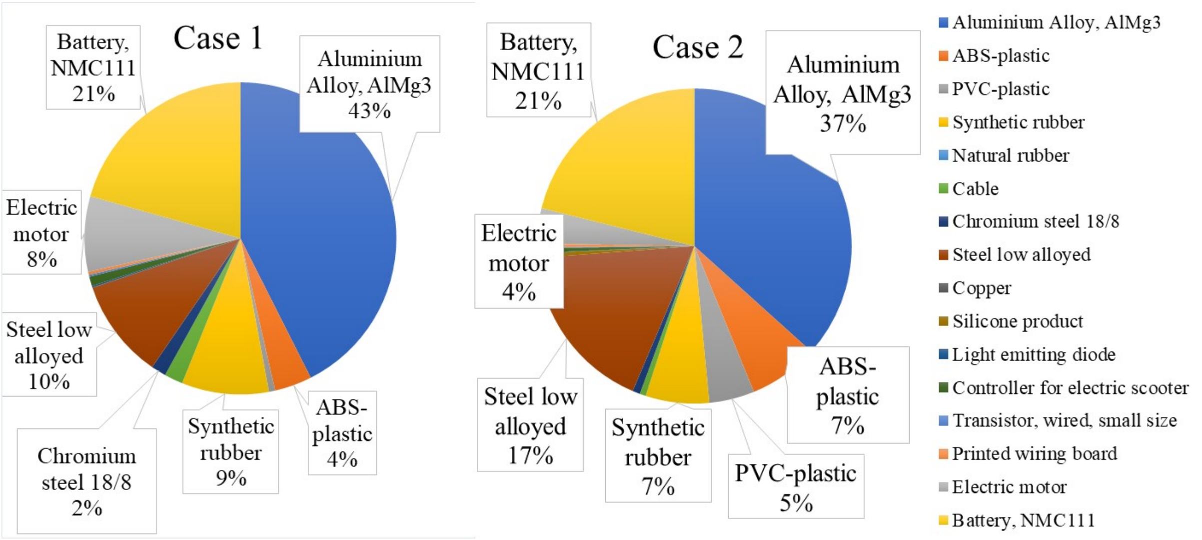

Figure 2. Bill of materials for the two analysed cases.

The ESs were assumed to be manufactured in China, and the batteries – in South Korea. The emission factors for the electricity mixes for these countries, as given in Ecoinvent 3.8, were used in the simulation for the production phase. The transportation of the batteries from South Korea to China was not included. Due to a lack of data on the origin of the materials used to produce the ES, market values from Ecoinvent 3.8 were used. The library for a cut-off by classification was used for all material streams. A proportion of recycled material (15–20%) was considered for aluminium.

The production steps for both cases were assumed to be identical, and the following processes were included: powder coating, aluminium sheet production, wire drawing for steel, and injection moulding. The production processes were assumed to use electricity (medium voltage) and heat for process heating. The electricity demand is based on data given by the ESSS companies, except for processes of aluminium arc welding and powder coating, based on Ecoinvent 3.8 data on the production of electric bicycles.

Transportation from the production site to Sweden

The ESs were assumed to be transported from China to Europe by container ship. The transport also included one trip by Euro 3 lorry from the inland factory to the port and one Euro 5 lorry in Europe for the final leg. The environmental impacts of the different transport modes were estimated using data from Ecoinvent 3.8. The journey route was based on information from the ESSS companies. However, the choice of transport modes is our assumption. Other modes, such as railway, are also possible. However, cargo trains have a higher climate impact than ships [18].

Use phase

The use phase comprises three main processes: (1) charging the ES batteries, (2) collecting the batteries or the ES (Case 2 or Case 1, respectively) for charging, maintenance, and redistribution (both cases), and (3) repairs by using spare parts.

Charging. The charging includes only the electricity required to charge the battery, based on the energy demand per ES and driven distance. The estimated energy demand is based on the average given by the ESSS companies, and this is also confirmed by the analysis of the ESSS data collected during the project. The estimated values are 0.017 kWh/ km for Case 1 and 0.016 kWh/ km for Case 2. These estimates include losses during idle times of the ES.

Collection for maintenance, charging, and redistribution. This process includes the environmental impact of the vehicles used to collect the ES for battery charging, maintenance, and redistribution. The Case 1 ES has an integrated battery, and the entire ES needs to be collected for charging. The estimated total driven distance for charging, maintenance and redistribution for Case 1 is 100 m/ES km based on estimates from ESSS companies. Diesel and electric vans are used at 51% and 49%, respectively. The environmental impact of the diesel van was estimated by a large diesel car of Euro 5 from the Ecoinvent 3.8 database. In contrast, the impact of the electric van was approximated by an electric car. For the use phase of the electric vehicles, a Swedish electricity mix was used (0.04 kg CO_2 eq./kWh, similar to the 2022 value for Swedish residual mix according to [19]). In Case 2, the ES has a swappable battery, and only the batteries must be collected for charging. Repairs and maintenance require the collection of the entire ES. The total driven distance for collecting batteries and scooters for Case 2 is 35 m/ES km. The distance is divided between diesel vans (40%), electric vans (26%) and cargo e-bikes (34%).

The energy needed for charging includes only the energy needed for the ES. It does not include energy use for buildings, changing the batteries, or performing repairs and maintenance. Further, no energy demand for running the servers to maintain the ESSS, perform navigation, or identification was included in the study.

The ESSS companies have registered an increase in the number of trips per vehicle per day (TVD) in Swedish cities since the introduction of ES. This trend can be attributed to several factors, including expanding markets with an increased number of users, improvements in the availability of ESs, and increasing market shares, among others. The Case 1 ES does not have a swappable battery, making it less available for sharing and, hence, has a lower TVD. The Case 1 ESs are also less robust and unsafe, making them less attractive. For Case 1, the TVD was estimated to be 1.3 based on data from the ESSS companies and our own trip data analysis. For Case 2, the TVD was estimated to be 2.5 based on ESSS companies and [16]. The average trip distance for both cases was estimated to be 1.9 km, based on data from the ESSS companies, including data from other operators via third-party data provider Flucto[†], and from our data analysis of trip data. The estimated lifetime for Case 1 was based on literature data. However, for our analysis, the more significant metric is the total distance driven during the lifetime of the ES, which is called the lifetime mileage. The calendar lifetime of the ES is partly dependent on the intensity of its use, which is determined by both the trip distance and the number of trips per day. The lifetime mileage defines the scenarios evaluated, but a corresponding lifetime in years is also given, see **Table 2**. The base case scenarios for Case 1 and Case 2 have lifetimes of 2 and 5 years, respectively.

Table 2. Lifetime mileages for the scenarios evaluated; base cases underlined

Lifetime [yr]	1	2	3	4	5	8
	km per e-scooter					
Case 1	880	<u>1760</u>				
Case 2		3470	5200	6930	<u>8670</u>	13870

Table 3. Spare parts considered for the two cases

Part name	Case 1	Case 2
Battery lock		x
Mainboard		x
Motor		x
Battery-extra due to swappable		x
Tyres	x	x
Phone charger	x	x
Bell	x	x
Power cable	x	x
Throttle	x	x
IOT		x
Steering bearing cup	x	x
Brake lever	x	x
Steering bearing set	x	x
Rear light	x	x
Blinkers and light	x	x
Front fork and suspension		x
Kickstand	x	x
Handlebar	x	x

[†] Flucto is a data provider in the mobility sector, see https://fluctuo.com/

Spare parts. Repairability is one of the main changes from the first-generation to the later-generation ES. This study assumes the number of reparations per 10,000 trips based on data from the ESSS companies for the newer generation ES (corresponding to Case 2), considering a selection of spare parts. **Table 3** shows the included spare parts in each case. For Case 1, fewer parts are considered repairable, but the same frequency of repairs per 10,000 trips as in Case 2 is used.

End-of-life

The end-of-life phase involves the allocation of materials between material recovery and incineration. The open-loop assumption is applied, meaning that the energy demand for recovery is allocated to the system or product that uses the recovered material. The same approach is used in the production phase to maintain consistency. For instance, in the case of recycled material used in ES production, the estimated energy demand for material recovery is allocated to the ESs (i.e., the system that uses the recycled material).

The two ESSS companies that provided data for this study follow a similar end-of-life process for their ESs. At the end of its useful life, an ES is disassembled and sorted into its respective material and recycling categories, which are then recycled accordingly by a professional recycling company. There is a small energy demand for this process, which has been accounted for in the calculations. The estimate of the shares of the ESs that end up in material recycling, incineration, and landfill (see **Table 4**) is based on data from the recycling company used by the two ESSS companies in Sweden.

Table 4. Shares [%] of material recycling/ energy recovery/ landfilling of the e-scooters according to the recycling company commissioned by the Swedish ESSS companies

Material	Recycling	Energy recovery	Landfill
Li-ion batteries	50	50	0.0
Mixed metals	95	5	0.0
Mixed aluminium	93	4	3.3
Electronics	73	20	7.0
Mixed hard plastic	100	0	0.0
Soft plastic	100	0	0.0
Cardboard	100	0	0.0

ESSS companies might also have reselling programmes where ESs are refurbished and sold on a second-hand market and/or spare parts are collected for use in repairs to their active fleets before being sent to the recycling company. This study has not considered these processes due to insufficient relevant data. However, these can be important processes that impact the environmental impact of ES.

Life cycle assessment

The LCA-modelling software SimaPro version 9.4.0.2 and the methods EF.3.0 and Cumulative Energy Demand (CED) were used for calculating the environmental impacts.

RESULTS

The results of the two cases are presented below, along with the results of some sensitivity analyses regarding the lifetime mileage of the ES.

Environmental impact and resource efficiency

The results presented in **Figure 3** show that, for both Case 1 and Case 2, the production phase (including raw materials, production of components and manufacturing) is the main contributor to the environmental impacts across all investigated impact categories. For Case 1 ES, the second largest contribution to the environmental impact across all the impact categories comes from collecting the ESs for charging, maintenance, and redistribution (hereafter called collection & redistribution).

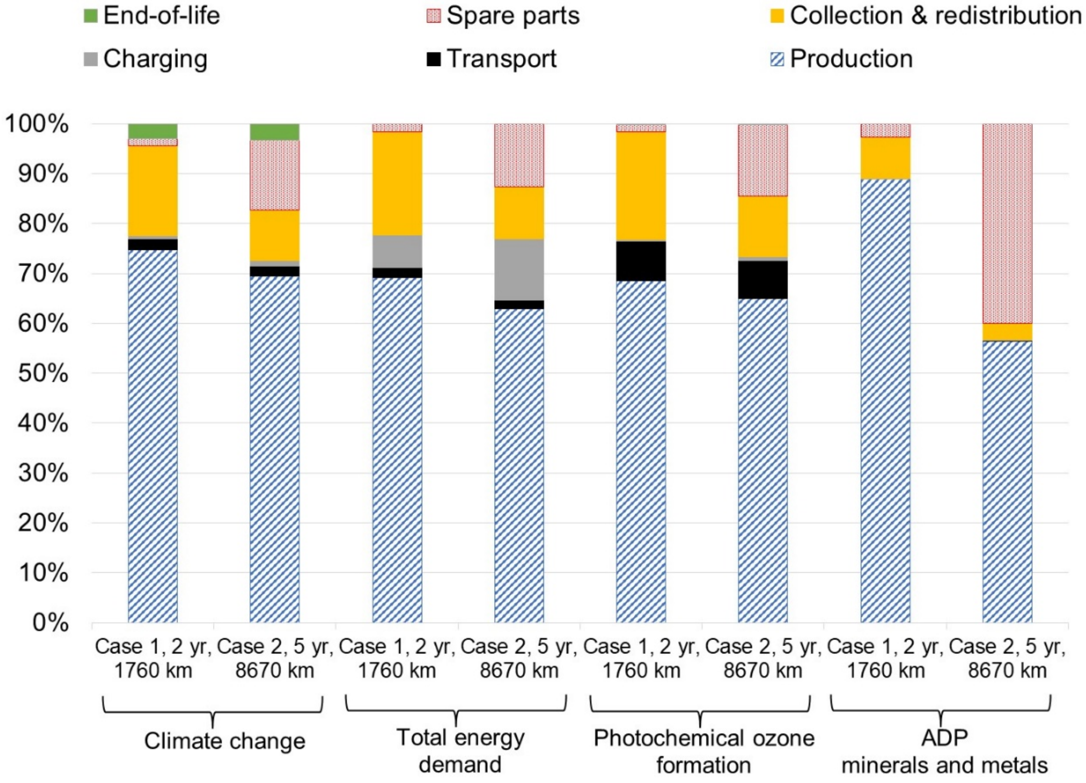

Figure 3. Stacked environmental impact for the different phases of the life cycle of the ESs

For Case 1, the production phase and the collection & redistribution together account for 93%, 90% and 97% of the climate change, total energy demand, and resource use minerals and metals, respectively. Charging has the smallest contribution to the climate impact, at only 0.6%, but accounts for 6.5% of the total energy demand. The reason for the smaller contribution to the climate impact is the low emission factor of the Swedish electricity mix. Transportation of the ES from the manufacturing site to the user contributes 8% to the total impact of photochemical ozone formation.

For Case 2, the spare parts in the use phase generate the second largest contribution to all the impact categories. It should be noted that the production of spare parts is considered during this phase. The production of the 0.4 extra batteries assumed to be needed for the ES with swappable batteries is included in the production phase. The maintenance and redistribution for Case 2 ES contribute to 10% of the total climate impact. The contribution to the total energy demand is similar for the three parts of the use phase, i.e., charging, collection & redistribution, and spare parts. The largest contributions to the photochemical ozone formation come from the production phase, followed by spare parts and collection & redistribution. Transport from the manufacturing site to the user contributes almost 8% of the total impact of photochemical ozone formation.

Case 1 and Case 2 are similar in that the battery, aluminium alloy and printed wiring board generate the largest contributions to the climate impact and cumulative energy demand from the production phase (**Figure 4** and **Figure 5**).

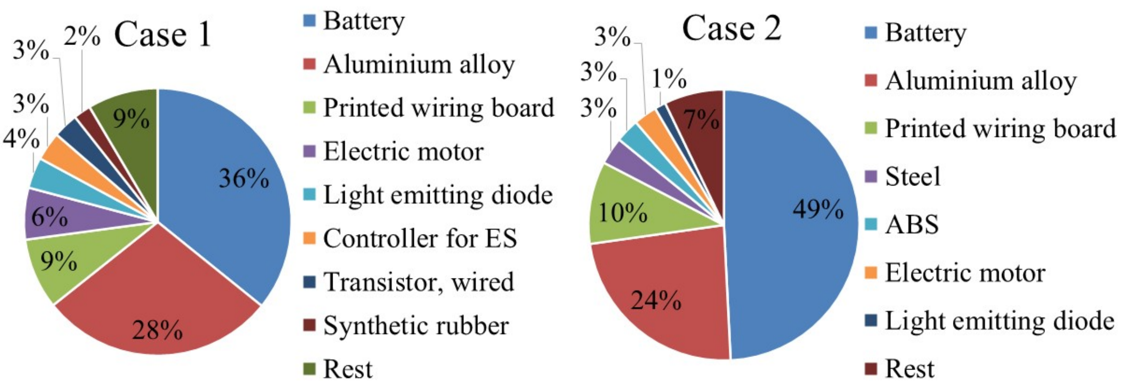

Figure 4. Contributions to the climate impact of the production phase from specific materials and components

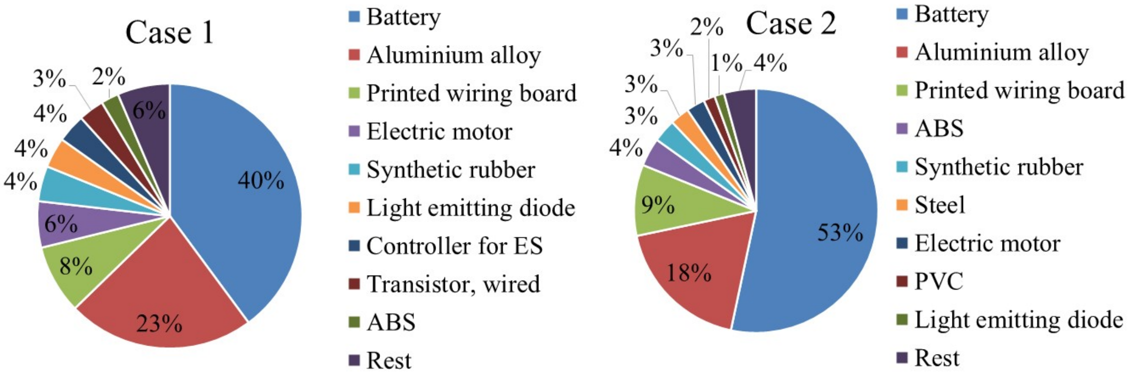

Figure 5. Contributions to the cumulative energy demand of the production phase from specific materials and components

Figure 6 displays the absolute impacts for the base cases of the two ESs. Only the impact of the spare parts increases from Case 1 to Case 2. All other processes decrease in Case 2 compared to Case 1, as the lifetime and distance driven increase significantly for the Case 2 ES. Furthermore, more parts are assumed to be exchangeable/repairable for Case 2 ES.

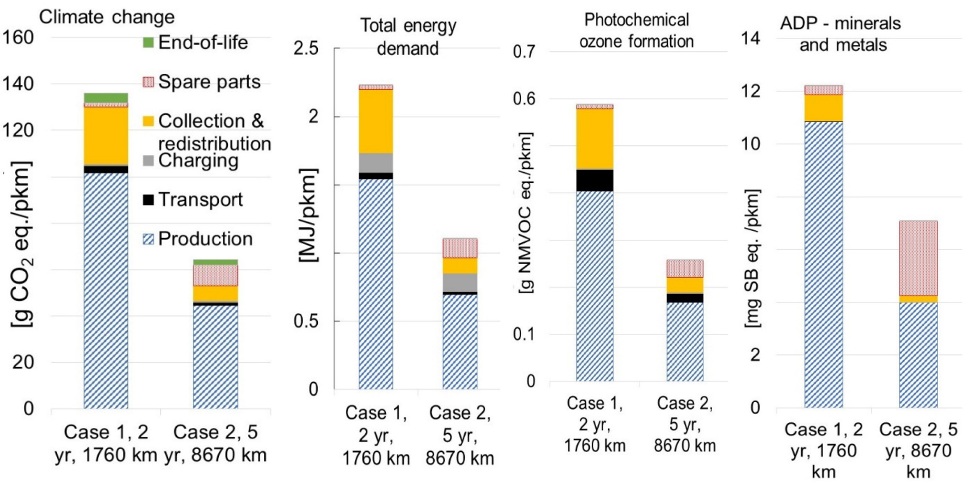

Figure 6. Environmental impact of the base case scenarios for the two cases divided upon the different phases of the life cycle

Sensitivity analysis for lifetime mileage

Figure 7 displays the results of a sensitivity analysis of the lifetime mileage of the considered cases. The higher the lifetime mileage, the lower the impact. The result for Case 1 is shown by a horizontal line and text in **Figure 7**.

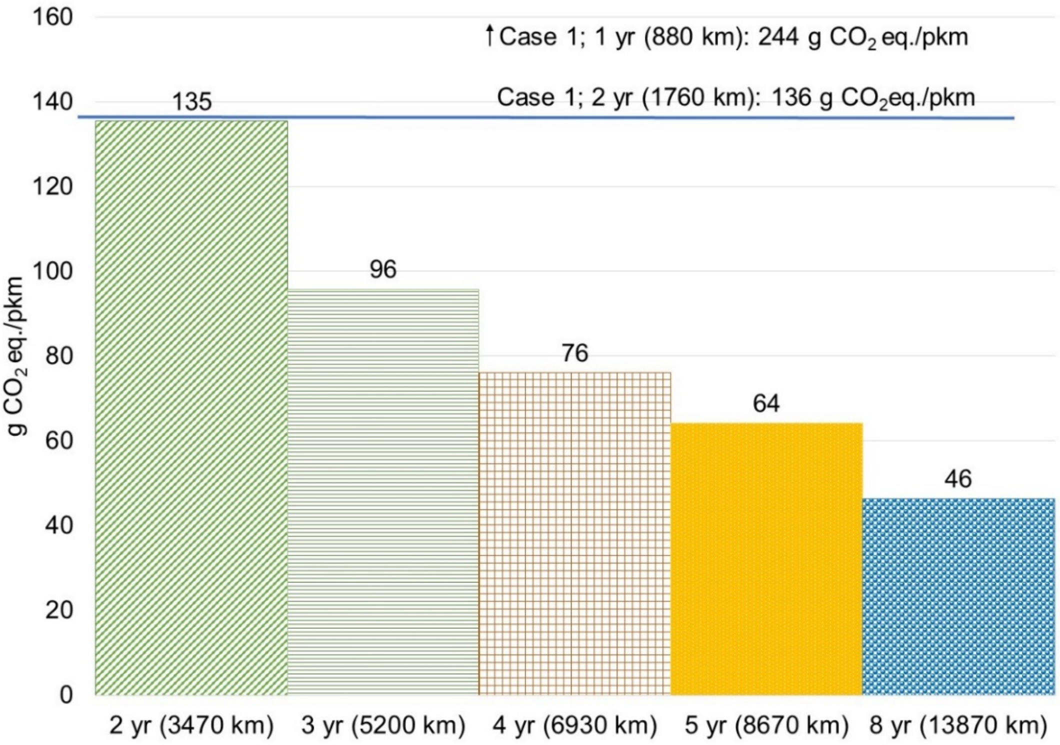

Figure 7. Climate impact of Case 2 for different assumptions regarding lifetime/lifetime mileage, compared to two scenarios for Case 1

The result shows that the total number of km travelled during the ES lifetime needs to almost double to have a lower climate impact than the Case 1 ES. If the lifetime mileage is not doubled for the Case 2 compared to the Case 1 ES, the climate impact will be higher for the Case 2 scooter. The results for the other impact categories are shown in **Table 5**.

Table 5. Total environmental impacts for different lifetime mileages

Scenario	Total energy demand [MJ/pkm]	Abiotic depletion potential – mineral and metals [mg Sb eq./pkm]	Photochemical ozone formation [g NMVOC eq./pkm]
Case 1, 2 yr (1,760 km)	3.8	12.2	0.59
Case 2, 2 yr (3,470 km)	2.2	13.1	0.54
Case 2, 3 yr (5,200 km)	2.2	9.7	0.38
Case 2, 4 yr (6,930 km)	1.6	8.1	0.31
Case 2, 5 yr (8,670 km)	1.3	7.1	0.26
Case 2, 8 yr (13,870 km)	1.1	5.6	0.19

DISCUSSION

There are many aspects to consider concerning the results of an LCA; thus, the discussion is divided into subsections.

The impact of the production phase

The results of this study show that the production phase is the most important part of the life cycle, contributing the largest share to the overall environmental impacts for the categories: climate impact, total energy demand, resource depletion minerals and metals, and photochemical ozone formation. In line with previous studies results, future efforts to reduce the environmental impact should also be directed towards the production phase. Many countries' electricity generation and industrial sectors are transitioning towards lower GHG emissions, so the impacts for these parts of the ES production phase will likely decrease. Moving the production of ES or components to areas with better availability of clean energy could be one way to speed up this improvement.

Our results show that aluminium and battery are the two parts of the ES that make the largest contribution to the environmental impacts of the production phase. Using more recycled aluminium or reducing the amount of aluminium could be important efforts to reduce the environmental impact of the production. Previous studies have also pointed this out [5]. Reducing the environmental impact of the batteries could be done in several ways, including the intensified use of renewable energy in production. The need for battery capacity could also be reduced by the right battery sizing or by prolonging the battery lifetime (through improved handling during the use phase, such as avoiding extreme temperatures and complete depletion of charging [20]).

The development of the ES to improve lifetime, robustness, safety, and repairability has led to heavier scooters. The heavier scooter requires using more material, but an increase in the lifetime mileage could offset the larger environmental impact if it can be increased sufficiently. The results of this study show that the lifetime mileage needs to nearly double or more (depending on the impact category) to get a lower impact compared to the lighter ES. Efforts to reduce the environmental impact by improved ES design and choice of materials should also consider the consequences for the ES lifetime mileage. Sustainable solutions should have a low environmental impact from the production and a long lifetime mileage.

The new heavier ES models entered the Swedish market approximately two years ago, and their implementation has been gradual. None of the new ESs has reached a lifetime of 5 years yet, but this is the expected lifetime according to ESSS companies based on observed decommissioning rates. It also substantiates this study's chosen base case lifetime of the Case 2 ES.

The sensitivity analysis shows the reduced environmental impacts resulting from significantly shorter and longer lifetimes. The lifetime mileages have been calculated assuming the same utilisation rates (trips per day and trip lengths) for each lifetime. If the utilisation rates can be increased, the lifetime mileage can be increased with more modest lifetimes in calendar days. Future evaluations should follow up on the total lifetime mileage of the new ES models. The lifetime mileage is also important for cities implementing new policies to follow up. The lifetime mileage depends on the use intensity, which can be impacted by, e.g., local regulation. Regulations that limit the number of actors and/or the number of ESs for each actor can influence the use intensity of the ES, which in turn can significantly affect the environmental impact of the ESs.

The impact of the use phase

The results show that the environmental impacts of the collection of ES or batteries for charging, maintenance and redistribution have been reduced significantly due to the lower demand for transports by using swappable batteries and by replacing the vehicles used for collection with smaller ones with less environmental footprints. ESSS companies further develop this positive trend by enabling swapping stations where users are nudged (e.g., through free rides) to swap depleted batteries, reducing the need for transports.

The charging of the ES, i.e., the use of electricity during the use phase, gives a small contribution to the overall environmental impacts for both Case 1 and Case 2 ES. The Swedish electricity mix has a relatively low environmental impact; in another context, with electricity having a significantly higher environmental impact from production, the contribution of the use phase would increase significantly.

The ESSS companies have systems for reusing parts of the ES that are still functional when the ESs meet their end of life. The reuse of spare parts was not considered in this study. If spare parts are extensively reused from decommissioned ES, the estimated impact of spare parts in this study is overestimated. However, the environmental impacts of spare parts, as estimated in this study, show the environmental benefits of reusing these components. For example, if 50% of the spare parts are reused parts from decommissioned ES, the impacts from the spare parts could be reduced by 50%.

The impact of the end-of-life phase

The ESSS companies also have systems for reselling refurbished ESs that are still functional when they meet end-of-life in their service. Resell programmes are not considered in this study. Previous LCA studies of ES have omitted the end-of-life because most parts of the ES have ended up in a stock of spare parts [7].

Other environmental impact categories

One important environmental impact category for urban transport is particulate matter (PM). This category was not included in this study since no appropriate data are available for the direct emissions from the wear of tyres and breaks during the use phase. For other vehicles, this is the main source of PM. The other source of local PM emissions from the use phase would be the vehicles used for collection and redistribution. All other PM emissions will occur at other places (e.g., at the sites of material, component, and ES production, by transport from the manufacturing site to the users or at end-of-life), which is not considered to have an impact on the local air quality in the cities where the ES are being used.

Comparison to other modes of transport and the modes replaced by electric scooters

To compare the impact of the shared ESs to the other modes of transport that the ESs trips replace gives an additional aspect to their environmental impact. It was not the focus of this study, but according to previous studies, shared ESs have a higher climate impact than the modes they replace, whereas privately owned ESs have a lower climate impact than the modes they replace [10]. If looking into details, the shared ES has a higher climate impact than the active modes of transport, such as walking or biking [6]. Compared to electric bikes, they also have a higher climate impact [5]. However, when it comes to public transport, it could be better or worse depending on the actual lifetime mileage and the specific impact of the public transport (comparative figures vary between 80−130 g CO_2 eq./pkm for buses and between 10−60 g CO_2 eq./pkm for trams or commuter trains, based on the results from [5, 6]. It is most likely that the ES has a lower impact than personal cars. Central estimates of the climate impact from a life cycle perspective for a midsize diesel-driven car is 167 g CO_2 eq./km and 183 g CO_2 eq./km for a gasoline-driven [21]. Cars smaller than midsize have lower impacts, and many alternative fuels also result in lower impacts.

Recommendations for policymakers

The comparison of the environmental impact of the shared ESs in Sweden indicates that there have been significant improvements since the first ES models were introduced. However, compared to transport modes replaced by ES, the climate impact of ES is still high. The most important factors for the environmental impacts of shared ES are the production phase and the lifetime mileage of the ES. The lifetime mileage is determined by the utilisation rate (trips per day per ES and trip lengths) and the lifetime of the ES. The utilisation rate and lifetime or lifetime mileage are parameters that policymakers should follow up on to estimate the actual environmental impacts of shared ES in their city.

Even if it does not have a significant impact on overall energy use and climate impact, it should be noted that losses during idle time could be significant. This issue was not investigated in the present study, but according to [22], losses from the battery during idle time could be as much as 30% of total consumption during the use phase.

Future studies

The impact of ESSS on people's mobility in cities is complex. Although some studies have analysed the types of trips being replaced by ESSS trips, there are likely additional indirect effects on public transportation, congestion, and other factors. Further research is needed to comprehensively understand the environmental impact of ESSS.

In addition, future studies should investigate the environmental impact of the digital systems required for the sharing service. This aspect was not considered in the present study or the previously mentioned LCAs of shared ES services.

CONCLUSIONS

The lifetime mileage of the ES is crucial to determine whether the environmental impact of the heavier ES is smaller than that of the lighter scooter. The hypothesis that the environmental impact of the heavier ES would be lower, although the impact from the production phase increases compared to the lighter ES, is rejected unless the heavier ES can achieve a lifetime mileage that is more than doubled compared to the lighter ES. It is sufficient with a doubling of the lifetime mileage for the heavier ES to have a lower climate change impact, total energy demand and photochemical ozone formation compared to the lighter ES. For the resource depletion mineral and metals category to be lower for the heavier ES than for the lighter ES, the lifetime mileage needs to be more than double that of the lighter ES.

The hypothesis that the production phase would be the largest contributor to the environmental impact of the shared ES in Sweden is not rejected. The second largest contribution to the environmental impact of both cases comes from the use phase, i.e., for the lighter ES from the collection & redistribution and the heavier ES from the spare parts.

The change to swappable batteries has significantly reduced the impact of collection & redistribution, decreasing demand for distance driven by collection vehicles per ES and converting the vehicle fleet to smaller vehicles and vehicles with lower environmental impacts.

In the Swedish case, the electricity used for charging and the end-of-life phase are small contributors to the overall environmental impact.

The parameters most important for policymakers' ability to estimate the environmental impact of ESSS are the lifetime mileage of the ES, the utilisation rate (i.e., trips per ES per day and trip length), and the lifetime of the ESs. Information on the environmental impact of ESs production could also be requested from ESSS companies. Furthermore, the vehicles used by the ESSS companies for collection & redistribution should have low environmental impacts.

ACKNOWLEDGMENTS

This study was conducted within the eSPARK project financed by the Swedish Energy Agency Dnr 2020-011467, project No. 51095-1. Financial means for finalising this paper were also provided by the "eFast – Shared micromobility as part of a multimodal transport system" project funded by the Swedish Energy Agency, No. P2022-00414.

We want to thank Birgit Brunklaus, RISE LCA expert in IoT solutions and transport service, for reviewing our methodological choices in the LCA. We are also grateful for the help Mats Zackrisson, RISE, provided for modelling the environmental impact of vehicle batteries.

We would also like to thank the two e-scooter-sharing service companies for sharing data on their vehicles and operations for this study.

NOMENCLATURE

Abbreviations

ABS	Acrylonitrile-Butadiene-Styrene copolymer
ADP	Abiotic Depletion Potential
BoM	Bill of Materials
CO_2 eq.	Carbon Dioxide equivalent
ES	Electric Scooter (here, stand-up)
ESSS	Electric Scooter Sharing Service
GHG	Greenhouse Gas
GWP_{100}	Global Warming Potential considering 100 years time span
LCA	Life Cycle Assessment
NMVOC eq.	Non-Methane Volatile Organic Compound equivalent
pkm	Person kilometre
PM	Particulate Matter
PVC	Polyvinylchloride
Sb eq.	Antimony equivalent
TVD	Trips per Vehicle per Day
yr	Year

REFERENCES

1. H. Stigson and M. Klingegård, ‘Mapping accidents with electric scooters and how the accidents can be prevented’, (In Swedish, ‘Kartläggning av olyckor med elsparkcyklar och hur olyckorna kan förhindras’), Folksam, Stockholm, Sweden, Research report, Aug, 2020, [Accessed: Feb. 08, 2023], https://nyhetsrum.folksam.se/sv/files/2020/08/Folksam-Rapport-Elsparkcyklar-aug-2020-1.pdf.
2. Region Stockholm, ‘Elsparkcyklar i delningsekonomin - Studie med fokus på regional utveckling’, Region Stockholm Tillväxt- och regionplaneförvaltningen, Stockholm, Sverige, TRN 2019-0107, 2019. [Accessed: Jan. 09, 2023], https://www.regionstockholm.se/globalassets/4.-regional-utveckling/publicerade-dokument/rapport-elsparkcyklar_200305.pdf.
3. H. Badia and E. Jenelius, 'Shared e-scooter micromobility: review of use patterns, perceptions and environmental impacts', Transport Reviews, vol. 43, no. 5, pp. 811–837, Sep. 2023, https://doi.org/10.1080/01441647.2023.2171500.
4. J. Hollingsworth, B. Copeland, and J. X. Johnson, 'Are e-scooters polluters? The environmental impacts of shared dockless electric scooters', Environmental Research Letters, vol. 14, no. 8, p. 084031, Aug. 2019, https://doi.org/10.1088/1748-9326/ab2da8.
5. S. Severengiz, S. Finke, N. Schelte, and N. Wendt, 'Life Cycle Assessment on the Mobility Service E-Scooter Sharing', in 2020 IEEE European Technology and Engineering Management Summit (E-TEMS), Mar. 2020, pp. 1–6, https://doi.org/10.1109/E-TEMS46250.2020.9111817.
6. A. de Bortoli and Z. Christoforou, 'Consequential LCA for territorial and multimodal transportation policies: method and application to the free-floating e-scooter disruption in Paris', Journal of Cleaner Production, vol. 273, p. 122898, Nov. 2020, https://doi.org/10.1016/j.jclepro.2020.122898.
7. H. Moreau, L. de Jamblinne de Meux, V. Zeller, P. D'Ans, C. Ruwet, and W. M. J. Achten, 'Dockless E-Scooter: A Green Solution for Mobility? Comparative Case Study between Dockless E-Scooters, Displaced Transport, and Personal E-Scooters', Sustainability, vol. 12, no. 5, 2020, https://doi.org/10.3390/su12051803.
8. A. de Bortoli, 'Environmental performance of shared micromobility and personal alternatives using integrated modal LCA', Transportation Research Part D: Transport and Environment, vol. 93, p. 102743, Apr. 2021, https://doi.org/10.1016/j.trd.2021.102743.

9. P. Cazzola and P. Crist, 'Good to go? Assessing the Environmental Performance of New Mobility', ITF International Transport Forum, ITF Corporate Partnership Board Report, 2020, [Accessed: Nov. 23, 2022], https://www.itf-oecd.org/sites/default/files/docs/environmental-performance-new-mobility.pdf.
10. D. J. Reck, H. Martin, and K. W. Axhausen, 'Mode choice, substitution patterns and environmental impacts of shared and personal micro-mobility', Transportation Research Part D: Transport and Environment, vol. 102, p. 103134, Jan. 2022, https://doi.org/10.1016/j.trd.2021.103134.
11. H. Engdahl et al., 'Electric Scooters' Trip Data Collection and Analysis', presented at the 33rd Electric Vehicle Symposium (EVS33), Portland, Oregon US, Jun. 2020, p. 11, [Accessed: Apr. 06, 2022], https://www.ri.se/sites/default/files/2021-02/EVS33-Electric_Scooters_trip_Data_Collection_and_Analysis_FinalSubmitted.pdf.
12. ISO, 'ISO 14044:2006 environmental management - life cycle assessment - requirements and guidelines', International Organization for Standardisation, Geneva, Switzerland, 14044:2006, 2006.
13. M. S. Koroma et al., 'Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management', Science of The Total Environment, vol. 831, p. 154859, Jul. 2022, https://doi.org/10.1016/j.scitotenv.2022.154859.
14. European Commission et al., Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods – Version 2, from ILCD to EF 3.0. Publications Office, 2018, https://doi.org/10.2760/002447.
15. G. Myhre et al., 'Anthropogenic and Natural Radiative Forcing - Chapter 8 in', in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change., T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2013.
16. S. Habibi, 'Neighbourhood effects on demand of e-scooter services - - A comparison between spatial regression models and convolutional neural network (CNN).', presented at the ATBR, 16th International Conference on Travel Behaviour Research, Santiago, Chile, Dec. 11, 2022.
17. M. Zackrisson, 'Life cycle assessment of long life lithium electrode for electric vehicle batteries - cells for Leaf, Tesla and Volvo bus', Stockholm, Sweden, Swerea IVF, Project Report 24603/2, Jan. 2017, [Accessed: Mar. 28, 2023], http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1131667&dswid=4469.
18. NTM, 'NTMcalc Advanced 4.0', Network for Transport Measures, Stockholm, Sweden, 2023, [Accessed: Feb. 08, 2023], https://www.transportmeasures.org/en/.
19. AIB, 'European Residual Mixes - Results of the calculation of Residual Mixes for the calendar year 2022', Association of Issuing Bodies, Brussels, Belgium, Version 1.0 2023-06-01, 2023, [Accessed: Apr. 17, 2024], https://www.aib-net.org/facts/european-residual-mix/2022.
20. J. Gubman, A. Jung, T. Kiel, and J. Strehmann, 'Shared E-Scooters: Paving the Road Ahead'. Agora Verkehrswende, 2019, [Accessed: Aug. 17, 2021], verkehrswende.de/fileadmin/Projekte/2019/E-Tretroller_im_Stadtverkehr/Agora-Verkehrswende_Shared-E-Scooters-Paving-the-Road-Ahead_WEB.pdf.
21. J. Buberger, A. Kersten, M. Kuder, R. Eckerle, T. Weyh, and T. Thiringer, 'Total CO2-equivalent lifecycle emissions from commercially available passenger cars', Renewable and Sustainable Energy Reviews, vol. 159, p. 112158, May 2022, https://doi.org/10.1016/j.rser.2022.112158.
22. A. Li, P. Zhao, X. Liu, A. Mansourian, K. W. Axhausen, and X. Qu, 'Comprehensive comparison of e-scooter sharing mobility: Evidence from 30 European cities',

Transportation Research Part D: Transport and Environment, vol. 105, p. 103229, Apr. 2022, https://doi.org/10.1016/j.trd.2022.103229.

APPENDIX

Table A1. Bill of materials [kg] for the two e-scooters analysed

Material	Case 1	Case 2
Aluminium Alloy AlMg3	6.6	11.8
ABS-plastic	0.6	2.3
PVC-plastic	0.1	1.5
Synthetic rubber	1.4	2.1
Natural rubber	0.0	0.0
Cable	0.3	0.2
Chromium steel 18/8	0.24	0.25
Steel low alloyed	1.6	5.6
Copper	0.001	0.0
Silicone product	0.001	0.15
Light emitting diode	0.026	0.02
Controller for electric scooter	0.15	0.15
Transistor, wired, small size	0.031	0.03
Printed wiring board	0.05	0.12
Electric motor	1.2	1.16
Battery, NMC111	3.2	6.8
Total mass	15.5	32.2

Table A2. Included process steps for e-scooter production and energy requirements

Production processes	Unit	Case 1	Case 2
Powder coat, aluminium sheet {GLO}| market for | Cut-off, U	m^2	0.58	0.98
Wire drawing, steel {GLO}| market for | Cut-off, U	kg	1.67	5.60
Welding, arc, aluminium {GLO}| market for | Cut-off, U	m	0.75	1.28
Injection moulding {RoW}| processing | Cut-off, S	kg	0.68	3.84
Electricity, medium voltage {CN}| market group for | Cut-off, U	kWh	1.56	3.25
Heat, district or industrial, natural gas {GLO}| market group for | Cut-off, U	MJ	4.36	9.06
Heat, district or industrial, other than natural gas {RoW}| heat production, light fuel oil, at industrial furnace 1 MW | Cut-off, U	MJ	0.16	0.34

Table A3. Assumptions regarding the transport of e-scooters from the production site in China to Sweden

Segment of transport from China to Sweden	Length [km]	Transport mode and vehicle
Lishui − Wenzhou	138	Road, lorry, 16−32 t EURO 3
Wenzhou − Hamburg	21,106	Ship, container
Hamburg − Gothenburg	776	Road, lorry, 16−32 t EURO 5

Table A4. Materials and components with the largest contribution to climate impact from the production phase (excluding spare parts)

Share of contribution to climate impact from the production phase					
Case 1			Case 2		
No.	Component/ material	Percentage of total	No.	Component/ material	Percentage of total
1	Battery	36	1	Battery	49
2	Aluminium alloy	28	2	Aluminium alloy	24
3	Printed wiring board	9	3	Printed wiring board	10
4	Electric motor	6	4	Steel	3
5	Light emitting diode	4	5	ABS	3
			6	Electric motor	3
Sum of the five largest		83	Sum of the six largest		92

Table A5. Materials and components with the largest contribution to cumulative energy demand from the production phase (excluding spare parts)

Share of contribution to cumulative energy demand from the production phase					
Case 1			Case 2		
No.	Component/ material	Percentage of total	No.	Component/ material	Percentage of total
1	Battery	40	1	Battery	53
2	Aluminium alloy	23	2	Aluminium alloy	18
3	Printed wiring board	8	3	Printed wiring board	9
4	Electric motor	6	4	ABS	4
5	Synthetic rubber	4	5	Synthetic rubber	3
Sum of the five largest		81	Sum of the five largest		87

Paper submitted: 15.12.2023
Paper revised: 17.04.2024
Paper accepted: 04.05.2024