

Article

Dockless E-Scooter: A Green Solution for Mobility? Comparative Case Study between Dockless E-Scooters, Displaced Transport, and Personal E-Scooters

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Abstract: This study applies a life cycle assessment (LCA) to the shared dockless standing e-scooter system that is established in Brussels. The results are given for four impact categories: global warming potential (GWP), particulate matter formation, mineral resource, and fossil resource scarcity. Regarding GWP, the use of the shared e-scooters in the current system causes 131 g of CO₂-eq. per passenger-kilometer while the mode of transportation displaced has an impact of 110 g of CO₂-eq. Thus, at present, the use of e-scooters shows a higher impact than the transportation modes they replace. The high results for the shared e-scooter, in terms of GWP, are mainly caused by the short lifespan of the shared e-scooter. Nevertheless, as the market further matures, the lifespan of e-scooters could increase and the impact per kilometer travelled could decrease accordingly. Regarding the use of the personal e-scooter, the LCA results show an impact of around 67 g of CO₂-eq. This study quantifies the LC impacts of the current situation based on local, 'real-life' data. However, potential changes on soft mobility patterns induced by the use-oriented product-service system (PSS), such as a shared e-scooter system, could not be quantified.

Keywords: e-scooter; life cycle assessment; product-service system; environmental assessment; mobility

1. Introduction

The transport sector contributes as much as 15.5% to the total world-wide global warming potential (GWP) [1]. In particular, urban mobility is an important contributor to GWP and also causes other negative externalities, such as other air pollutants and traffic congestion. In Brussels, the transport sector is the second most contributing sector to greenhouse gases emissions after residential buildings [2]. Recently, shared dockless e-scooters have been proposed by some companies as an alternative to conventional urban mobility. The shared dockless e-scooter is a short-term rental system of electric standing e-scooters that allows a user to pick up an e-scooter where it is located and drop it off wherever he/she chooses. Shortly after their introduction on the American market, the shared

dockless e-scooter arrived on the European market, and more precisely in Brussels, during the summer of 2018. Over the last year period, ten different providers have launched their e-scooters in the streets of Brussels. Even though the vast majority of those providers have removed their fleet since, this indicates how emerging and promising this market is. All the e-scooter providers have in common that they position e-scooters as a “green” solution for mobility, but the verification of this claim remains a gap in the literature. For example, the company ‘Tier’ states that the energy efficiency of an e-scooter is higher than any other powered mode of transportation and, thus, it is a myth that “E-scooters are bad for the environment” [3]. Additionally, 25% of Brussels e-scooter users declared that one of the reasons why they first used the e-scooter was in order to lower the air pollution [4]. As their motor is electric, they have no tailpipe emissions during the trips, unlike any other modes of transportation that use a thermic motor. However, previous life cycle assessments (LCAs) comparing internal combustion engine vehicles with electric vehicles (cars, motorcycles, bicycles), have shown that the manufacturing phase is, in proportion to the total life cycle, more impacting for electric vehicles than for internal combustion engine vehicles. Such studies found the same results for a car [5] and a motorcycle [6]. Additionally, a life cycle assessment (LCA) of an electric bicycle [7] in New Zealand has demonstrated that the manufacturing phase is the most contributing phase to the total net impacts of electric bicycle use. Therefore, in order to know if e-scooters are really a green mobility solution, their environmental impacts need to be assessed from a life cycle perspective. Hence, the main contribution of our work is to provide scientific arguments on whether or not, and under which conditions, the use of e-scooters is a green solution for mobility.

E-scooters have received a great deal of criticism in the media. Most criticism concerns i) The parking of the e-scooter when it is parked on the sidewalk; ii) the number of accidents and of injuries; iii) Their short lifespan [8]; and iv) the unstable contracts offered to the independent battery chargers. The subject of e-scooter user injuries is the most abundant topic related to e-scooters in the scientific literature [9–14]. The parking of e-scooters has been the subject of one article [15]. Thus far, only one paper [16] has performed an LCA of a dockless e-scooter system. The authors assessed the dockless e-scooter in the city of Raleigh, North Carolina, USA and found a global warming potential (GWP) of 125 g CO₂-eq/passenger-kilometer. Even though the system they studied has many differences (see Section 1.2) to the case study in Brussels and a direct comparison is difficult, the results are helpful to situate our study results and to complete the picture for different e-scooter systems.

Therefore, the purpose of our work is to assess the environmental performance of a dockless e-scooter system and to support decision-makers with quantitative information on whether or not, and under which conditions, e-scooters are a sustainable solution from an environmental point of view with first-hand data on material use and the displacement of transport modes. Thus, we perform a life cycle assessment of a shared dockless e-scooter system in Brussels and compare it with other transportation modes.

1.1. Dockless E-Scooter, a Product-Service System

The concept of product-service systems (PSS) has its origin in the late 1980s [17] but was already mentioned before under different terminologies, such as servitization [18]. PSS was used as such in a report in 1999 by Goedkoop et al. [19]. Since then it has been widely spread in the scientific literature [20]. The concept of PSS refers to “a system of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer needs and have a lower environmental impact than traditional business models” [21]. The PSS business models are considered by some authors as business models that could support the creation of sustainability and are potentially able to lower the environmental impacts in comparison to a traditional business model [18,22–24]. In that perspective, the concept of PSS is not specific to one type of sector but, rather, belongs to the category of sustainable and circular business models [25]. As such, it can be considered as a smaller loop inside the circular economy model, focusing on the intensification of the product use or its dematerialization. In 2004, Tukker [26] proposed a three category classification for the PSS which

has been widely accepted since. *Product-oriented*, in which a product is sold with a service attached to it, *use-oriented*, in which the use of a product is sold but the product ownership remains to the provider and, finally, *result-oriented*, in which the provider sells a result and decides about the way to reach that result. The dockless e-scooter belongs to the second category, the use-oriented PSS and more precisely to the sub-category *product renting or sharing*. This sub-category is defined as follows: “the product in general is owned by a provider, who is also responsible for maintenance, repair and control. The user pays for the use of the product. [. . .] The same product is *sequentially* used by different users” [26]. In the mobility sector, many examples of use-oriented PSS exist, but two examples of mobility offers are often put forward and make the linkage between use-oriented PSS and mobility: car and bike sharing. The environmental or sustainability performance of those PSS in the mobility sector has been assessed in many case studies [27–31]. All of them find better results for the PSS than its equivalent in the linear system. The term ‘linear system’ is used in opposition to the circular system and describes a system in which a product is being produced, sold, used, and then sent to end-of-life treatment (take-make-waste). Finally, the LCA of a shared bicycle system [32] showed that the modes of transportation replaced by the use of the shared bicycles have more impacts than the bicycles. Hence, the authors conclude that, as such, the shared bicycle is an environmentally friendly solution able to lower pollution.

From the literature we identified many claims on how specific mechanisms of the use-oriented PSS are supposed to support the environmental sustainability. Those mechanisms are mainly linked to the fact that the provider remains the owner of the product and has the incentive to have a product with the longest lifespan as possible. Therefore, in theory, the provider is supposed to promote the eco-design of its product, to pay more attention to their maintenance, and to encourage their reuse, refurbishing, and recycling in order to maintain their value as long as possible. Another main argument is that in a PSS in which the product is being shared, the use intensity of the product is higher than in an ownership model. Therefore, less resources would be needed to satisfy the same needs (more services provided per unit of resource used). Since each PSS is different, it is impossible to make a general statement about the veracity of these claims. Nevertheless, through our case study we will provide some insights.

1.2. Case Study

Before presenting the system boundaries, it is necessary to describe the e-scooter system of our case study in Brussels. The functioning of the offer is similar between providers, the key difference being the e-scooter itself and its robustness. When a new provider joins the Brussels market, it starts by deploying its fleet at some strategic location in the street and releases a mobile phone app that the users must download. Users can then add their payment information on the app and unlock the e-scooter with the help of a QR code. User can, hence, drive the e-scooter within a perimeter defined by the provider and finally park the e-scooter wherever it is authorized. Once the battery is low or when maintenance is needed, an independent worker, a charging supplier, or one of the provider’s employees will collect the e-scooter and either bring it to a charging place or to the provider’s warehouse. Once the battery is fully charged, the e-scooter is then redeployed to strategic locations and users can use them again. Many providers started their services with low-quality e-scooters and had to stop their offers after only a few months [33]. Even though no official explanations were given from the providers, the premature deterioration of the e-scooter was pointed out in the media and in the interviews we conducted. At the time this article was written, only three providers remain in Brussels who have developed their own eco-designed e-scooter that cannot be found on the market for individual purchase. All the providers that did not develop their own e-scooter have left the market or announced a temporary break.

The main differences between our case study in Brussels and the case study in Raleigh [16] are:

- The e-scooter used by our provider is a different model from the one used in Raleigh: materials are quite similar, but quantities are different.

- The municipal legislation in Raleigh forbids e-scooters to remain in the street during the night which means that all e-scooters, even the fully charged ones, must be collected every day causing additional trips.
- The city of Raleigh is significantly more spread out than the Brussels Capital Region, which generates longer trips for collection and deployment of the fleet.
- The modes of transportation displaced by the e-scooter are different in Raleigh as the importance of car trips is greater in Raleigh, and in the US in general.
- Electricity mix for charging is different from North Carolina to Belgium.

2. Materials and Methods

In order to calculate the environmental impacts of the e-scooter, we chose LCA as method since it is the most recognized method to quantitatively assess environmental impacts [34]. It is also the most frequently used method to assess the environmental performance of a PSS [35]. LCA is a quantitative environmental impact assessment method. It permits the calculation of the impacts of a product or a service through all the life cycle phases on the environment. The main goal of a LCA are to calculate impacts, to compare different products and/or services, and to highlight improvement options. The method consists in inventorying all inputs and outputs from the different phases, to link those inputs and outputs with substance emissions and finally to link emissions with environmental impacts. For our case study we performed an attributional LCA, with the software SimaPro 8.5 (Amersfoort, The Netherlands) [36] and the database Ecoinvent 3.4. (Zurich, Switzerland) [37]. Following the ISO 14044 standard, we will define the goal and scope of the LCA as well as the inventory method in the following subsections.

2.1. Goal and Scope

The goals of the study focus on different levels of actions. The first goal is to estimate the impacts caused by the use of a dockless e-scooter and to identify the most impacting phases. The second goal is to answer the question of whether or not the use of dockless e-scooters is more impacting than the use of the mode of transportation replaced by the e-scooter. The third goal is to compare the impact of the dockless e-scooters to those of personally-owned e-scooters. Completing those three goals on the assessment level will allow us to propose improvements to the provider and to support strategic policy development.

Figure 1 shows the system boundaries of the studied system. It includes all the components of the e-scooter and their materials, manufacturing, transport to Brussels, distribution phase composed of deployment and collection and, finally, electricity for charging. In the current system, all e-scooters that are out of service are stored in the company's warehouse. Mechanics dismantle the end-of-life e-scooters and use the parts in good condition to repair the other e-scooters. As a result, there is very little waste for treatment at present but, rather, the constitution of a stock of spare parts. Since no end-of-life treatment has been done so far, this phase is excluded from the system boundaries. The provider we study receives the e-scooters from China. Thus, transport from the Guangdong region (China) to Brussels is included. The same system boundaries are applied to the systems to which the e-scooter is compared later in the article.

To assess the environmental impacts, we chose the ReCiPe2016 [38]: a harmonized life cycle impact assessment method at midpoint and endpoint levels. The ReCiPe2016 [38] method provides characterization factors for all substance emissions and resource extractions from the inventory. The characterization factors allow to calculate impact scores for 18 impact categories at midpoint level using the same unit of stressor, e.g., kg CO₂-eq for global warming. Due to their particular importance for transport means, we present the global warming potential, the fine particulate matter formation, and mineral and fossil resource scarcity. The functional unit is the travel of one person for one kilometer. We chose to use the cut-off approach, i.e., the recycled content allocation method in which a recycled material that is used bears only the impacts of the recycling processes, not of the primary production.

Accordingly, the new system that produces a recycled material does not receive a credit. Since we do not have exact data on the origin of the materials used in the manufacturing and the proportion of recycled content we use market values from Ecoinvent. This means that materials used to manufacture the e-scooters include some recycled material taking into consideration the market proportion, e.g., 27% of recycled aluminum in the aluminum mix.

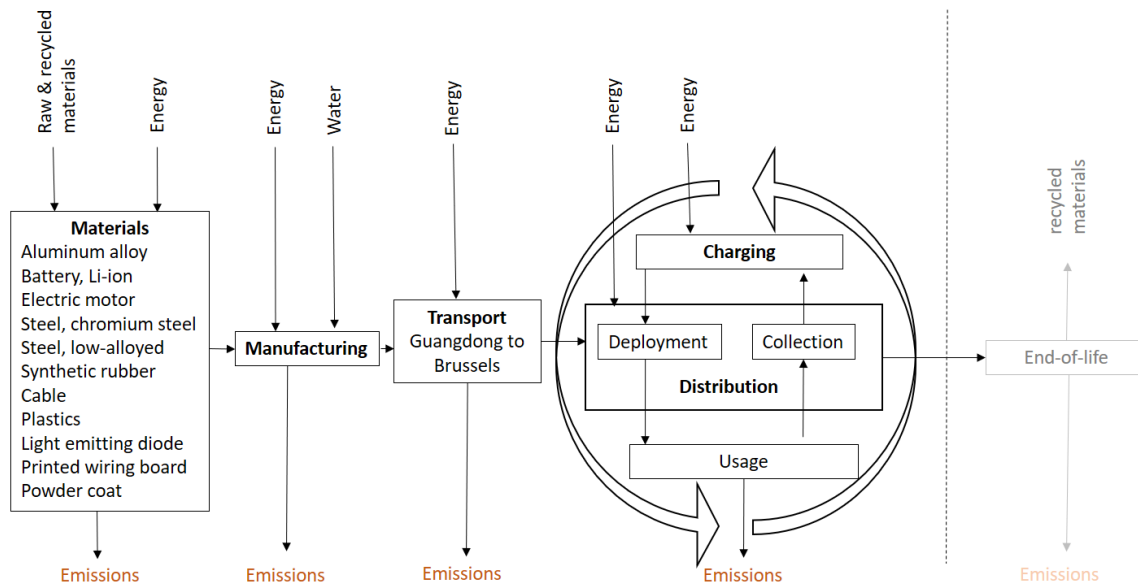


Figure 1. System boundaries of the shared dockless e-scooter system in Brussels.

2.2. Inventory Data for the E-scooter

The data needed to perform the LCA was provided by one of the dockless e-scooter provider in Brussels which will remain anonymous. The provider allowed us to dismantle one of its e-scooters and to characterize and inventory all the components. We, hence, listed all the e-scooter components and identified the components materials. For ferrous materials, the magnetic properties were used to distinguish different alloys. Copper is easily identified thanks to its color and aluminum is identified based on its density. Regarding polymers, acrylonitrile butadiene styrene (ABS) was identified based on indications molded onto the components. Each material was then matched with an Ecoinvent dataset. For the cables, the loudspeaker, the lamps and the printed circuit boards, the identification of individual materials is practically impossible and proxies (see Table S1 of the Supplementary Materials) from Ecoinvent were selected.

For the manufacturing phase, due to lack of data from the Chinese factory, we followed the recommendations from Hollingsworth et al. [16] and used the manufacturing of an electric bicycle (proportional to its weight) as proxy data. The transport phase was modeled based on the data from the provider, the e-scooter being transported by lorry from the factory to Shenzhen, then shipped from Shenzhen harbor to Rotterdam's harbor and, finally, by lorry from Rotterdam to Brussels. To model the impacts from electricity for charging we used Ecoinvent data for the electricity consumption mix in Belgium which we updated to the situation in 2019. The electricity needed to transport one passenger for one kilometer corresponds to the capacity of the battery (0.344 kWh) divided by the distance that correspond to the autonomy with a fully-charged battery (20 km).

For the distribution phase, composed of the deployment and the collection of the e-scooter, data were collected through two different channels. First, with the data from the provider and second with the interviews of independent chargers as well as charging suppliers and provider employees. Four semi-directed interviews took place during summer 2019. We questioned both contact persons

from the provider's network and workers we met on the street while they were performing the e-scooter collection.

2.3. Inventory Data for the Displaced Modal Shares

From June to August 2019, Brussels Mobility, the Brussels Capital Region administration of mobility conducted a survey on the use of the e-scooter [4]. The online survey was spread out through the Brussels Mobility web page, social media, flyer distribution, and two e-scooter providers. The survey received 1181 usable answers from which 87% of the respondents had used, at least once, a dockless e-scooter, and 42% used, at least once, a personal e-scooter. Due to a lack of enumeration data on the e-scooter user population, the representativeness of our sample cannot be verified. However, a large sample and diversified collection sources tend to reduce the representativeness bias. On the user profiles, men are overrepresented as they represent 66% of the users. Additionally, 25–34 year olds is the most represented age group as they represent 44% of the users, while comprising only 17% of the Brussels Capital Region population. One of the survey questions was: "Before the arrival of e-scooters, what mode of transportation would you have used for the same type of trips?" [4]. This question allows the calculation of the modal share, i.e., the mode of transportation displaced by the use of the e-scooter. The replies to this question are given separately from the users of dockless e-scooters and users of personal e-scooters, but also from frequent users to occasional users. The response included some mix of transportation mode such as "public transportation combined with walking" or "public transportation combined with biking". To further model the mix of modes of transportation displaced, data had to be refined. The first step was to adjust the data by calculating the substitution rate based on the frequency of use among respondents. As second step we separated the different modes of transportation into the mode of transportation for which data are available on Ecoinvent, i.e., excluding the metro. This second step was done by combining the survey's data with the data on modal share also from Brussels Mobility [39] and the data from the bicycle observatory in the Brussels Capital Region [40]. Table 1 shows the percentage of the different modes of transportation that is being displaced by the dockless e-scooter users and the personal e-scooter users in Brussels.

Table 1. Mode of transportation displaced by the use of dockless and personal e-scooters.

Mode of Transportation Displaced	Dockless Users n = 757	Personal Users n = 329
Public transportation	29.2%	30.2%
Car	26.7%	28.4%
Walking	26.1%	21.1%
Bicycle	14.2%	15.5%
Electric bicycle	1.5%	1.6%
Additional trips	1.8%	1.5%
Other	0.1%	1.1%
Motorcycle	0.4%	0.6%

Additional trips correspond to users that responded "I would not have made this trip". Regarding the mode of transportation that is being displaced, the survey data indicates that the main difference between shared or personal use is the importance of walking. Dockless users replace walking 5% more than personal users do. This may be the consequence of a higher use of the dockless e-scooter for leisure purpose, while the personal one is more often used to travel to the workplace.

2.4. Inventory Data for the Personal E-scooter

In order to compare our PSS case study to the ownership model we have modeled another e-scooter which can be found on the market. We modeled it based on the inventory given in the appendices in Hollingsworth et al. [41] who disassembled and inventoried all the materials of the different components. As the owner of an e-scooter charge it at home, no distribution phase is included in this model. As there are no data available on the average lifespan of personal e-scooters, we chose the warranty period of the e-scooter from the manufacturer [42] as the lifespan of the e-scooter, which corresponds to one year. Since this warranty is most likely the minimum lifespan of the e-scooter, it is considered as a worst case scenario.

3. Results and Discussion

The results of the dockless e-scooter use for one passenger·kilometer are presented in Table 2 and Figure 2.

Table 2. Impact assessment results for the dockless e-scooter use in Brussels for the four impact categories analyzed per passenger·kilometer ($\text{p}\cdot\text{km}^{-1}$). Calculated with SimaPro 8.5.

Impact Category	Total	Materials	Manufacturing	Transport	Distribution	Charging
Global warming (kg CO ₂ eq.* $\text{p}\cdot\text{km}^{-1}$)	0.131	0.096	0.008	0.003	0.019	0.005
Fine particulate matter formation (kg PM _{2.5} eq.* $\text{p}\cdot\text{km}^{-1}$)	2.96×10^{-4}	2.33×10^{-4}	1.29×10^{-5}	1.38×10^{-5}	3.15×10^{-5}	4.54×10^{-6}
Mineral resource scarcity (kg Cu eq.* $\text{p}\cdot\text{km}^{-1}$)	1.97×10^{-3}	1.78×10^{-3}	1.39×10^{-5}	3.46×10^{-6}	1.49×10^{-4}	2.41×10^{-5}
Fossil resource scarcity (kg oil eq.* $\text{p}\cdot\text{km}^{-1}$)	3.16×10^{-2}	2.15×10^{-2}	1.71×10^{-3}	8.77×10^{-4}	5.94×10^{-3}	1.61×10^{-3}

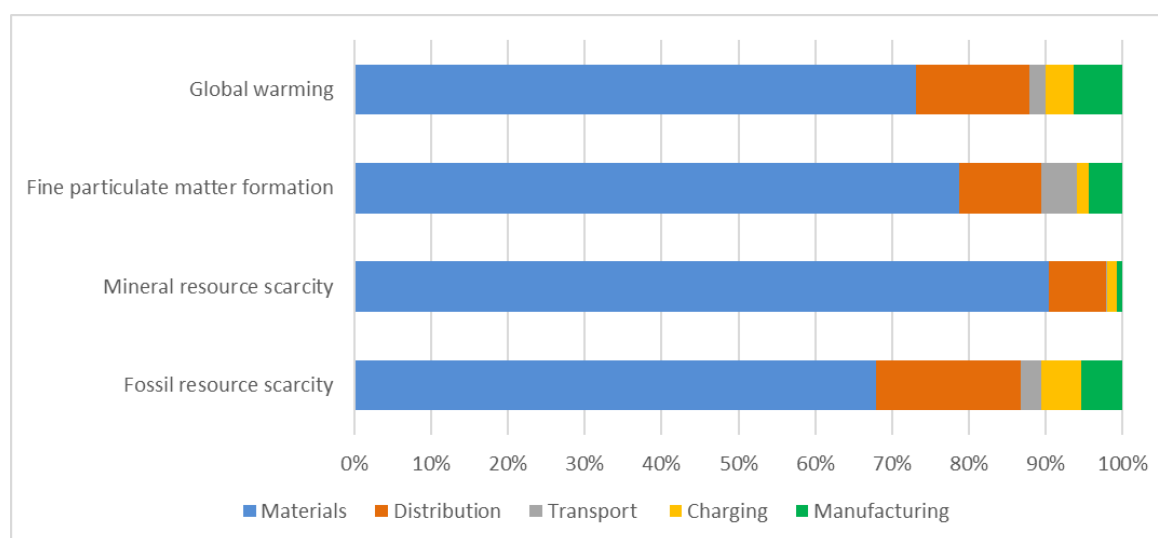


Figure 2. Contribution of the five phases on the impacts of one passenger·kilometer of shared dockless e-scooter usage in Brussels for the four impact categories analyzed.

The results show a GWP of 131 g CO₂-eq.* $\text{p}\cdot\text{km}^{-1}$. With a contribution between 68% and 90% of the total impacts, the materials phase is by far the most impacting phase for the four analyzed impact categories. As indicated in Figure 3, the impacts of the material phase are mainly driven by the aluminum which constitutes almost half of the e-scooter weight. In addition to the high mass share, the aluminum production has a high impact intensity, for example regarding the energy

consumption necessary to separate the metal from the oxide. The Li-ion battery, the wiring boards, and the electric motor are the following impacting elements of the e-scooter. The global warming score of the polytetrafluoroethylene (PTFE) is due to the presence of fluorine and the emission of fluorinated compounds. Numerical data for Figure 3 and the following figures are given in the Supplementary Materials.

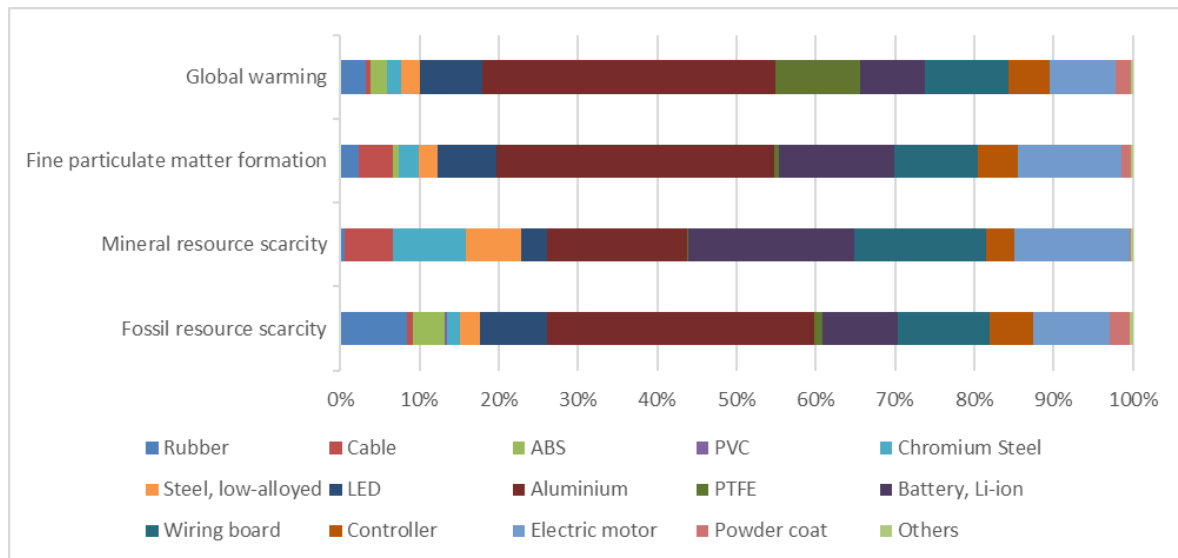


Figure 3. Contribution analysis of the material phase for the four impact categories analyzed. ABS: Acrylonitrile butadiene styrene; PVC: Polyvinylchloride; LED: Light emitting diode; PTFE: Polytetrafluoroethylene.

The relative importance of the material phase depends on the total distance (in kilometer) driven during the lifetime of the e-scooter. This total distance driven can be expressed through the following equation:

$$km_{\text{e-scooter}} = km_{\text{day}} \times \text{day}_{\text{Lifespan}} \quad (1)$$

The number of kilometers driven during a day (km_{day}) corresponds to the use intensity of the e-scooter. In our case study the e-scooter are driven in average 6.39 km per day. The daily variation of the use intensity mainly depends on the weather and on the day of the week. For example, in France, the use intensity is higher during the weekend than during the week [43].

The number of days the e-scooter remains on use ($\text{day}_{\text{Lifespan}}$) is the lifetime of the e-scooter.

The lifetime of the e-scooter depends mainly on the four parameters: Eco-design, usage, vandalism, and maintenance.

As explained in 1.2, the eco-design of the e-scooter is the main parameter influencing the lifespan. The importance of that parameter is demonstrated by the failure of the provider who did not develop their own robust e-scooter. The usage of the e-scooter also has an importance on their lifetime as a wrong usage leads to a premature deterioration. The provider explains that users riding fast on paved streets cause a faster deterioration of the e-scooters. However, according to the provider, most of the deterioration in Brussels is caused due to the damaged infrastructure, such as holes in the pavement. Other usage behaviors leading to faster deterioration is when two people use an e-scooter together, especially if they try to go up-hill and when users go up the edges of sidewalks at high speed. The vandalism of the e-scooter has been one of the most treated topics in the media but has not been discussed in the scientific literature so far. The e-scooter provider did not provide precise data, but estimated that the vandalism in Brussels is lower than in French cities, but higher than in Scandinavian cities. A sociological study about the vandalism behaviors of the e-scooter or any mode of transportation involved in a use-oriented PSS would be interesting for further study. Finally, the

maintenance of the e-scooter is the key instrument for the provider to prolong the lifespan. In Brussels, the actual lifetime of e-scooters that are analyzed in this case study is seven and a half months. Since the introduction of dockless e-scooters in Brussels, their lifetime has been increased quickly. Indeed, the first generation of e-scooter did not last long, but due to the maintenance and the replacement of broken parts, some of the first e-scooter have been in service since the start. Hence, as this service is very new, the lifetime is still expanding. This means that the lifespan used in our LCA is going to expand as the actual e-scooters remain in use. Thus, a final estimate of the average lifespan of those e-scooters will only be available when all e-scooters reach their end-of-life.

3.1. Sensitivity Analysis

To test the sensitivity of our results, we varied the parameters that are considered to be affecting the results significantly. The share that the e-scooter materials represented in the overall impacts (see Figure 2) indicates that the lifetime is such an important parameter. The lifetime was modeled from one month to 2.5 years. The one-month lifespan corresponds to what was previously calculated by a consultant for the case study of Louisville, Kentucky [8]. Two and a half years correspond to the lifespan before the battery would need to be changed considering the actual use intensity. As the functional unit is one person per kilometer, the number of kilometers driven during a day (use intensity) is likely to be an influential parameter as well. To test the sensitivity of the results to this parameter, the use intensity was varied between 1.2 and 20 km per day. The first distance corresponds to the average single use length in Brussels, the latter corresponds to the autonomy. As the daily collection for charging represents 43% of the GWP in the Raleigh case study [16], the distance traveled by the chargers was changed adding or removing 50% of the traveled distance per e-scooter charged to test the importance of this parameter. We also tested a 100% renewable electricity mix, based on the actual Belgian renewable electricity mix. The reason for testing the 100% renewable electricity is because some of the providers put forward in their communication that they charge their e-scooters with renewable electricity. The Brussels public authorities also recommend to the e-scooter providers to use renewable electricity for charging. It is, indeed, possible to select an electricity supplier that buys only renewable electricity from large producers and then resells it to the final consumers. As such, some suppliers source only from renewable producers. By buying from such suppliers, one pays slightly more for electricity than for regular electricity. By purchasing in this way, one decides that the money will only be invested in renewable energy. However, the electricity actually consumed is essentially the same for everyone because there is only one transport network and one distribution network and it is not possible to decide where the electrons will go once they are fed into the grid. Thus, we are testing what it would be like to use a 100% renewable electricity mix, but, in physical reality, this is not the case. The distance traveled between each charge was varied from 6.39 km, which corresponds to charging the e-scooter every day, to 20 km between two charges, which correspond to only charging the e-scooter when its battery is completely discharged.

Figure 4 shows the results of the sensitivity analysis, indicating, in the green scenario, results that are lower than the base case and, in the red scenario, results that are higher than the base case.

The sensitivity analysis indicates that results are more sensitive towards changes in the use intensity or in the lifespan than other changes in the distribution, electricity or the distance travelled between two charges. This analysis also shows that the providers that launched basic e-scooters and then stopped their offer after only a month must have had a comparatively high impact, of around 0.8 kg of CO₂-eq.*p·km⁻¹ which is over the use of a car.

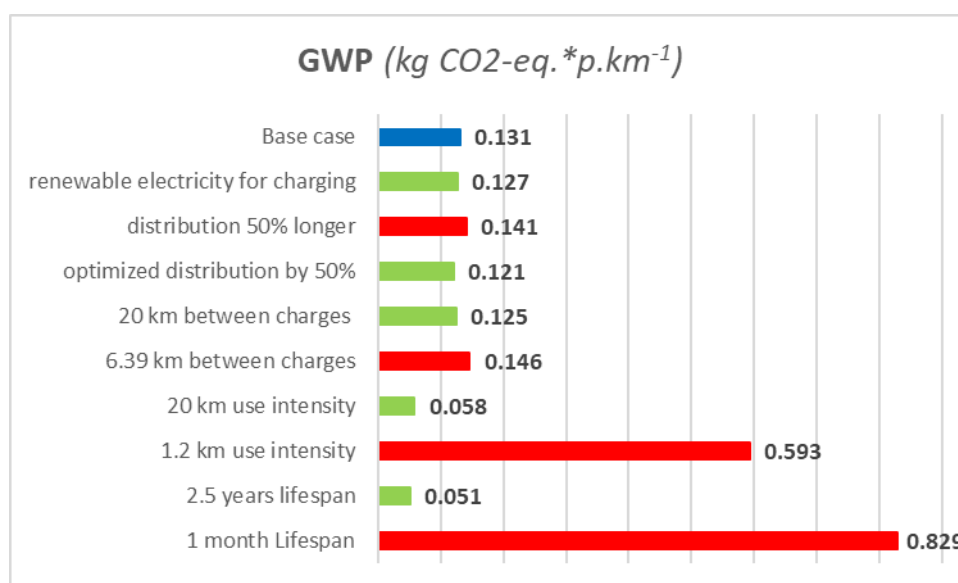


Figure 4. Sensitivity analysis.

3.2. Contribution Analysis in a Prolonged Lifetime Scenario

As we observed that the lifetime is the most sensitive parameter, it is important to analyze changes in the contribution of each life cycle phase when the lifetime is prolonged. To do so, we modeled three lifespan scenarios with one year, 2.5 year, and five year lifetimes. The main changes in the inventory is the replacement of the battery after 2.5 years in the five-year scenario, corresponding to 500 cycles of charging. The tires are also changed once in the five-year scenario.

Table 3 presents the results for the three scenarios as well as the modal share, while Figure 5 shows the contribution analysis for the three scenarios and the base case.

Table 3. Impact assessment results for the dockless e-scooter usage in Brussels, the modal share, the one year, the 2.5 year, and the five year scenarios for the four impact categories analyzed per passenger-kilometer.

Impact Category	Unit	Base Case	Modal Share	1 Year	2.5 Years	5 Years
Global warming	kg CO ₂ eq.	0.131	0.110	0.091	0.051	0.040
Fine particulate matter formation	kg PM2.5 eq.	2.96×10^{-4}	1.44×10^{-4}	1.99×10^{-4}	1.01×10^{-4}	7.6×10^{-5}
Mineral resource scarcity	kg Cu eq.	1.97×10^{-3}	5.76×10^{-4}	1.30×10^{-3}	6.24×10^{-4}	4.66×10^{-4}
Fossil resource scarcity	kg oil eq.	3.16×10^{-2}	3.43×10^{-2}	2.26×10^{-2}	1.36×10^{-2}	1.12×10^{-2}

Compared to the base case results (of 131 g of CO₂-eq.*p.km⁻¹), the expansion of the lifespan of only 4.5 months leads to a reduction of the GWP to 91 g of CO₂-eq.*p.km⁻¹. As the lifespan increases, the impacts decrease but slower in proportion. Hence, in a hypothetical 5 year lifespan scenario, the GWP would be equal to 40 g of CO₂-eq.*p.km⁻¹, which gets close to the use of an electric bicycle (26 g of CO₂-eq.*p.km⁻¹) from the Ecoinvent data. Figure 6 shows the variation of the impacts in terms of greenhouse gas emissions depending on the lifespan of the e-scooter. Maintenance and part replacement is modeled at 2.5 years (913 days) lifespan explaining the increased impact at this point.

The contribution analysis highlights a shift in the most impacting phase from the material and manufacturing phase to the distribution phase. This shift occurs when the lifetime reaches 1250 days. Through this contribution analysis we show the importance for the providers to concentrate on expanding the lifespan of their e-scooter first. It also shows that once the lifespan is longer, the optimization of the distribution phase will become priority. To optimize the distribution phase, one of

the suppliers is currently working on the development of an e-scooter with a removable battery so that it can be charged without carrying the e-scooter [3]. This would make it possible to carry much more batteries in the vans than carry e-scooters in the same van (70 per van at the moment). Another optimization option proposed by the supplier is to use switchable batteries collected and redeployed by an e-cargo bicycle [3].

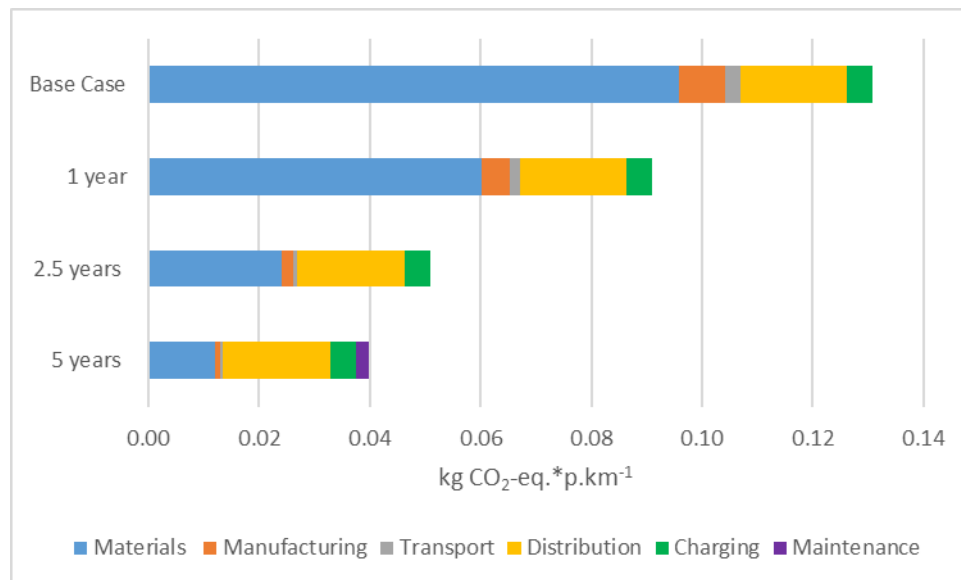


Figure 5. Evolution of the contribution of the life cycle phases for the different prolonged lifetime scenarios on the global warming impact category.

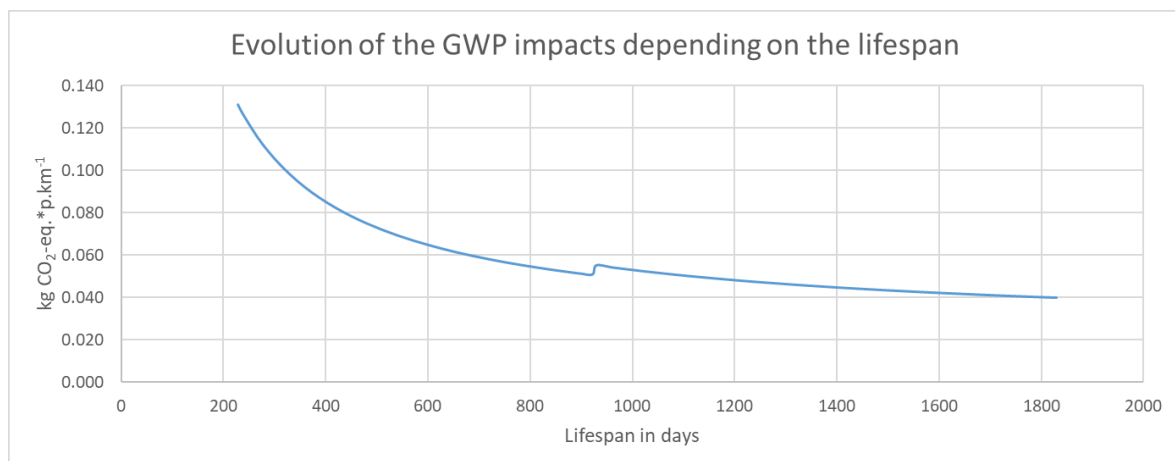


Figure 6. Graphical representation of the evolution of the GWP based on the extending of the lifespan of the e-scooter while the use intensity remains the same.

The contribution analysis also shows that the electricity for charging causes only 11.7% of the GWP in the five-year scenario. In the 100% renewable scenario, the contribution of the electricity for charging is reduced to 3% into the five-year scenario while the actual 3.6% in the base case gets down to 0.9% with the renewable electricity. Thus, even if companies that promote the purchase of green electricity could really consume 100% renewable electricity, this would only reduce the current impacts by 2.7% in terms of GWP. With the current lifespan of e-scooters and the distribution system in place, using green electricity to charge e-scooters has a minor effect in relation to all impacts but would represent a good option in a five-year lifespan scenario (8.7% reduction of GWP impacts).

3.3. Comparison with the Displaced Modes of Transport

3.3.1. Brussels Displaced Modal Share

The data presented in part 2.3 allows to model the equivalent of one kilometer if the e-scooter was not an option. To do so, since 100% displacement represent 1 km with our functional unit, we defined that 0.1% of a mode of transportation is equal to 1 meter. As such, the modal share compared to dockless users is composed of 292 m of public transportation, 267 m of car, 142 m of bicycle, 15 m of electric bicycle, and 4 m of motorcycle use. The rest is walking, which is considered as not having impacts. Finally, we can compare the use of the dockless e-scooter to the use of the mode of transportation displaced. Figure 7 shows the results of this comparison incorporating the prolonged lifetime scenarios. The results for the four impact categories are expressed proportionally to the most impacting scenario which is expressed as 100%.

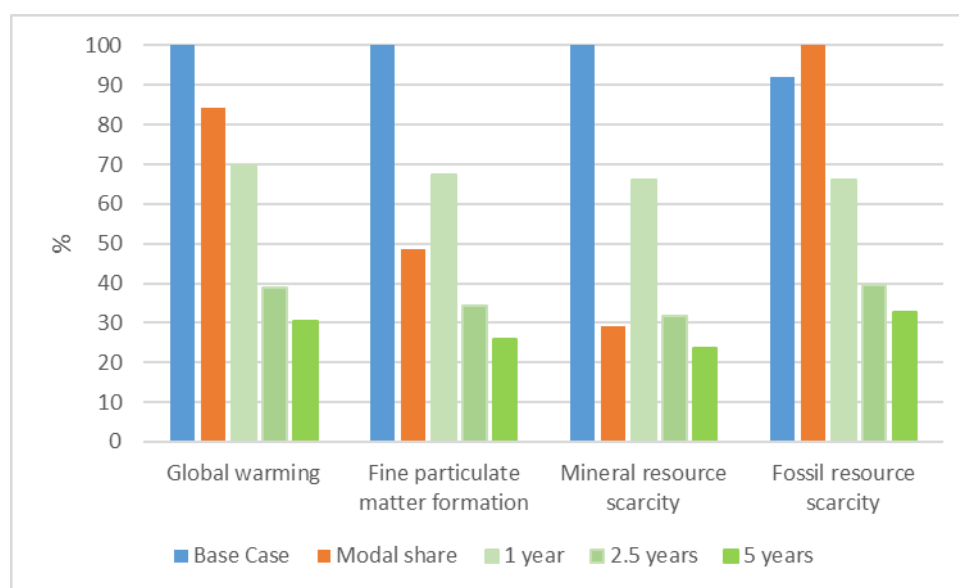


Figure 7. Comparison of impacts from the displaced modal share with the e-scooter (base case) including different lifetime scenarios. Unit: % of the most impactful.

The use of the e-scooter in the base case scenario has higher GWP, fine particulate matter formation, and mineral resource scarcity impacts than the mode of transportation it displaces, but lower impacts on fossil resource scarcity. Results for fossil resource scarcity are higher for the modal share due to the important share of car use which induces a higher consumption of fossil fuels, such as oil. The use of the e-scooters generates more fine particulates matter than the transport modes they replace. It should be noted that the fine particulates due to e-scooters originate from the materials and manufacturing phases which take place in China. Indeed, the driving of e-scooters in Brussels does not directly generate fine particulate matter pollution (apart from tire wear and brake friction).

These results show that shared dockless e-scooters are not the best environmental solution in their current state. Regarding GWP and fossil resource scarcity, the three prolonged lifetime scenarios have lower impacts than the displaced modes of transportation. Results for the two other impact categories show that the five-year lifetime scenario is the only one that has lower impacts in all categories. We also calculated that the point at which the modal share becomes more impacting than the base case from a GWP perspective is when a lifespan of 284 days is reached. This corresponds to an increase of the actual lifespan of only 55 days. As explained earlier, since the lifespan will increase in the future, this threshold should be reached. At that point the use of dockless e-scooter will represent a less impacting solution in terms of GWP.

3.3.2. Other Displaced Modal Shares

Comparative data on the modal share can be found for others cities. A statistical study [43] on a sample of more than 4000 dockless e-scooter users was carried out in France. Users were asked about their last e-scooter trip and answered which other mode of transportation they would have used in absence of the e-scooter. Unlike the Brussels Mobility study, in which several answers could be selected, only one answer could be given. The modal share is also calculated in Hollingsworth et al. study [16], but their sample consists of only 61 e-scooter users and the question is formulated differently: “If e-scooters were not available, what percentage of the time would you use these alternatives?” [41]. Another modal share is calculated based on a small sample of 56 users in [15] from the city of Rosslyn, Virginia, USA. Finally, a survey [44] on 3444 Portlander e-scooter users was conducted where the user was asked to determine one alternative transportation mode. All those modal shares are summarized in Figure 8.

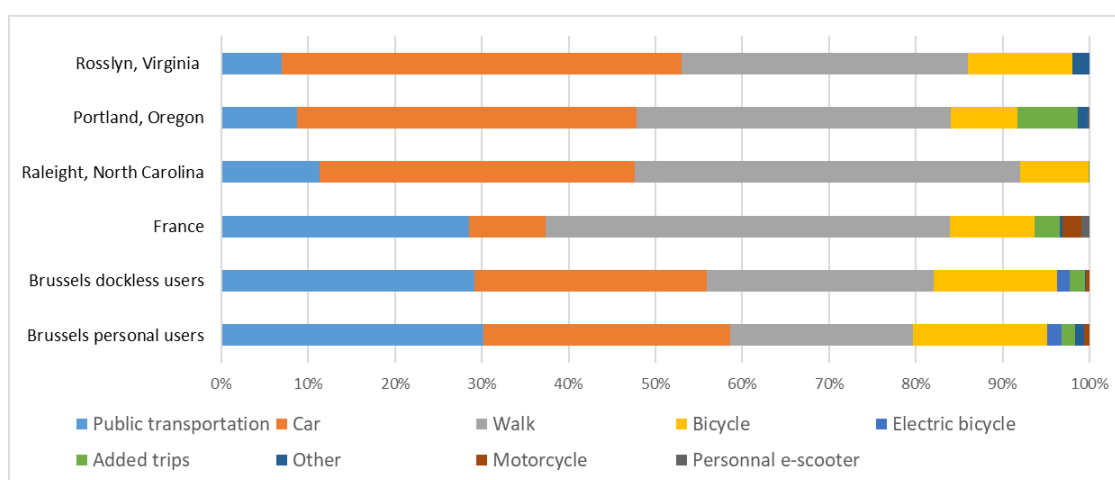


Figure 8. Modal share from e-scooter users to other mode of transportation.

This figure highlights that the modal share changes a lot from one city/country to another. The main observations are that the e-scooter users replace the use of a car way more in the US than they do in Europe. While in Europe, users replace to a larger extent the use of public transportation than they do in the studied American cities. Nevertheless, an in-depth study of city characteristics, such as average weather conditions, topography, the size of transit networks, and their complexities, would be necessary to interpret these modal shifts.

3.4. Comparison between the PSS and an Ownership Model

Figure 9 compares the PSS model and the ownership model for each LC phase. We also included the mode of transportation displaced for each case. Since no specific data exist for the use intensity of personal e-scooter we made the hypothesis of the same use intensity as of the shared e-scooter (6.39 km/day). As such this comparison is theoretical.

The GWP of the use of the personal e-scooters is equal to 67 g of CO₂-eq*p.km⁻¹. Figure 9 shows that while the dockless e-scooter emits 21 g of CO₂-eq. more than the modal share, the personal e-scooters emit 50 g of CO₂-eq. less than what they replace. Therefore, in the case of the e-scooter, the PSS model is more impacting than the ownership model for two main reasons. In the first place, the lifespan of the personal e-scooter is longer due to better usage and the reduction of vandalism or misuse. Secondly, no collection and deployment by van is needed. The electricity for charging remains the same. Figure 9 also emphasizes that the GWP of the mode of transportation displaced by the users of personal e-scooter is 6% higher than those of the dockless e-scooter users. This makes the use of the personal e-scooter a more sustainable option than the use of dockless e-scooter, even if the impacts of their usage were the same.

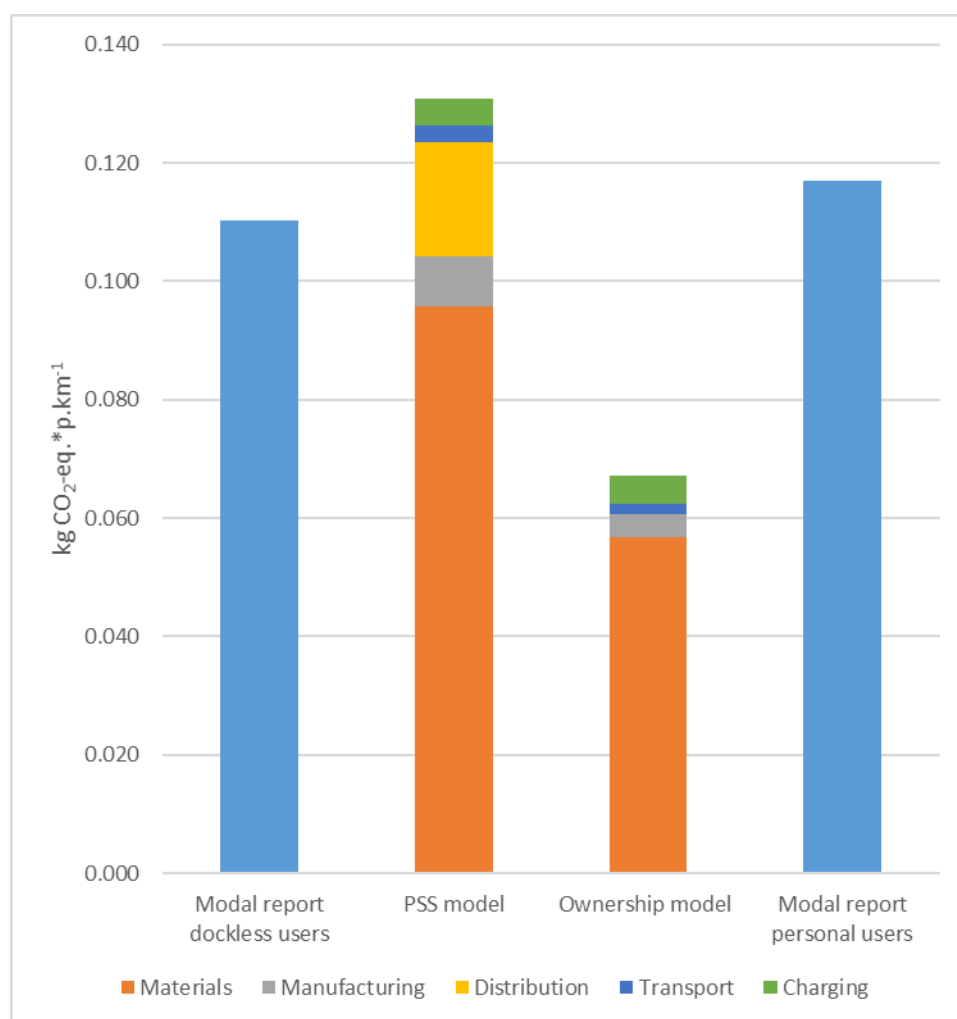


Figure 9. Comparison of the GWP between the use of shared dockless e-scooter vs. personal e-scooter including the impacts of the mode of transportation they both replace. Unit: kg CO₂-eq.*p.km⁻¹.

4. Conclusions

This article has studied and compared the environmental impacts of shared dockless e-scooter use in Brussels. We found that in the current situation, the use of the shared dockless e-scooter causes 131 g of CO₂-eq.*p.km⁻¹ from a life cycle perspective compared to 110 g of CO₂-eq.*p.km⁻¹ caused by the use of the mode of transportation displaced by the e-scooter users. Nevertheless, as the dockless e-scooter system becomes more mature, the e-scooter lifespan may increase and, therefore, decrease the global impact per passenger-kilometer. With a lifespan of 284 days, the use of the e-scooter will have lower GWP than what they substitute. Hence, from a global warming perspective, we can state that dockless e-scooters need a lifespan of at least 9.5 months to be a green solution for mobility in the current use situation. However, it is important to remind that some data rely on assumptions, such as the energy and water consumption of the manufacturing phase of the e-scooter accounting for 0.7–6.4% of the impacts depending on the impact category. Finally, no end-of-life treatment was included in the assessment because none is taking place at the moment. This both neglects the impacts from the end-of-life treatment, and possible credits for the provided recycled materials. Further studies on this aspect will be necessary when the end-of-life reality of the system changes.

This study has shown the importance of the lifespan in the calculation of the environmental impacts of dockless e-scooter use. The potential environmental impacts from the dockless e-scooter usage in Brussels are higher than those of the modes of transportation they replace or in comparison to

the use of the personal e-scooters. On the one hand, the provider has to put more effort to design and manufacture a product that can last longer. On another hand, the vandalism rate needs to be decreased and the users should handle the e-scooters more carefully.

The lifespan of e-scooters has been continuously increasing since they were launched in Brussels. As such, it is likely that the point at which the distribution phase generates most of the impacts will be reached in the coming years. As mentioned, it will, therefore, become more profitable to work on optimizing the distribution phase. Companies have their share of work to do, but it is also possible to consider a role for public authorities. For example, new electric charging stations that are installed in the city could also include charging devices for e-scooters. Thus the supplier could set up a financial incentive for the users to drop the e-scooter off at charging areas and plug them in. Thus, the need for van trips would be considerably reduced. This development could also be beneficial to other use-oriented product-service systems in the mobility sector, such as (seated) electric scooters and electric bicycles, which have shown an increasing use trend recently. We have also demonstrated that, in the current situation, the use of renewable electricity for charging as recommended by the Brussels public authorities, does not influence significantly the total impacts of the dockless e-scooter. However, it will gain importance with the extension of the lifespan.

In this study we demonstrate that the PSS option, i.e., the shared dockless e-scooter is more impacting than the ownership model. However, many of the e-scooters owners bought their own e-scooter after having tried the PSS option. We also observed that the e-scooter owner replaces more frequently the use of the car than the users of dockless e-scooters. This highlights one of the limits of this LCA study. We quantified the environmental impacts of the current situation, but we could not take into account secondary effects such as the deeper societal changes that may be triggered. Our case study demonstrates that dockless e-scooters are not yet environmentally beneficial compared to a certain modal share, but if they induced positive changes in the urban mobility, their implementation might finally be profitable in the long term. Incorporating those long-term effects within environmental impact assessments remains a future research topic. Additionally, we remind that users that replace walking or (non-electric) biking with the use of e-scooters will always have a negative environmental impacts while those that replace the use of a car will reduce their impacts.

In our analysis we have shown the crucial importance of lifespan on the results of life cycle analysis. However, we have not been able to establish a quantifiable link between this lifetime and the factors that influence it, such as eco-design, use, vandalism, and maintenance. There is, therefore, a need for research at this level to quantify this link and thus be able to vary parameters. There is also a need for further research on the link between intensity of use and lifespan.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/5/1803/s1>, **Table S1.** List of the e-scooter materials, **Table S2.** Impact assessment results for the dockless e-scooter use in Brussels for the eighteen impact categories per passenger-kilometer. **Table S3.** Absolute values of the contribution analysis of the material phase for the four impact categories analyzed. **Table S4.** Evolution of the contribution of the life cycle phases for the different prolonged lifetime scenarios on the global warming impact category. **Table S5.** Impact assessment results for the displaced modal share, the e-scooter use base case and the three different lifetime scenarios. **Table S6.** Mode of transport displaced by e-scooter users in five different locations. **Table S7.** Comparison of the GWP between the use of shared dockless e-scooter vs. personal e-scooter including the impacts of the mode of transportation they both replace.

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