Assessment of environmental impacts of electric scooter through life cycle analysis

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ABSTRACT

The electric scooter sharing system emerged in Lisbon as a new form of mobility for short distances, presenting itself as an innovative system that does not pollute during its use for being an electric transport mode. E-scooters differ mainly from the fact that they are dockless. However, these need to be collected, charged and distributed on the city streets by conventional vehicles that pollute during their use. The main objective of this work is to perform a Life Cycle Analysis (LCA) in order to account the environmental impacts for all life stages of an e-scooter, from its production, use and end-of-life. For the Base Scenario of the Climate Change category, an e-scooter emits 804 to 1679 grams of $CO_2\ eq$ per kilometre. The reason these values are high is due to the low use of e-scooters by users and the low scooter life span. The impacts associated with the production of an e-scooter are more than 70% of the total impact, the impacts associated with the collection and distribution process are approximately 6% and the use of the vehicle corresponds to about 17%. A sensitivity analysis was also carried out, varying the life span of the e-scooter, the kilometres per day and the frequency of collection. In conclusion, increasing life expectancy reduces environmental impacts by 26% to 47%; Increasing the number of kilometres per day, reduces the results between 50% to 80%; And a less frequent collection allows to optimize the results between 7% 42 %.

Keywords: Life Cycle Assessment, LCA, Electric Scooters, Environmental Impacts, Transportation.

1. INTRODUCTION

The transport sector is responsible for one third of the final energy consumption in the European Union (EU) [1]. Most of that energy consumption is associated with the consumption of petroleum products, which means that transports are responsible for around one fourth of the EU's greenhouse gases (GHG) emissions [2][1]. For the specific case of Portugal, in 2017, the transport sector accounted for around 24% of GHG emissions [3]. As a result, to reduce the adverse effects of transports less polluting and more efficient modes of transport are being promoted, by implementing new technologies, energy sources and more sustainable infrastructure [1]. With the increasing awareness of environmental problems, most companies are looking for fewer polluting alternatives, increasing the need to promote more sustainable solutions, with electric mobility playing a fundamental role in this matter. The main objective is to promote more efficient vehicles, which eliminate local pollution with particular relevance in urban context and also contributing to the reduction of noise pollution [4].

One of the electric mobility options to recently arise for urban context are electric scooters (e-scooters), mostly directed to micro-mobility focused on first and last mile trips. Even if they do not emit CO_2 during its use, one of its drawbacks is that they have reduced lifespans, with information available online shows pointing that they last on average one month due to battery failure [5], [6].

Furthermore, this information does not consider the complete scooter's life cycle neither the collection/distribution process done in most cases by conventional vehicles. This need to consider the full life cycle of a product is well established for electric vehicles (EV) [7]–[11]. EV have lower impacts during their use, but their production has at least the same impact as a conventional vehicle and the end of an EV life may have a higher impact due to process complexity in battery production and recycling [12]. Many studies had already focused in LCA of electric mobility, ranging from motorcycles [13], [14], bikes [13]–[16] and light-duty vehicles[7]–[11], demonstrating that EV impacts are on average higher in its production processes than conventional vehicles. Nonetheless, few studies have dealt with the LCA of an e-scooter. Chester assessed the total life cycle of an e-scooter and concluded that a e-scooter emits between 200 to 400 g CO_2/km, depending on how the scooter collection / distribution process is carried out [17]. Hollingsworth *et al.* also published a detailed LCA of e-scooters coming to the conclusion that CO_2 emissions from an e-scooter range from 94 to 305 g CO_2/km, in which 50% of total impacts are due to its production and 43% result from the collection and distribution process. These values are highly influenced by the mileage performed over the life of the e-scooter [18].

One of the most widely spread operators on the market, Bird, stated in its official that its e-scooters emit 61 g CO_2/km [19] in a full life-cycle approach,. In an European context, Voi made a micro-mobility report with a complete LCA for its e-scooters, presenting an emission of 35 g

CO_2/km for its e-scooters, justifying such low number with the electrification of vehicles used in the collection/distribution, to the use of replaceable batteries and of renewable energies, as well as to of recycling of materials [20]. However, these analyses are very dependant of location and address aspects like collection/distribution of recycling without detail. n Lisbon the situation appears to be different. Consequently, the main objective of this work is to quantify the life-cycle environmental impacts of e-scooters, covering the production, use and end-of-life of an e-scooter, thus incorporating the material component, but also the energy intensity of the processes used from the extraction of raw materials to the production of the vehicle, as well as maintenance, collection/distribution processes and the use of electricity.

2. DATA AND METHODS

The approach applied for analysing the environmental sustainability of e-scooters is presented in Figure 1. Firstly, a search was made for the actual components of the e-scooters, the respective materials, characteristics and weights. Then, the modeling tool and the database was explored and the method to be used was defined. Within the database, the existing processes that best match an e-scooter are an electric motorcycle and an electric bicycle, allowing it to be possible to understand which model is most suitable for make an adaptation to the e-scooter. The developed analysis was applied to the context of the city of Lisbon, Portugal.

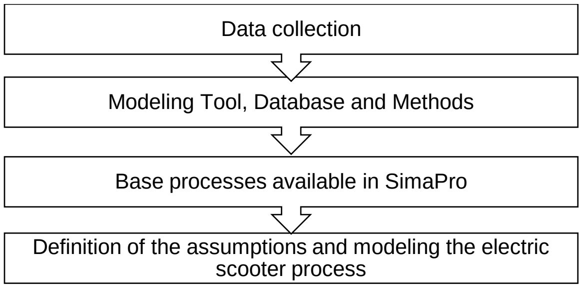


Figure 1 – Schematics for the applied methodology

2.1. Interviews and Scooter Operational Data

During this research, the information available was not enough to understand some details associate to e-scooters logistics in the city of Lisbon, Portugal. As such, 2 interviews with workers from different operators were conducted, in order to obtain relevant missing data. The main conclusions from both interviews were:

- E-scooters are collected every day, due to the constant vandalism they suffer. However, in most operators, collection is only done for scooters unloaded below 30%;
- Collection is done in vans with conventional propulsion technology;
- To ensure the safety of users, a quick maintenance is made: tests that guarantee if the e-scooters structure is in good condition, if screws are well tightened and if brakes are working;
- Most e-scooters are disassembled, and pieces are used for other scooters. In other words, the scooter never gets damaged as a whole, because pieces are constantly being replaced;
- The mechanical part of an e-scooter usually fails first because they are structurally fragile and suffer constant vandalism;
- Day trips made by e-scooters are uncertain. Scooters can either make 3 trips in one day or be stopped for the rest of the days; and
- In Portugal, there are no procedures to deal with damaged scooters and batteries in their end-of-life.

It was also possible to have access to the one-month (mid-October to mid-November 2019) operation data of e-scooters from a company that worked with one of the operators. This included maintenance data divided into "hard fixes" (mostly changes of batteries and electric motors) and "easy fixes" (quick parts changes). This data indicates that, in a month, each scooter goes to maintenance in total 2,76 times, in which 0,68 times the battery and/or the electric motor are changed. Assuming that each e-scooter reaches its end-of-life when it changes the battery and/or the electric motor, it was possible to estimate an average lifetime of one month and a half.

We also had access to data regarding collection and redistribution operations during that month. In one month, on average 52 e-scooters were collected and distributed over 82 kilometres per day. Also, it was possible to estimate the load factor of the distribution vans for each day. By assuming a maximum load of 99 e-scooters (maximum load verified), an average 53% load factor was estimated. From the data analysis, it was possible to estimate that on average 97 scooters were collected per day and that several scooters were not actually collected every day. The frequency of collection of these e-scooters is of from 3.5 to 3.5 days. For one month, it was estimated that e-scooters are collected on average about 8 times, which is also equivalent to an average collection from 3.5 to 3.5 days.

2.2. Definition of e-scooter process

In order to quantify environmental impacts of an e-scooter in a life cycle perspective, real world data was combined with existing data in the Ecoinvent 3 database from SimaPro software [21]. In more detail, a thorough characterization of the components of e-scooters, in terms of its respective materials, characteristics and weights. The evaluation method used was the ILCD 2011 Midpoint+ with the APOS model [22]. The database did not have a process for an e-scooter, so existing methods of an electric motorcycle and of an electric bicycle were adapted with specific real world e-scooter data for obtaining the e-scooter process, since these were considered the best available approximation. The functional unit for the analysis is performing 1 km with an e-scooter, even if the implementation in SimaPro was performed by simulating the full lifetime of the e-scooter.

Production

The production of the e-scooter consists of the manufacturing of a lithium-ion battery, of the structure of the vehicle without the battery and of the battery charger. The remaining structural part - electric scooter without a battery - is subdivided into the glider and the powertrain. The powertrain consists of the controller and the electric motor, as shown in Figure 2. This process was based on the SimaPro electric motorcycle process. The production of 1 e-scooter was considered with a total weight of 14.06 kg (including the charger) based on the average weights of the *Momas E-Scooter 1.0* [23] and the *Glion Electric Scooter Model 200* [24]. This scooter has an average weight of 13.45 kg, a battery with 2.22 kg, electric motor with 2.74 kg, charger with 0.61 kg and the weight of the controller was acquired separately for the same voltage used in batteries of both models of scooters, 36 V [25]. The powertrain is the sum of the weights of the electric motor and the controller (2.92 kg) and the glider is the difference between the electric scooter without the battery and the powertrain (8.31 kg). The constitution of the glider was based on the materials used in the process of an electric bicycle, since the mechanical and structural constitution of an e-scooter is similar to an electric bicycle. The main materials are aluminium, steel, plastic and rubber. The weight values of the glider's constituent materials were calculated for 1 kg of an e-scooter.

Use

The use of the e-scooter includes the energy spent battery charging, maintenance and the road use during its useful life. These impacts are modelled for each kilometer driven in the e-scooter, but simulated in Simapro for the full lifetime of the e-scooter. The use phase process is identical to the use processes of an electric motorcycle and of an electric bicycle and is shown in Figure 2.

The energy required to charge the scooter during its use was assumed to be low-voltage electricity (in kWh) selected from the Portuguese electricity mix of 2020 [22]. It does not matter whether a scooter is 30% or 80% charged because the electricity depends on kilometres that the e-scooter travels throughout its life. The road component represents the costs and requirements for the construction of road, tunnel and bridge infrastructure, the recovery of different layers of roads and their eventual disposal. All environmental exchanges refer to one meter-year (m * y).

The electric scooter use process unit is the distance driven in kilometres (km), which is a combination of the lifetime of the e-scooter and of the daily distance travelled. Four scenarios were considered for the total lifetime of an electric scooter: **1 month** (30 days), **1.5 months** (45 days), **3 months** (90 days) and **6 months** (180 days). As for the daily mileage, three scenarios were considered: **1 km**, **2 km** and **5 km** per day. Table 3 shows the possible values for the kilometres that an electric scooter makes over its total life. A **Base Scenario (**bold and underlined value in Table 3) was considered for a **life span of 45 days** and **daily use of 2 km**, based on the data collected and interviews.

The maintenance is mainly the replacement of plastic and steel pieces and it does not include the replacement of the battery. In the electric motorcycle's process, the maintenance value for 1 km is 2E-05 pieces, meaning that, for its total lifetime corresponding to 50.000 km, the electric motorcycle would suffer 1 maintenance. For the e-scooter's process, a weight correction was performed on that factor: $\frac{13.45\,kg}{144\,kg} = 9.34E-02\,pieces$, where 13.45 kg is the weight of the e-scooter and 144 kg is the weight of the electric motorcycle considered by its maintenance process. For the e-scooter's process, it is also necessary to know the number of pieces maintained per kilometre, so this scale factor is divided by the kilometres driven by an e-scooter throughout its total life for each scenario. Table 3 also indicates the maintenance done per kilometre for each total life scenario.

Collection and Distribution Operation

According to the obtained data, it is assumed that scooters are collected every day and every three days.

Table 1 indicates the number of times that a scooter is collected in its total lifetime for each scenario. The collection and distribution operation of e-scooters considers the use involves the use of a light commercial vehicle between 3.5 to 7.5 tons of gross vehicle weight. This vehicle is associated with a unit of 1 ton * km, with the following formula: ton*km = P × d × N, where P is the weight of the e-scooter transported by the vehicle in tonnes (0.01345 tonnes), d is the distance travelled by the collection vehicle (82 km) over its total life (in kilometres) and N is the number of collections.

Table 1 - Number of collections for 1 month, 1,5 months, 3 months and 6 months (Baseline Scenario presented in bold and underlined).

	Number of colections			
	30 days	**45 days**	**90 days**	**180 days**
Collection every day	30	45	90	180
Collection every 3 days	10	**15**	30	60

The class of this vehicle (3.5 - 7.5 tonnes) considers a default load factor of 20%. This value was increased to 53%, which corresponds to the average load for the collection vehicle according to the collected data for Lisbon. The collection vehicle assumes that transports on average 53% cargo, and the consumption of diesel is associated with the cargo that is transported. A round trip to a warehouse where scooters are charged and later distributed is considered with a distance travelled of 82 km based on the collected data for Lisbon. Table 2 indicates the distance travelled by the collection vehicle over the life of an e-scooter for each scenario. As already stated, maintenance is independent of collection, because otherwise the transport would happen as often as the number of maintenances.

Table 2 – Distance travelled (km) due to collection over total life for 1 month, 1,5 months, 3 months e 6 months (Baseline Scenario presented in bold and underlined).

	Kilometres of collection over total life (km)			
	30 days	**45 days**	**90 days**	**180 days**
Collection every day	2460	3690	7380	14760
Collection every 3 days	820	**1230**	2460	4920

Thus, it is possible to complete the collection operation by converting to ton-km, which is done by multiplying the weight of the e-scooter (0.01345 tons) with the values presented in Table 2. The resulting values for the collection phase are shown in Table 3. Figure 2 shows e-scooter's process without the end-of-life phase. The simulation in SimaPro is performed for the total life of an electric scooter.

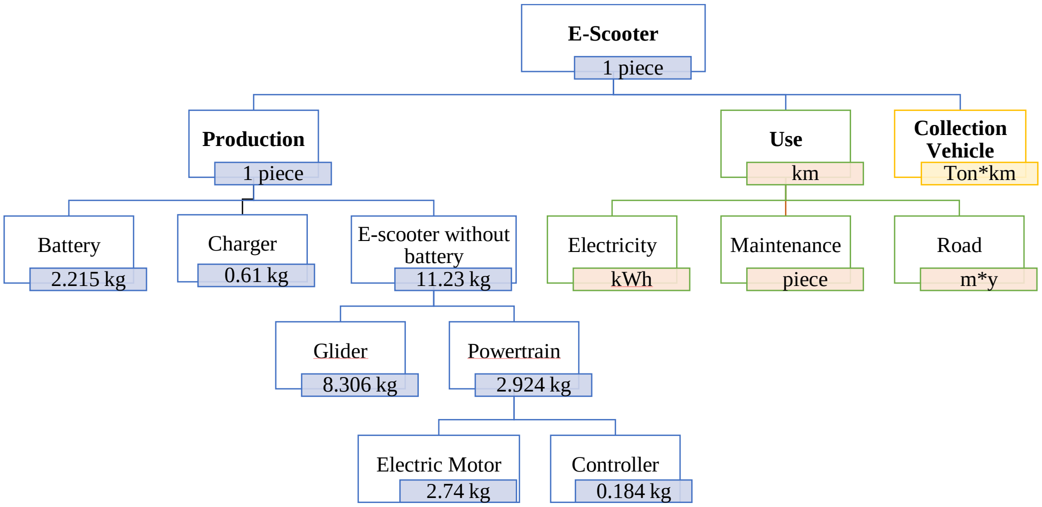


Figure 2 – Final process of production, use and collection of an e-scooter.

End-Of-Life

The end-of-life considers that all vehicles undergo a manual dismantling process by disaggregating their various material components. The treatment involves dismantling the glider and powertrain which are later disposed of in specific waste disposal facilities. The materials obtained go to different types of waste treatment and can go to recycling, energy recovery by incineration or landfill. The materials selected for the end of life are the main constituents of the scooter glider: aluminium, steel, rubber and plastics (polyethylene (PE) and polyurethane (PU)). Based on this information, three end-of-life scenarios were created:

- **Scenario 1**: Most materials go to a landfill and the remaining percentage is recovered energetically. It is a scenario without recycling;
- **Scenario 2**: Most materials are recycled, but the battery and powertrain are 100% recovered energetically.
- **Scenario 3:** Same as Scenario 2, but the battery and powertrain are recycled according to their constitution, that is the battery is 10% recycled and the powertrain is 83% recycled. These percentages correspond to aluminium, steel, rubber and plastic that constitute battery and powertrain.

2.3. Definition of Scenarios

Finally, all scenarios are summarized in Table 3 with the respective input data. These data refer to the total lifetime (total kilometres driven) of an e-scooter, the ton-km the collection vehicle does and the maintenance. The Base scenario is identified in bold and underlined. Scenarios 1, 2 and 3 correspond to end-of-life scenarios, each divided according to the lifetime, the frequency of collection and the mileage performed by one trip per day.

Table 3 - Input data for simulation in SimaPro of life cycle of e-scooter for each end-of-life scenario (scenarios 1, 2 and 3) (Baseline Scenario presented in bold and underlined).

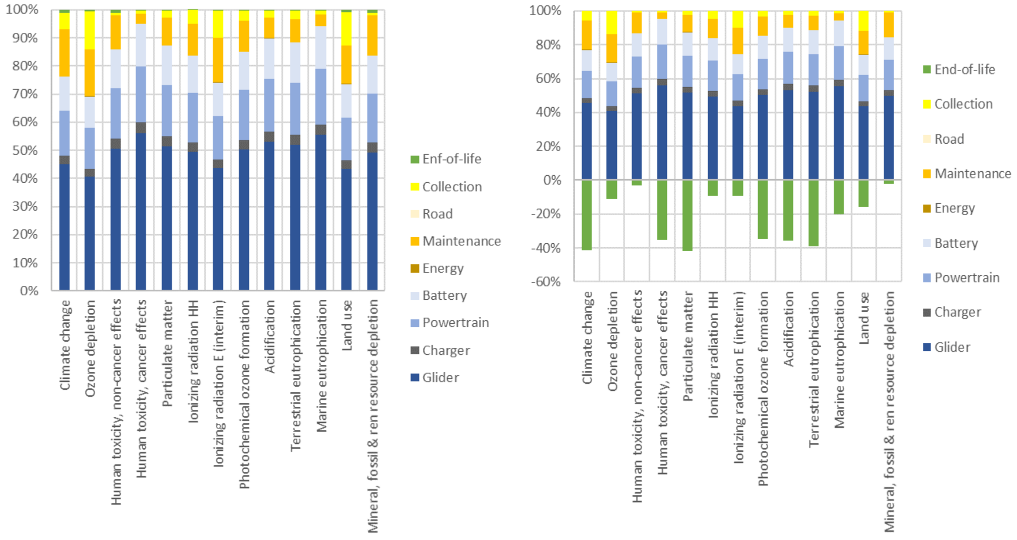
Lifespan (days)	**Collection Frequency**	**One trip per day of 1 km for Scenario 1, 2 and 3**		
		Total mileage (km)	**Collection Vehicle (ton.km)**	**Maintenance (pieces)**
30	**1 in 1 days**	30	33.10	3.11E-03
	3 in 3 days	30	11.00	3.11E-03
45	**1 in 1 days**	45	49.60	2.07E-03
	3 in 3 days	45	16.50	2.07E-03
90	**1 in 1 days**	90	99.20	1.04E-03
	3 in 3 days	90	33.10	1.04E-03
180	**1 in 1 days**	180	198.40	5.19E-04
	3 in 3 days	180	66.10	5.19E-04
Lifespan (days)	**Collection Frequency**	One trip per day of **2 km** for Scenario 1, 2 and 3		
		Total mileage (km)	**Collection Vehicle (ton.km)**	**Maintenance (pieces)**
30	**1 in 1 days**	60	33.10	1.56E-03
	3 in 3 days	60	11.00	1.56E-03
45	**1 in 1 days**	90	49.60	1.04E-03
	3 in 3 days	**90**	**16.50**	**1.04E-03**
90	**1 in 1 days**	180	99.20	5.19E-04
	3 in 3 days	180	33.10	5.19E-04
180	**1 in 1 days**	360	198.40	2.59E-04
	3 in 3 days	360	66.10	2.59E-04
Lifespan (days)	**Collection Frequency**	One trip per day of **5 km** for Scenario 1, 2 and 3		
		Total mileage (km)	**Collection Vehicle (ton.km)**	**Maintenance (pieces)**
30	**1 in 1 days**	150	33.10	6.22E-04
	3 in 3 days	150	11.0	6.22E-04
45	**1 in 1 days**	225	49.60	4.15E-04
	3 in 3 days	225	16.50	4.15E-04
90	**1 in 1 days**	450	99.20	2.07E-04
	3 in 3 days	450	33.10	2.07E-04
180	**1 in 1 days**	900	198.40	1.04E-04
	3 in 3 days	900	66.10	1.04E-04

3. RESULTS AND DISCUSSION

This chapter begins with a detailed analysis of the main impact categories for the Base Scenario (1, 2 and 3), then focuses only on the Climate Change impact category expressed in g $CO_{2\text{-eq}}$/km where the various scenarios are compared according to the variables: frequency of collection, kilometres travelled per day and lifetime of the scooters. Finally, a comparison between with different transport modes (electric vehicle, electric motorcycle and electric bicycle) is performed.

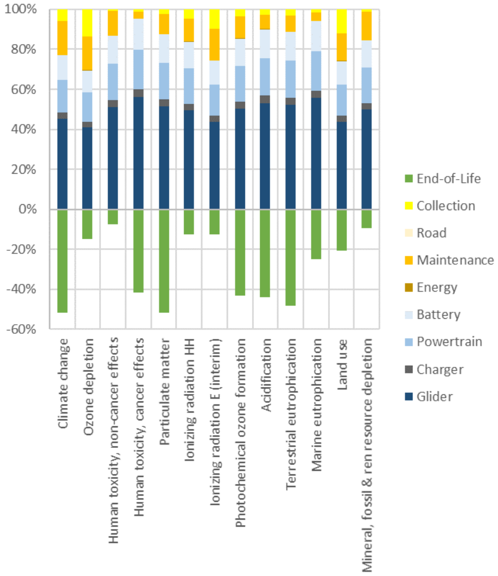
3.1. Base case assessment

The distribution along the different life-cycle stages in terms of climate change impacts (in kg $CO_{2\text{-eq}}$), are presented in Figure 3. Within the same base scenario, the values corresponding to production, use and collection are the same for the respective impact categories, as the variables remain constant. Between base scenarios 1 to 3, the phase that changes is the end of life



a)

b)



c)

Figure 3 - Graphical representation of results for all impact categories (in%) **a)** for base scenario 1, **b)** for base scenario 2 and **c)** for base scenario 3.

The remaining impacts in terms of climate change (in kg CO_{2}-eq), human toxicity (non-cancerous and cancerous) (in CTUh) and particulate matter (in kg $PM_{2.5-\ eq}$) for all life stages (production, use, collection / distribution and end-of-life) for the Base Case, divided by the main components, are presented as supplementary material (Tables SM1 to SM3).

For **Climate Change**, the production is responsible for more than 70% of the total impacts, which corresponds to the emission of 115 kg CO_{2}-eq. Usage corresponds to 17% of impacts, of which 16.9% corresponds to maintenance and collection issues 5.8%. In the impact category of **Non-Cancerous Human Toxicity**, the production of an e-scooter corresponds to more than 80% of the impacts. Utilization contributes 12.2%, in which maintenance corresponds to the total value and collection represents 0.9%. For **Cancerous Human Toxicity**, the total impacts of this category are almost exclusively due to the production of an e-scooter (more than 90%). The use of the vehicle represents 3.7% of the total impacts and the collection contributes 1.1%. For **Particulate Matter**, the production of the electric scooter represents about 85% of the total impacts, the use corresponds to approximately 10%, the collection contributes about 2.5%

The main difference in the base scenarios regards the end of life. In the **Base Scenario 1**, the end of life contributes 1% to the Climate Change category, with positive impacts, instead of reducing them through the recycling of materials. In total, the e-scooter emits 1680 g CO_{2}-eq/km for the lifetime of 90 km. For Non-Cancerous Human Toxicity, the end-of-life contributes 1.1% to with a total emission of 2.47E-04 CTUh per kilogram issued. For Cancerous Human Toxicity, end-of-life represents 0.2% with a total emission of 3.79E-05 CTUh per kilogram issued. For Particulate Matter, the end-of-life phase corresponds to 0.2%, emitting a total of 1.69 g $PM_{2.5-\ eq}$ /km.

In **Base Scenario 2**, for Climate Change, recycling and material recovery reduces impacts by 40%, which corresponds to less than 62 kg CO_{2}-eq. In total emits 974 g CO_{2}-eq/km. The Non-Cancerous Human Toxicity is the one that presents a lower negative contribution in the total impacts, its end of life corresponds only to - 3%. On the contrary, for Cancerous Human Toxicity, recycling plays a large part in reducing positive impacts, by around - 35%. In total, the Non-Cancerous Human Toxicity corresponds to 2.36E-04 CTU and the Cancerous Human Toxicity corresponds to 2.44E-05 CTUh. As for Particulate Matter, the end of life contribution is of around 42%, with a total emissions value of about 1 g$PM_{2.5-\ eq}$ /km.

As for **Base scenario 3**, for Climate Change, approximately half of the production, use and collection impacts of the total impacts are reduced (by - 52%) if the main materials are recycled. This scenario corresponds to an emission of 808 g $CO_{2}\ eq$/km. As for the Non-Cancerous Human Toxicity, the end of life of materials represents around -7%, while for the Cancerous Human Toxicity it reduces the impacts by 42%. Overall, the Non-Cancerous Human Toxicity category results in 2.26E-04 CTUh / km and the Cancerous Human Toxicity category in 2.21E-05 CTUh / km. For the Particulate Matter category, recycling allows 52% of impacts to be fully recovered, with a total emission of 0.81 kg de $PM_{2.5-\ eq}$/km.

3.2. Comparison of scenarios

The analysis of the effect of frequency of collection, kilometres travelled per day and lifetime of the scooters focuses on the Climate Change impacts, since it is the most widely discussed impacts category in terms of policy making. Table 4 presents the results in grams of CO_{2}-eq per kilometre for all scenarios.

Table 4 – Results for every scenario for the Climate Change category in g CO_2/km (and is organized with a colour scale, where red corresponds to the worst results and green indicates the best results. The base scenarios are in bold and underlined).

		Scenario 1			**Scenario 2**			**Scenario 3**		
Lifespan (days)	**km/day** **Collection**	**1km**	**2km**	**5km**	**1km**	**2km**	**5km**	**1km**	**2km**	**5km**
30	**1 in 1 days**	5325	2665	1067	3199	1602	642	2699	1352	542
	3 in 3 days	4932	2469	988	2806	1406	563	2306	1156	463
45	**1 in 1 days**	3746	1875	751	2328	1167	468	1995	1000	401
	3 in 3 days	3353	**<u>1679</u>**	673	1936	**<u>971</u>**	389	1602	**<u>804</u>**	323
90	**1 in 1 days**	2169	1086	436	1461	731	294	1294	648	260
	3 in 3 days	1778	890	357	1069	535	215	902	452	182
180	**1 in 1 days**	1380	691	278	1025	514	207	942	472	190
	3 in 3 days	988	495	200	633	318	129	550	276	112

The worst scenario corresponds to the emission of 5325 g $CO_{2\text{-eq}}$/km, for a lifetime of 30 days, daily use of 1 km and daily collection for the Scenario 1. It can be observed that lifetimes between 30 and 45 days, with a daily use of 1 km to 2 km, considering Base Scenario 1, tend to have the higher impacts. On the other hand, the scenarios with the best results concentrate on the lifetimes of 90 days and 180 days, with a daily use of 5 km. It is also expectable that the best results correspond to end-of-life scenarios 2 and 3, due to recycling and treatment of materials. Therefore, the best scenario corresponds to the emission of 112 g $CO_{2\text{-eq}}$/km, with a life span of 180 days and daily use of 5 km for scenario 3. The worst scenario emits 47.5 times more grams of $CO_{2\text{-eq}}$/km than the best scenario. Scenario 1 is the one that corresponds to the current reality, at least for the reality of Lisbon, Portugal, because little attention is being given to procedures for the disposal and recycling of the materials, based on the interviews.

Collection Frequency

Table 5 shows the percentages of reduction from a daily collection to a collection every 3 days in each scenario. Here the percentages of reduction remain constant according to the number of kilometres travelled per day for each end-of-life scenario, as they are values in the same order of magnitude. The variations between end-of-life scenarios 1, 2 and 3 are low, with no more than 10% varying from scenario 1 to scenario 2 and varying 3% to 4% from scenario 2 to scenario 3. The lifetime is the variable that most influences the percentages, as they present greater differences from scenario to scenario.

Table 5 - Percentages of reduction from daily collection to collection every 3 days for each scenario.

	Scenario 1			**Scenario 2**			**Scenario 3**		
km/day **Lifespan (days)**	**1km**	**2km**	**5km**	**1km**	**2km**	**5km**	**1km**	**2km**	**5km**
30	-7%	-7%	-7%	-12%	-12%	-12%	-15%	-15%	-15%
45	-10%	-10%	-10%	-17%	-17%	-17%	-20%	-20%	-20%
90	-18%	-18%	-18%	-27%	-27%	-27%	-30%	-30%	-30%
180	-28%	-28%	-28%	-38%	-38%	-38%	-42%	-42%	-42%

For the lifespan of 30 days, the results vary between -7% to -15% depending on the end-of-life scenario. For the life span of 45 and 90 days, the results reduce between 10% to 20% and between 18% to 30% respectively. For 180 days, the variation is more significant, ranging from -28% to -42%. The best scenario (Scenario 3 for 180 days) reduces about 42% when changing a daily collection to a collection every 3 days. According to the lifespan, the difference in the frequency of collection varies between -7% to - 28% for Scenario 1. Scenario 3 ranges from -15% to -42%. For Scenario 2 and Scenario 3, the difference between the values is not significant. However, Scenarios 2 and 3 allow reducing approximately half of the total impacts, and the collection system can be further improved, for example, using an electric vehicle to collect e-scooters. In order to understand the difference between the use of a conventional vehicle (ICEV) and an electric vehicle (EV) in the collection process of an e-scooter, the use of an electric vehicle for scenarios 1 and 3 (with a daily travel of 2 km, life span of 45 days, for both types of collection) was also modelled in SimaPro. The results show that the using an EV in the collection stage would reduce the Climate Change impacts between 10% to 23% for Scenario 3 and between 5% to 12% for Scenario 1, from daily collection to a collection in 3 in 3 days.

Distance travelled by day

Table 6 represents how the results vary when changing the number of kilometres travelled per day, from a daily trip of 1 km to 2 km, from 2 km to 5 km and finally from 1 km to 5 km. The percentages are the same for End of Life Scenarios 1, 2 and 3 and remain constant for different e-scooters lifetimes.

Table 6 - Reduction percentages between a daily trip from 1km to 2km and a daily trip from 2km to 5km for each scenario.

		Scenario 1, Scenario 2 e Scenario 3		
Lifespan (days)	**km/day** **Collection**	**1-2 km**	**2-5 km**	**1-5 km**
30, 45, 90 e 180	**1 in 1 days**	-50%	-60%	-80 %
	3 in 3 days	-50%	-60%	-80 %

Changing a trip of 1 km per day to a daily trip of 2 km reduces 50% of the results, by allowing the e-scooter to do an extra kilometre it decreases exactly half of the results. Increasing the daily use of the scooter by three kilometres, which corresponds to changing a trip from 2 km to 5 km daily, reduces 60% of the initial impacts. In total, the difference between daily use of the 1 km e-scooter for daily use of 5 km represents a decrease of 80% from the initial results (daily trip of 1 km).

Lifespan

Finally, the results were analysed according to the e-scooters lifetime. The percentages corresponding to the respective reduction differences are shown in Table 7 and Table 8 for daily collection and collection every 3 days respectively. For both tables, the smallest percentage reductions correspond to a change in life span from 30 days to 45 days, about 26% to 30% for daily collection and 30% to 32% for collection every 3 days. Changing the lifespan from 45 days to 90 days represents the greatest reduction in percentage in the final impacts, from 35% to 42% and 44% to 47% for daily collection and collection every 3 days respectively. The percentages do not vary by more than 10% between Scenario 1, 2 and 3 and do not vary by more than 15% for different lifetimes.

Table 7 - Reduction percentages between scenarios with a lifetime from 30 days to 45 days, from 45 days to 90 days and from 90 days to 180 days with daily collection.

	Scenario 1			**Scenario 2**			**Scenario 3**		
km/day **Lifespan (days)**	**1km**	**2km**	**5km**	**1km**	**2km**	**5km**	**1km**	**2km**	**5km**
30 – 45	-30%	-30%	-30%	-27%	-27%	-27%	-26%	-26%	-26%
45 – 90	-42%	-42%	-42%	-37%	-37%	-37%	-35%	-35%	-35%
90 – 180	-36%	-36%	-36%	-30%	-30%	-30%	-27%	-27%	-27%

Table 8 - Reduction percentages between scenarios with a life span from 30 days to 45 days, from 45 days to 90 days and from 90 days to 180 days with collection every 3 days.

	Scenario 1			**Scenario 2**			**Scenario 3**		
km/day **Lifespan (days)**	**1km**	**2km**	**5km**	**1km**	**2km**	**5km**	**1km**	**2km**	**5km**
30 – 45	-32%	-32%	-32%	-31%	-31%	-31%	-31%	-30%	-30%
45 – 90	-47%	-47%	-47%	-45%	-45%	-45%	-44%	-44%	-44%
90 – 180	-44%	-44%	-44%	-41%	-41%	-40%	-39%	-39%	-39%

The reduction percentages become less relevant as the end-of-life scenario is optimized and as the life span increases. The longer the e-scooter lasts and, in turn, its use over those days, the smaller the differences in impacts between the scenarios. As an example, the scenario that changes from 45 days to 90 days (collection every 3 days) has a reduction ranging from 44% to 47%. This reduction corresponds to a difference of 45 days. When the life span is changed from 90 days to 180 days, the difference of 90 days corresponds to a smaller impact reduction, varying between 39% to 44%.

3.3. *Transport mode comparison*

An e-scooter emits according to the basic assumptions between 855 to 1731 g $CO_{2\text{-eq}}$/km for a life span of 90 km. According to the collected literature, electric vehicles emit an average of 177 g $CO_{2\text{-eq}}$/km for an average life span of 150 thousand kilometres [7],[8], electric bicycles emit 51 g $CO_{2\text{-eq}}$ /km for an average life span of 85 thousand kilometres [13], [14], [15], [16], and electric motorcycles (or electric scooters) emit an average of about 52 g $CO_{2\text{-eq}}$ /km for an average lifespan of 31 thousand kilometres [13], [14]. Figure 4 indicates the emissions of CO_2 per kilometer for each mode of transport and for the respective lifetimes on the logarithmic scale.

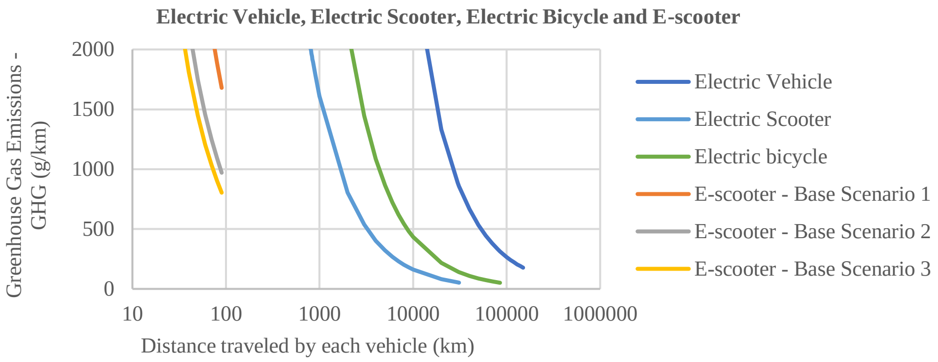


Figure 4 - Emissions of CO_2 per kilometre for the electric vehicle, electric scooter, electric bicycle and e-scooter.

Figure 4 shows that the electric bicycle and the electric scooter are the transport modes with the lowest CO_2 emission values, followed by the electric vehicle and finally the e-scooters have the highest values. All types of transport (with the exception of the e-scooter) have long life spans, allowing emissions to be offset by their use, something that does not occur with the use of the e-scooter, as it has such a short life span. It should also be noted that the electric vehicle allows transportation for at least four people, while the e-scooter only carries one passenger.

The e-scooter emits about 4.5 to 9.5 times more than an electric vehicle for the Scenario Base 3 and Scenario Base 1 respectively. For the e-scooter to be able to emit the same as an electric vehicle (that is 177 g $CO_{2\text{-eq}}$/ km), it must cover 855 kilometers, 494 kilometers and 409 kilometers for Base Scenarios 1, 2 and 3 respectively. The electric bicycle and e-scooters are identical transport modes, focused on micro-mobility, but e-scooters emit about 15.8 times more than an electric bike for the Base Scenario 3 and emit 33 times more than the electric bicycle for ethe Base Scenario 1. For an e-scooter to have the same GHG emission as an electric bicycle, the e-scooter needs to do 2950 kilometres, 1700 kilometres and 1410 kilometres for the respective Base Scenarios 1, 2 and 3. These values correspond to a life span ranging from 24 months (2 years) to 49 months (approximately 4 years) considering daily trips of 2 km. If the e-scooter was used for the same lifetime as an electric bicycle , it would emit about 2 g $CO_{2\text{-eq}}$/km in the worst case and 1 g $CO_{2\text{-eq}}$/km in the best case.

4. CONCLUSIONS

This study quantifies the life cycle impacts of e-scooters, with the results in the Base Scenario varying from 804 to 1679 g $CO_{2\text{-eq}}$/ km, dominated by the component of materials and their production. This phase corresponds to approximately 76% of the total emissions of CO_2. The use and operation of collection / distribution correspond to 23% of the final impacts. However, the results can be greatly reduced when recycling materials at the end of their life. Effective recycling makes it possible to reduce CO_2 emissions by up to 50%, that is, half of its initial impacts.

This scenario is considered to represent the reality of Lisbon, Portugal, where available information indicates to low usage patterns and reduced e-scooters lifespans, either due to vandalism or the quality of products. This lifespans between 1 month to 6 months are low number when compared to previous studies, namely the ones by Hollingsworth et al (6 months to 2 years) [18], Voi (2 years) [20] and Chester (16 to 17 months) [17]. American reality indicates that the e-scooters are used more often. In the case of Lisbon, most of the impacts are associated with production of e-scooters, as a result of the short duration of the product: as the e-scooter travels so few kilometres throughout its life, it is not possible to spread for the impacts of its production through a longer time frame. The more kilometres travelled by the collection vehicle, the collection phase would have a greater environmental impact, reducing the environmental impacts from the remaining parcels (production and use). In addition, the lower the use of an e-scooter, the lower the energy required, and fewer times is collected and re-distributed. However, the optimization of collection and distribution operations should not be underestimated.

Additionally, there is a considerable difference in results of the various scenarios, ranging from the emission of 112 to 5325 grams of $CO_{2\text{-eq}}$ /km. These results are highly sensitive to the mileage over the entire life, since increasing the number of kilometres run per day reduces the results by 50% to 80%. A less frequent collection also reduces environmental impacts by between 7% and 42% and increasing lifespan allows a reduction between 26% and 47% in final impacts. The use of an electric vehicle in the collection / distribution of e-scooters still manages to reduce impacts between 5% to 23%.

As for the use of shared transport modes in urban environment, it is concluded that the e-scooter pollutes more than an electric bicycle, an electric motorcycle and even has greater impacts than an electric vehicle. Only in the most optimistic scenario, is it possible to compete with an electric vehicle. In order for e-scooters to have a place in the competitive urban environment with other vehicles, it is necessary to define strategies that guarantee the minimum levels of use of an e-scooter: ensure that they make more trips per day and make more kilometres per day; and ensure that the physical structure and materials of e-scooters are strong and protected from vandalism.

To improve the e-scooters sharing system, it is necessary to reduce the frequency of collection in order to reduce the burdens associated with the vehicles used in the collection and distribution process; Additionally, reinforce anti-vandalism laws to reduce the misuse of e-scooters, which results in shorter lifespan, therefore high CO_2 emissions associated with the production and materials phase. The operators themselves can also electrify their fleet in order to make the collection process less polluting. As an example, the Voi e-scooter collection system has electrified its entire fleet, implemented replaceable batteries and optimized its collection routes. The replaceable batteries make it possible to collect them by bicycle-trailers. The use of personal e-scooters should also be promoted, since they are not vandalized and tend to last longer than sharing systems. Finally, the conditions for the circulation of active modes continue to be promoted in many cities such as Lisbon, namely through the expansion of the cycle network that also serves e-scooters, thus allowing the improvement of comfort and safety conditions in the respective use.

Given the current situation of the world pandemic COVID19, electric scooters may be attractive for replacement of public transport trips, as, like bicycles, they allow social distance, increasing the efficiency of the system.

Following this work, there are several aspects that could be improved such as: disassemble an e-scooter and perform a life cycle analysis for the constituent materials with the respective real weights; and monitor an e-scooter system in order to have access to all relevant data for this study in order to improve the results.

As a result, this study can serve all those involved in the transport sector, whether they are escooter manufacturers trying to reduce environmental impacts in the production of their “vehicles”, or even consumers who are more aware of the issues of sustainability that want to make a more informed and environmental choice.

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Supplementary Material

Table SM1 - Results of Base Scenario 1 for the impact categories "Climate Change", "Non-cancerous Human Toxicity", "Cancerous Human Toxicity" and "Particle formation".

		Climate Change (kg CO_2-eq)	Human toxicity, non-cancer effects (CTUh)	Human toxicity, cancer effects (CTUh)	Particulate matter (kg $PM_{2.5}$-eq)
Production	Battery	1.84E+01	3.38E-05	5.76E-06	2,13E-02
	Charger	4.60E+00	8.45E-06	1.44E-06	5,32E-03
	Powertrain	2.42E+01	4.44E-05	7.56E-06	2,79E-02
	Glider	6.79E+01	1.25E-04	2.12E-05	7,85E-02
Total Production		**1,15E+02**	**2.12E-04**	**3.60E-05**	**1.33E-01**
Use	Maintenance	2.55E+01	3.00E-05	1.40E-06	1,52E-02
	Energy	2.10E-01	3.65E-08	4.89E-09	1,54E-04
	Road	8.22E-03	1.62E-09	6.35E-10	7,85E-06
Total Use		**2,57E+01**	**3.00E-05**	**1.41E-06**	**1.54E-02**
Operation	Collection	8.80E+00	2.28E-06	3.98E-07	3,85E-03
Sub-total w/o End-of-Life		**1,50E+02**	**2.44E-04**	**3.78E-05**	**1.52E-01**
End-of-Life	Landfill	1.31E-01	2.31E-06	4.37E-08	1,41E-04
	Recovery	1.38E+00	4.04E-07	4.05E-08	1,15E-04
Total End-of-Life		**1,51E+00**	**2.71E-06**	**8.42E-08**	**2.56E-04**
Total		**1,51E+02**	**2.47E-04**	**3.79E-05**	**1.53E-01**
Total (g/km)		**1,68E+03**	**-**	**-**	**1.69E+00**

Table SM2 - Results of Base Scenario 2 for the impact categories "Climate Change", "Non-cancerous Human Toxicity", "Cancerous Human Toxicity" and "Particle formation".

		Climate Change (kg CO_2-eq)	Human toxicity, non-cancer effects (CTUh)	Human toxicity, cancer effects (CTUh)	Particulate matter (kg $PM_{2.5}$-eq)
Sub-total w/o End-of-Life		1.50E+02	2.44E-04	3.78E-05	1.52E-01
End-of-Life	**Recycling**	-6.81E+01	-1.75E-05	-1.41E-05	-7,22E-02
	Recovery	5.82E+00	9.39E-06	6.57E-07	8,58E-03
Total End-of-Life		-6.23E+01	-8.11E-06	-1.34E-05	-6.36E-02
Total		8.77E+01	2.36E-04	2.44E-05	8.84E-02
Total (g/km)		9.74E+02	-	-	9.82E-01

Table SM3 - Results of Base Scenario 3 for the impact categories "Climate Change", "Non-cancerous Human Toxicity", "Cancerous Human Toxicity" and "Particle formation".

		Climate Change (kg CO_2-eq)	Human toxicity, non-cancer effects (CTUh)	Human toxicity, cancer effects (CTUh)	Particulate matter (kg $PM_{2.5}$-eq)
Sub-total w/o End-of-Life		1,50E+02	2,44E-04	3,78E-05	1,52E-01
End-of-Life	**Recycling**	-8,12E+01	-2,05E-05	-1,62E-05	-8,55E-02
	Recovery	3,94E+00	2,39E-06	5,03E-07	6,81E-03
Total End-of-Life		-7,73E+01	-1,81E-05	-1,57E-05	-7,87E-02
Total		7,27E+01	2,26E-04	2,21E-05	7,33E-02
Total (g/km)		8,08E+02	-	-	8,14E-01