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Lifecycle Analysis of E-scooters in Sharing Services

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ABSTRACT

E-scooters in sharing services are becoming increasingly popular as an alternate mode of transport to replace short distance car journeys. But this business model is clouded by questions that suggest they might be causing more harm to the environment than decreasing it. There is a growing consensus that emissions associated with the production of e-scooters and the collection and distribution process contribute to the most emissions. In this paper, we look at different production locations in China, UK and Sweden and compare the net emissions output from production in these countries. We also try to understand the impact of using sustainable vehicles during the collection and distribution processes (for charging) such as electric and fuel cell vehicles on the lifecycle of e-scooters. The results show how e-scooter lifespan, production locations, reimagining the distribution process and renewable energy concepts influence the green house balance compared to alternative means of transport. Manufacturing an e-scooter in the China, UK and Sweden results and using sustainable vehicles for e-scooter collection and distribution result in 234.2, 123.9 and 108.2 gCO2/mile. Lastly, a parallel is drawn to understand the benefits of using renewable energy sources for charging the e-scooter.

Keywords: *E-Scooters, Sharing Services, Emissions, Lifecycle Analysis, Carbon Di-Oxide, Micromobility, Manufacturing, Sustainable Vehicles.*

1. INTRODUCTION

Global greenhouse gas emissions from the transportation sector have long been a cause of concern. Hydrocarbons are used to power all modes of transport from cars, ferries and flights, but the burning of hydrocarbons from fossil fuels releases harmful gases into the atmosphere. The primary reason why emissions are harmful is because they prevent the long wave infrared solar radiation from escaping back into space, thereby trapping heat and raising global temperatures 1. Prominent greenhouse gases such as carbon di oxide and sulphuric oxides cause irreparable damage to the human respiratory system, not to mention the devastating effects on climate change [2].

Out of the number of greenhouse gases such as carbon di oxide (CO_2), sulphuric oxides (SO_x), nitrous oxides (NO_x), methane (CH_4) and chlorofluorocarbons, carbon di oxide is the most prominent making up 65% of the total greenhouse gas emissions [3]. The carbon di oxide emissions in 2021 was 36.3 billion tons, up 6% from 2020 [4]. Out of the 36 billion tons, 17% came from the transportation sector. To delve a little deeper, 4.52 billion tonnes came from the road transportation sector – the major contributor to emissions in the transport sector. Figure 1 describes this situation in further detail. In the UK, about 27% of the GHG emissions came from the transport sector in 2021 [5].

There has been a global trend to adapt to sustainable and innovative technologies such as electric cars, fuel cell vehicles, biofuel internal combustion engines, and the latest trend, e-scooters.

E-scooters first became popular in the United States with major players such as Bird and Lime enjoying widespread success. The trend soon shifted to Europe where again it has enjoyed decent success in countries like Germany, France and Sweden. E-scooters collectively fall under a niche mode of transport termed 'micromobility'. Micromobility refers to a range of small, lightweight vehicles that weigh less than 500kg, don't have internal combustion engines and have top speeds of no more than 25km/hr. E-scooters are staring to become a trend in the UK with sharing service companies such as TIER mobility, VOI and Ginger controlling a major share of the market. E-scooters were primarily introduced as a sustainable means of transport to replace car journeys and help ease the burden placed on electric cars [6].

But as in the case of electric cars, none of the electric modes of transport are actually green. Although the tailpipe emissions are zero, carbon di oxide is emitted during the manufacturing, assembly and transportation of EVs. Numerous studies have proved that the carbon emissions emitted during the production phase are considerably higher than a vehicle with an internal combustion engine [7]. However, several studies have also concluded that over the course of the lifetime of the EVs, they are able to offset the carbon emissions emitted during manufacturing.

A similar case cannot be made for e-scooters because of their relatively shorter lifespan. Warwick university during their study on e-scooters in May 2021 concluded that the average lifespan of an e-scooter used in a sharing service is around 3-6 months [8]. This might not be sufficient to offset the carbon emissions emitted during manufacturing and assembly. Note that this analysis corresponds to e-scooters used in sharing services and not for personal use.

Lastly, the UK government [9] in corroboration with other studies have firmly stated that collecting and distributing e-scooters for overnight charging is the second most contributor to carbon emissions after manufacturing. This study aims to understand two particular problem statements:

1. Majority of the e-scooters are manufactured in China which has a higher carbon output from the electricity grid. In this work, we will try to understand the impact on carbon emissions when e-scooters are manufactured in house in the UK and Sweden which will adversely eliminate and reduce the GHG emissions arising due to transportation from China.
2. The collection and distribution of e-scooters for charging through more sustainable methods such as electric vehicles and fuel cell vehicles.

This work uses the GREET2 (2021) model of the Argonne National Laboratory to perform a cradle to grave simulation of e-scooters. This model hosts all the necessary inventory data required to undertake this study and the outputs derived from this model is discussed in detail in the following sections. In the next section, we analyze the works and similar studies on lifecycle analysis on e-scooters conducted by different authors and discuss their findings.

2. BACKGROUND

Although the lifespan of an average e-scooter is limited, it still weighs incredibly (<20kg – typical weight of an e-scooter used by a dockless electric scooter program) lighter than a gasoline car (base model of Vauxhall Astra – 1248 kg) or an electric car (base model of Nissan Leaf – 1580 kg). Qiao et al., (2017) in their study on lifecycle CO2 emissions of conventional and electric vehicles in China concluded that the production of an average EV emits 60% more carbon emissions than a conventional vehicle with an internal combustion engine. This certainly begs the natural question then that if electric scooters weighed almost 100 times lesser than an average gasoline powered or electric car, shouldn't the manufacturing emissions also be significantly lesser? The short answer is yes. But these dockless vehicles rely on components such as lithium-ion batteries and electric motors – both are units that have higher GHG emissions during production. This theory is verified through Hao et al., (2017) who summarize that the production of lithium-ion batteries alone increases the GHG emissions by 30% compared to an internal combustion engine vehicle.

This is where the work of Chester (2018) although not peer reviewed provides major insights into why lifecycle analysis of e-scooters is important to understand their contribution towards sustainability in the transport ecosystem. In his article, he hypothesized that the emissions arising from collecting and charging the e-scooters every day was proof that e-scooters in fact contributed to an increase in emissions rather than decreasing them. The analysis showed that assuming an average lifespan of 45 days, e-scooters emitted anywhere between 320 and 750 gCO2/mile. It pointed out that these figures were largely outperformed by electric cars and public buses (89 gCO2/mile). Two suggestions in this article were to have manufacturing in house and the usage of sustainable methods for e-scooter collection and distribution for charging - which this study aims to understand.

To the author's knowledge, there are no previous works that have focused on manufacturing of e-scooters at different locations. The closest comparison would be the work of Pucker-Singer et al., (2021) who analyzed the production of battery packs in China and Navarra, Spain and observed close to 50% reductions in GHG emissions per kWh when produced in Navarra.

The average lifespan of an e-scooter in a sharing service is just 3 months [8]. This is due to the rough handling, mistreatment and sometimes, vandalism that users inflict on them. Between December 2020 and March 2021, the city of Bristol reported more than 50 incidents against e-scooter vandalism [14]. Severengiz et al., (2020) are convinced that increasing the reliability and durability of e-scooters through reliability engineering definitely has a positive influence on the durability of the vehicles. They argue that scooters used for personal use tend to be maintained well and are not subject to vandalism and hence are more reliable. A similar case cannot be made for e-scooters in sharing services and their analysis also explains that techniques such as predictive maintenance strategies tend to have lesser carbon outputs too. Although these methods are not used in this analysis, it is worth noting that there are methods that help improve the lifespan and durability of e-scooters and that these methods have a positive impact on the environment. Almost all the studies suggest that an increased lifespan reduce the net carbon emissions. To quote a few instances, Kazmaier et al., (2020) while performing a techno-economic LCA on e-scooters found that increasing the e-scooters' life to 15 months provided the lowest emissions at 46 gCO2/mile and Krier et al., (2021) while researching the influence of micromobility in Paris discovered that increasing the lifespan indeed reduced CO2 emissions but however failed to reach a neutral impact point.

David & Amey, (2020) compared the lifecycle analysis of station based and dock-less bike sharing systems and deduced that the bike rebalancing process – efforts used to collect and distribute the scooters pre and post charging yielded the most emissions. Their results showed that the total GHG emissions was around 118 gCO2-eq/bike-km. Out of which, collection and distribution of the scooters accounted for 73% of the carbon emissions. The authors also go on to show that sustainable methods and optimizing the bike distribution process tends to decrease the total GHG emissions. Hollingsworth et al., (2019) experiment various methods to determine the environmental impact from e-scooters and conclude that reducing the distance for collecting the e-scooters to an average of 0.6 miles reduces the global warming impacts by 27% while the use of sustainable vehicles for collection results in a 12% reduction.

So far, we've seen previous lifecycle analysis assignments enunciate that e-scooters in sharing services facing 3 critical challenges:
1. Very short lifespan,
2. Intense emissions associated with the manufacturing processes,
3. High emissions associated with the scooter rebalancing process.

This study aims to fill the knowledge gaps pertaining to the above problems and possibly provide a solution that could reduce these hinderances that the e-scooter market is facing. The next sections will deal with the methodology used to solve these problem statements and discuss the results in a chronological order.

3. METHODOLOGY

This study's framework is divided into goal and scope definition, lifecycle inventory analysis, lifecycle impact assessment and interpretation of results. The goal and scope of the project is to analyze the GHG emissions of e-scooters using the cradle-grave technique. This means that all the 5 stages in the lifecycle of an e-scooter namely manufacturing, assembly, transportation, use phase and disposal is carefully studied to present a well-rounded view on carbon emissions from this mode of transport. Maintenance and repair were not considered due to lack of public databases or databases with accurate information. Figure 1 depicts the different phases in the lifecycle and highlights the phases our problem statements come under.

The GREET 2 (2021) model from the Argonne National Laboratory served as both a lifecycle inventory and a modelling tool to simulate different production scenarios. This model was used for deriving precise carbon emissions from manufacturing, assembly and disposal stages of the lifecycle. The base case for the use case on daily basis and the collection and distribution of the scooters for charging was defined based on a number of studies on the same subject area [12,20]. The functional unit used to measure carbon emissions is gCO2 per scooter mile.

The next sections will deal with the research methodology of each lifecycle stage of the e-scooter.

3.1 Manufacturing

This study is based on the MI electric scooter 3 which seems to be the popular choice among major e-scooter sharing services. A table which reflects the accurate inventory details of this e-scooter can be accessed here. Basic details of the scooter such as weight, battery weight, battery type, motor current and voltage were catalogued based on the statements of the manufacturer. The GREET 2 model was used for in-depth production databases such as raw materials sourcing and production for the scooter, battery, and motor.

The manufacturing phase involves the carbon emissions from producing all the components of the e-scooter. Severengiz et.al identified the share of major components in an e-scooter [14]. Figure 2 below indicates that the aerospace grade aluminium body frame makes up close to 45% of the scooter weight followed by the lithium-ion battery. Table 1 represents the individual mass of major components of an MI electric scooter 3.

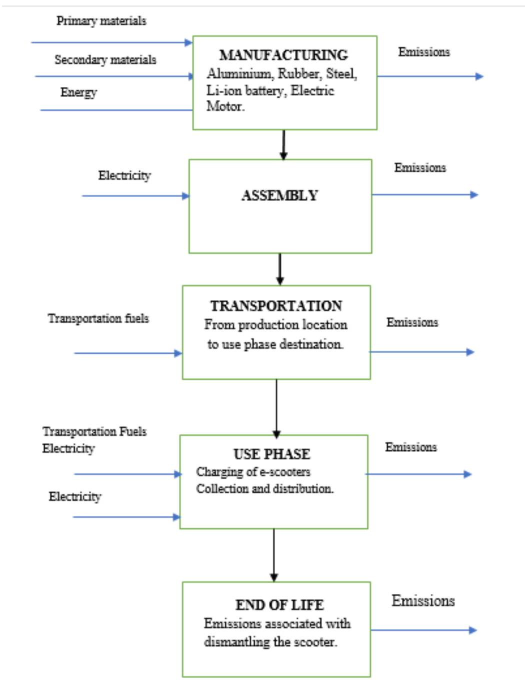

Figure 1: Systems boundary diagram of the 'cradle-grave' process.

T [illegible] his study, the carbon emissions as a result of e-scooter production in 3 different locations namely China, UK and Sweden are analyzed. The main difference in production in different countries is the carbon emissions per kWh generation of grid electricity. Sweden, Norway and Switzerland have the least carbon emissions from grid electricity in Europe. The reason behind focusing on Sweden as an alternate location is to eliminate long transport distances between the production location and United Kingdom (London). Table 2 below gives an account of the grid electricity carbon mix of China and some European countries. The GREET 2 model accounted for the grid electricity carbon mix of individual production locations. The results from these production locations is discussed in detail in section 4.

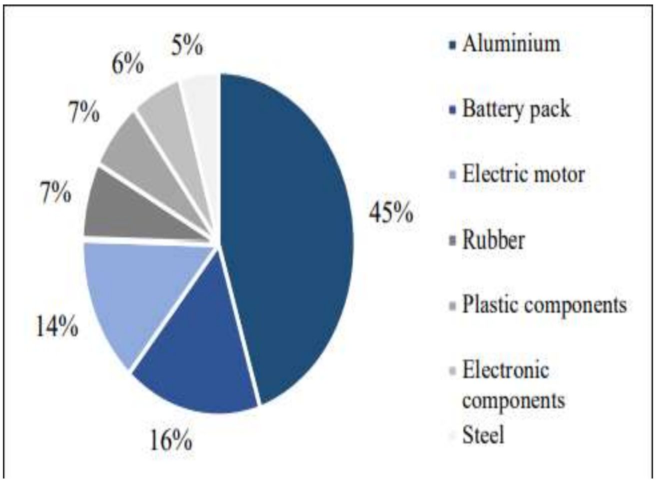

Figure 2: E-scooter material composition; Source: Schelte et. al (2020)

Table 1: Mass of individual e-scooter components.

Component	Mass (kg)
Aluminium	5.94
Li-ion battery pack	1.6
Traction motor	1.2
Rubber	1.0
Plastic parts	0.9

Table 2 *highlighting the grid electricity carbon mix in different countries. Source:* (Carbon Footprint, 2019)

Country	kgCO2e per kWh	Source	Year	Comments
China	0.6236	Climate Transparency (2018 Report)	2017	Emissions intensity of the power sector
United Kingdom	0.2773	UK Govt – Defra/BEIS	2019	Combined Generation + Transmission & Distribution factor
Sweden	0.0120	Association of Issuing Bodies (AIB)	2018	Production mix factor
Germany	0.4690	Association of Issuing Bodies (AIB)	2018	Production mix factor
Norway	0.0110	Association of Issuing Bodies (AIB)	2018	Production mix factor
France	0.0470	Association of Issuing Bodies (AIB)	2018	Production mix factor

3.2 Assembly

Based on interviews with scooter sharing providers, Severengiz et.al (2020), concluded that the energy required for the manufacture of the scooter and the assembly of the battery pack was 3.9 kWh [15]. Greenhouse gas emissions for the scooter assembly process as simulated in the GREET 2 model for the different production locations is illustrated below in Figure 2.

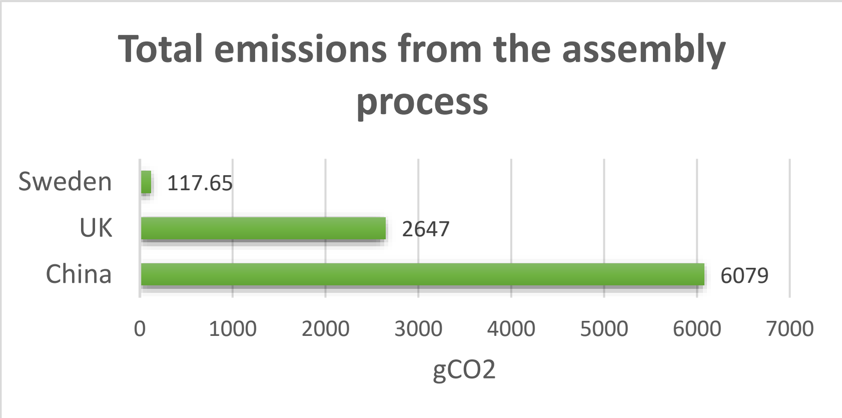

Figure 3: Overall emissions from the assembly process in the 3 locations.

3.3 Transportation to united kingdom

Rail and water borne transport is much less carbon intensive than air transport. The new silk road rail line connecting Asia and most of Europe has the potential to reduce carbon emissions from freight traffic owing to the reduced distances in rail line compared to water transport [22, 23]. Here, we consider the new silk road as the transportation pathway from China to United Kingdom to further reduce the GHG emissions. Besides, using rail transport seems accurate based on the statements of major European dockless electric scooter businesses such as TIER [24]. Transportation emissions for e-scooter production within the United Kingdom is considered to be zero.

3.3.1 China to United Kingdom: Yiwu station to London barking:

The new silk road rail to the UK originates at Yiwu station in China and terminates at London Barking. However, the scooters are actually manufactured in a place called Shenzen almost 1372 km away from Yiwu. Therefore, the total carbon emissions associated with the transport of one scooter will be the addition of two individual stages 1. Shenzen to Yiwu by rail and 2. Yiwu to London by rail.

The total weight including packaging and accessories is taken to be 17.5 kg [19]. The distance between Shenzen and Yiwu translates to 24t-km. It is assumed that the scooters are transported between these two cities by rail. According to Wen et.al (2021), the carbon emissions per ton-km for railway freight in China is approximately 0.028 kgCO_2/ton-km which translates to 672g or 0.67kg CO_2 emissions per e-scooter for the journey between Shenzen and Yiwu.

The Yiwu to London railway line covers almost 12,000 km (7456 miles) which equals 210 t-km. The European agency's last report on motorized emissions in Europe says that the average carbon emissions per ton-km of freight transport for the 2014-2018 period was 0.024 kgCO_2/ton-km [26]. This unit is taken into consideration. For this leg of the journey, the total GHG emissions estimates to 50.4 kg CO2. Adding both the figures results in approximately 51 kg CO2 emissions per scooter from Shenzen to London.

3.3.2 SWEDEN TO UNITED KINGDOM – STOCKHOLM TO LONDON: The distance between Stockholm and London by rail is approximately 2012.8 km which translates to 35.2 t-km. The total emissions per e-scooter by rail amounts to 600 gCO2 or 0.6 kg. Table 3 below highlights the GHG emissions from production in the 3 countries.

Table 3: Emissions associated with transportation from China and Sweden

Country of Production	kgCO2e per scooter
United Kingdom	0
China to UK	51.7
Sweden to UK	0.6

3.4 Use Phase

This section integrates emissions arising from both - charging of the e-scooters and collection and distribution of the scooters for charging. The e-scooter has a lithium-ion battery pack consisting of 30 units of 18650 cells. The battery weight and the total e-scooter weight as described by the e-scooter are 3.53 and 29.1 lbs respectively. It has 2 inflatable rubber tires of 8.5 inches each weighing 1.1 lbs. The total energy required to completely charge the battery of the e-scooter is 0.275 kWh [27] with a range of 18.6 miles on a full charge with a maximum speed of 25 km/hr. This means that the energy required to travel one mile would be 0.015 kWh.

In the early stages of e-scooter sharing providers, the average lifetime of these machines would range between 30 and 45 owing to poor maintenance and vandalism on a major scale. E-scooters have now become more reliable and durable increasing the average lifespan to 90 days. A range of different lifespans from 3-6 months has been considered in this analysis with the base case fixed at

3 months/90 days in accordance with popular e-scooter LCA studies. An extensive survey across London to understand the daily usage of an e-scooter revealed that on average, an e-scooter is used 5 times a day [28]. Ford Motors, following the launch of their Spin e-scooters, launched a survey in the Essex region to analyze user patterns and stated that the average distance per trip in an e-scooter was around 1.8 miles and under 23 minutes [29]. This number seemed to vary very little with other surveys across the country. This would amount the total distance of an e-scooter in a day to 9 miles and a total lifetime distance of 810 miles in 3 months.

The UK grid electricity carbon mix as described in table 2 as 0.2773 kgCO2e/kWh. The energy consumption of the battery pack is 0.275 kWh and this gives the GHG emissions to fully charge the e-scooter battery to be 81.68 gCO2 as explained in Equation 3.

$$\textit{Emissions from charging the e-scooter}, E_i = G_i * C_i * 1000 \quad \textit{Equation 1}$$

where,
G_i represents the grid electricity carbon mix in kgCO2e and
C_i represents the energy consumption of the battery pack in kWh
Emissions per mile of a fully charged scooter totals 9.1 gCO2e (Equation 2) and the lifetime emissions from charging one e-scooter would be 7,351 gCO2e (Equation 3).

$$\textit{Emissions per mile of fully chargeD scooter}, F_i = E_i / N_i \quad \textit{Equation 2}$$

where,

N_i represents the number of miles ridden in a day

$$\textit{Total lifetime emissions from an e-scooter} = E_i * T_i \quad \textit{Equation 3}$$

where,
T_i represents the total lifetime miles

3.4.1 Collection And Distribution: The primary method of collection considers a gasoline powered vehicle to pick up scooters for charging and distributing. Two other methods – an electric van and a hydrogen fuel cell van are also considered as viable options for collecting the scooters. We further classify the collection and distribution phase into 2 different scenarios defined by distance driven to collect the e-scooters and number of e-scooters picked up – a best scenario which involves driving 4 miles to collect and distribute 20 scooters and a worst-case scenario which involves driving 10 miles to collect 5 scooters. This is based on the work of Chester (2018) and accommodates for both urban and rural conditions.

Best Scenario: Driving 4 miles to collect 20 scooters

Let us first consider picking up the e-scooters that are produced in China with a gasoline powered car. The average carbon emissions of a gasoline powered car is 404 g/mile [30].

$$\textit{The total vehicle emissions for this process}, V_j = C_j * M_j = 1616\ gCO2 \quad \textit{Equation 4}$$

where,
C_j represents emissions of the vehicle per mile, and
M_j represents the number of miles travelled by the vehicle

$$\textit{Vehicle emissions per scooter per day}, D_j = V_j / S_j = 80.8\ gCO2 \quad \textit{Equation 5}$$

where,
S_j represents the number of scooters collected
Now, the vehicle emissions per scooter mile would be

$$P_j = D_j / N_i = 8.97\ gCO2 \quad \textit{Equation 6}$$

Therefore, the total lifetime emissions for an e-scooter with a lifespan of 90 days is

$$T_j = D_j * L_j = 7272\ gCO2 \quad \textit{Equation 7}$$

where,
L_j represents the total lifetime mileage
Similarly, the e-scooter emits 72,720 gCO2 in the worst scenario which is 10 times more carbon emissions than the best scenario. When comparing the lifetime emissions from using sustainable vehicles such as electric pickup vans and fuel cell vehicles, their average carbon output per mile – 200 and 276 gCO2 [31,32] was factored into the simulation process and compared.

3.5 Disposal
Returning to the GREET 2 (2021) model, the average disposal/recycling emissions per scooter come out to 3,592 gCO2e or 4.4 gCO2 per lifetime scooter mile. The production location for this stage does not matter as all e-scooters are assumed to be scrapped/recycled in the UK.

4. RESULTS AND DISCUSSION

In this section we discuss the results of the various simulations and scenarios. The base case here refers to the scenario with production in China and different methods for e-scooter collection and distribution. Case study 1 refers to production in the UK and case study 2 refers to production in Sweden.

4.1 Case study 1 – production in China

From Table 4, we see that manufacturing of aluminium is the highest contributor to GHG emissions. The primary aluminium production in China is overwhelmingly reliant on coal-fired electricity [33]. The total CO2 emissions from aluminium production in China in 2020 was 667 Mt. This was more than the total emissions from Indonesia across all the sectors. Therefore, coal-fired electricity makes aluminium an emissions intensive sector in China. The total emissions from aluminium for e-scooter production is 118,800 g which is 70.3% of the total emissions, followed by lithium-ion battery pack (17%), and electric motor (7.4%). The total emissions from manufacturing and assembling one e-scooter is 168.4 and 6.079 kgCO2.

A major problem with e-scooters is their relatively short lifespan. Electric vehicles need to have larger lifespans to offset the carbon emissions during production. Three likely lifespans of 90,135 and 180 days have been analysed where the scooters were considered to be collected with a gasoline powered car. Different e-scooter providers can understand from this study what the impact on carbon emissions would be based on their respective lifespans. For an e-scooter produced in China, having a lifespan of 90,135,180 and 365 days would emit 238.8, 165.2, 128.4 and 74 gCO2 per scooter mile (Figure 4). We observe that increasing the lifespan to 365 days reduces the emissions by more than 150 grams.

Table 4 illustrating the emissions arising from manufacturing different e-scooter components in China.

Material	Total lifetime emissions per scooter (gCO2)
Aluminium	118,800
Li-ion battery pack	28,600
Traction motor	12,480
Rubber tires	1072
Plastic	7446

Lastly, we take a look at the impact of using sustainable vehicles to collect the scooters for charging keeping the e-scooter lifetime as 90 days. In this section, it is obvious that the usage of electric vehicles would lead to lesser carbon emissions than gasoline powered or fuel cell vehicles. But the real question is by what magnitude does this method beat the rest of the field? Comparing the best scenarios – travelling 4 miles to collect 20 scooters, gasoline powered vehicles emit 7272 gCO2, electric vehicles emit 3600 gCO2 and fuel cell vehicles emit 4968 gCO2 over the course of the scooter's lifetime. This means that using electric vehicles for collecting 20 e-scooters reduces the emissions by 50%, while using fuel cell vehicles reduces the emissions by nearly 30% when compared to collection with gasoline powered vehicles.

The total emissions per lifetime mile of an e-scooter produced in China in the best scenario are 238.8, 234.3 and 236 gCO2 for gasoline powered, electric vehicles and fuel cell vehicles. Although these numbers are very similar, it is important to note that they represent values of one e-scooter and the benefits from using electric and fuel cell vehicles would be observed for a fleet of e-scooters as can be seen from Figure 5.

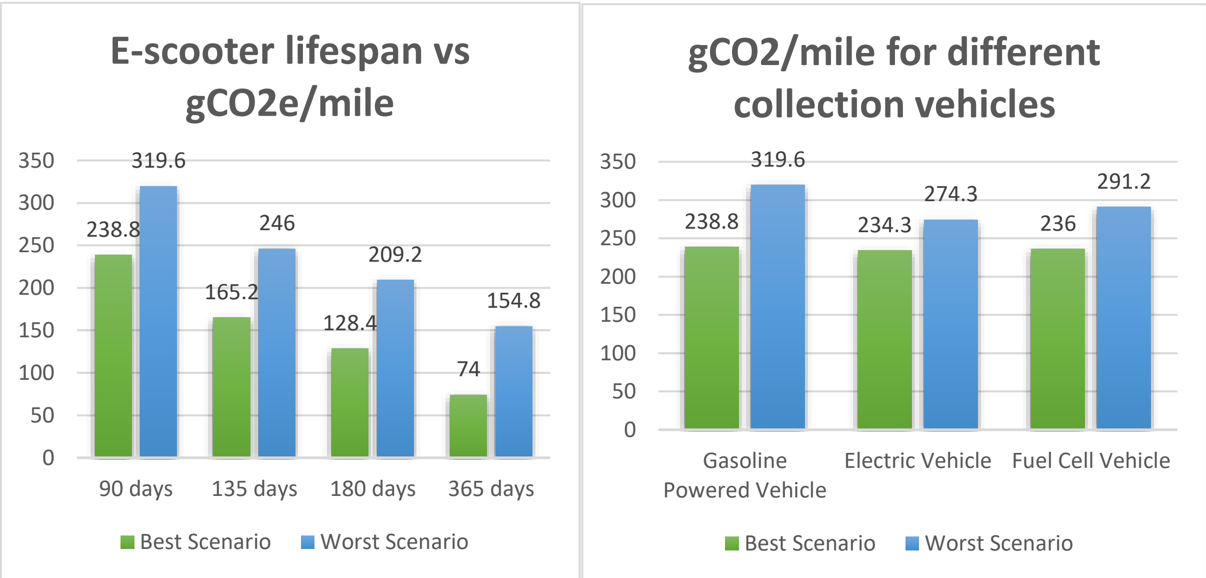

Figure 4: Left graph – Depicting carbon emissions from an e-scooter for a range of lifespans using a gasoline powered vehicle under the best scenario and Right graph – Depicting carbon emissions per mile based on different vehicles used for collection for a lifespan of 90 days.

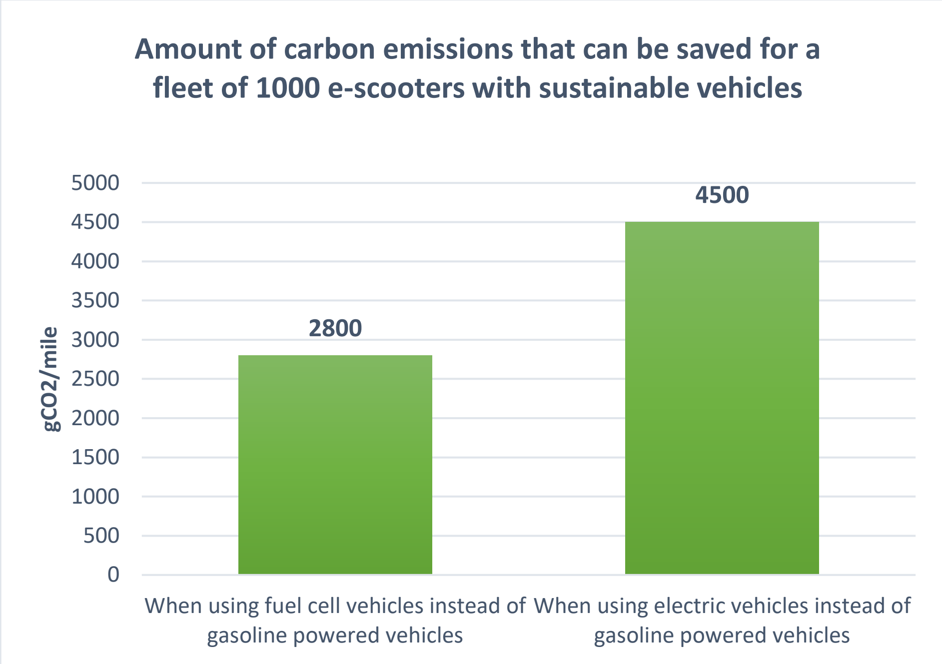

Figure 5 showing the saving per mile that can be achieved using sustainable vehicles for a fleet of e-scooters.

These results are in line with previous works in the same field as can be seen from figure 5. All the studies except for Moreau et. Al [34] were conducted either in Germany or U.S where the grid carbon emissions is more intense when compared to the UK. Still, our figures seem to be in the same range as these studies.

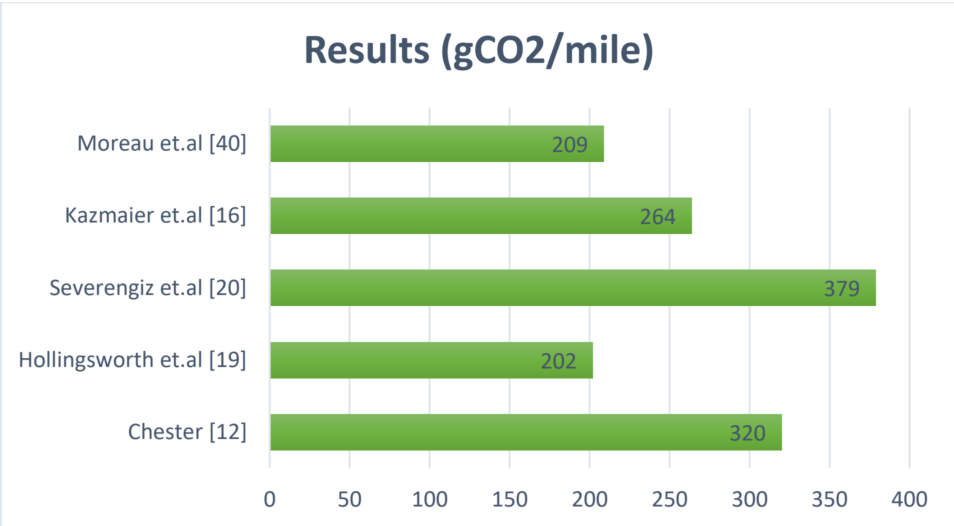

Figure 6: Comparing gCO2/mile emissions with previous studies.

4.2 Case study 2 – production in United Kingdom

The total emissions associated with manufacturing and assembly of an e-scooter in the United Kingdom is 81.8 kgCO2 and 2.365 kgCO2 (Table 5). Aluminium appears to be the major source of GHG emissions, and this is a common trait observed across all the 3 production locations. The emissions associated with aluminium amount to 67.7 kgCO2, a 43% reduction compared to production in China. Production of the li-ion battery and the electric motor emit 7.93 kgCO2 and 3 kgCO2 respectively. The production of plastics emits almost 3 times less carbon emissions when manufactured in the UK. The emissions from rubber were a meagre 476 g and again, a significant reduction from production in China. It is to be noted that about 16% of the UK's electricity supply in 2020 was from nuclear sources [35]. This factor was not considered in the study as this was beyond the scope of this work and could be analysed in future studies.

Table 5 illustrating the emissions arising from manufacturing different e-scooter components in the UK.

Material	Emissions per scooter (gCO2)
Aluminium	67,716
Li-ion battery pack	7,930
Traction motor	3080
Rubber tires	476
Plastic	2,619

Figure 6 demonstrates that for an e-scooter produced in the UK, using a gasoline powered car in the best scenario (travelling 4 miles to collect 20 scooters), lifespans of 90,135,180 and 365 days result in emissions outputs of 126.4, 90.3 and 72.2 and 44.8 gCO2/mile. As seen in the literature, the least emission output is for the highest lifespan. Under the same conditions, we observe a reduction of 45% in emissions on average when compared to an e-scooter produced in China for the same lifespans.
Lastly, using an electric van for collection and distribution results in a lifetime emissions per scooter mile of 121.9 gCO2 and 161.9 gCO2 in the best and worst scenarios. It's interesting to note that the figures for the worst scenario using EVs for a scooter produced in the UK still emits 77g lesser CO2/mile than the best scenario using EVs for a scooter produced in China. And using a fuel cell vehicle results in the emissions of 125.8 gCO2 and 183 gCO2 under the best and worst scenarios – an average reduction of 41.5% from the base case.

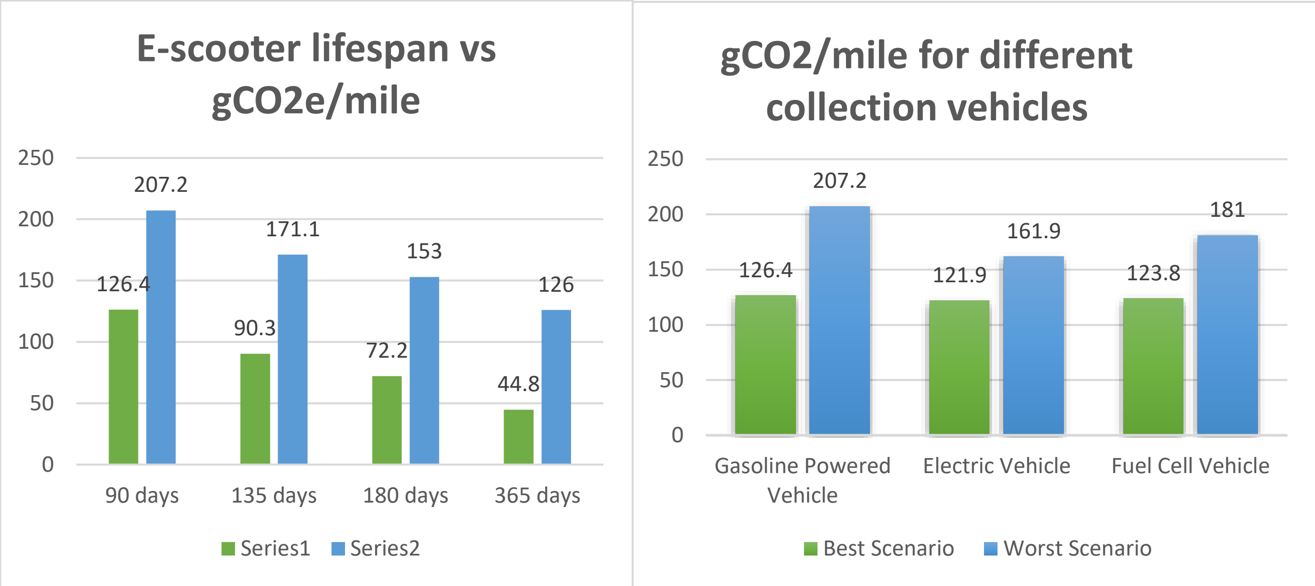

Figure 7: Left graph – Depicting carbon emissions from an e-scooter for a range of lifespans using a gasoline powered vehicle under the best scenario and Right graph – Depicting carbon emissions per mile based on different vehicles used for collection for a lifespan of 90 days.

4.3 Case study 3 – production in Sweden

NorthVolt – the battery manufacturer for Scania trucks in their statement declared that their lithium-ion batteries emit 10 kgCO2 per kWh, almost 5 times lesser when compared to Chinese, Europe and U.S manufacturers [36]. This can be seen in Table 6 where the emissions from battery pack production processes is almost 3.5 times lesser than when produced in the UK. Sweden has the least carbon emissions per kWh in the grid electricity – 0.012 kgCO2e/kWh (Table 3). This plays a huge role when it comes to production processes. The total carbon emissions from the e-scooter manufacturing process is 70.74 kg. A reduction of 15% emissions in the manufacturing phase can be achieved in Sweden when compared to the UK (81.8 kg). This is because the production of the electric motor and rubber tires together emit less than 200g CO2 which is a huge reduction compared to other production locations. Assembly in Sweden (118 gCO2) emits 95% lesser emissions than scooter assembly in UK (2365 gCO2).

Table 6 illustrating the emissions arising from manufacturing different e-scooter components in Sweden.

Material	Emissions per scooter (gCO2)
Aluminium	65,934
Li-ion battery pack	2750
Traction motor	149
Rubber tires	20.6
Plastic	1890

Varying the lifespan of the e-scooters has a similar effect to ones observed in base case and case study 1. For a lifespan of 90,135,180 and 365 days, using a gasoline powered car under the best scenario – travelling 4 miles to collect 20 scooters, the e-scooters emit 112.7, 81.8 66.4 and 42.9 gCO2/scooter mile. For a 90 day lifespan: e-scooters produced in Sweden emit 112.7 gCO2 – a drop in emissions by 12.2% compared with the same e-scooter produced in UK and a drop in emissions by 52% compared to an e-scooter produced in China under similar conditions.

Using Electric and Fuel cell vehicles to collect and distribute the e-scooters again shows signs of real promise. Considering a lifespan of 90 days, electric and fuel cell vehicles in the best scenario emit around 108.2 and 109.8 gCO2/ scooter mile. That being said, electric vehicles seem to be the best choice to collect and distribute e-scooters for charging, followed by fuel cell vehicles. Average reductions of 12.5% and 53% are observed when compared to similar scenarios for e-scooters produced in the UK and China.

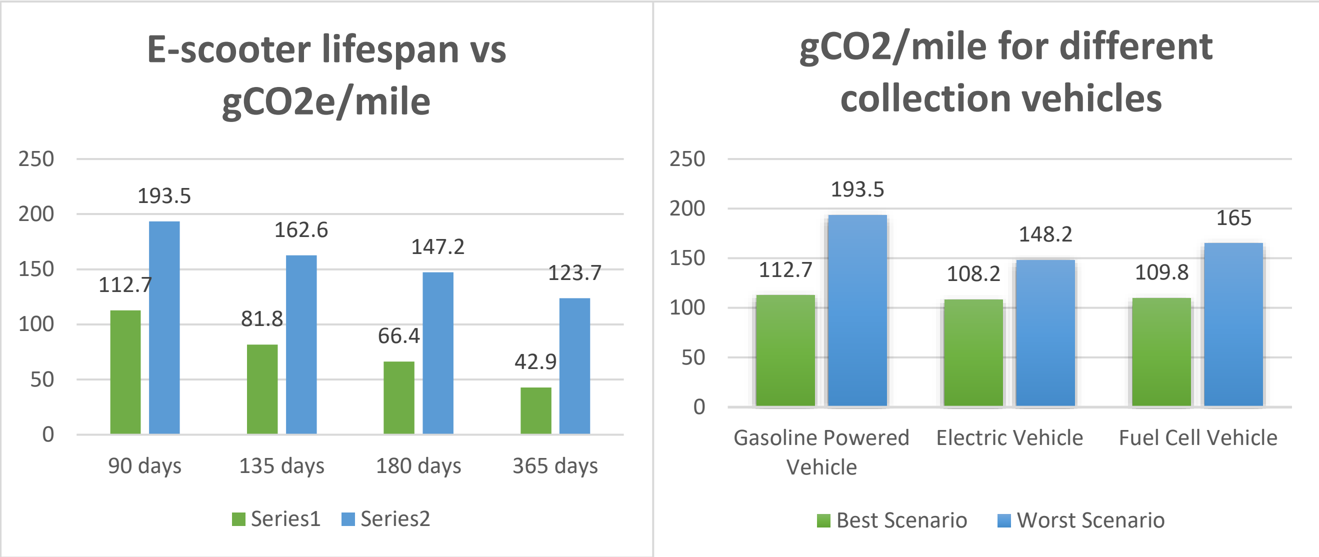

Figure 8: Left graph – Depicting carbon emissions from an e-scooter for a range of lifespans using a gasoline powered vehicle under the best scenario and Right graph – Depicting carbon emissions per mile based on different vehicles used for collection for a lifespan of 90 days.

4.4 COMPARISON WITH ALTERNATE MODES OF TRANSPORT AND RENEWABLE GRID ELECTRICITY MIX

In this section, we compare the results of e-scooters produced in European locations with other modes of transport. A lifespan of 90 days is considered for the best scenario and the collection and distribution process is performed in an electric vehicle which seems to be the best choice going by the results obtained. We see from Figure 8 that e-scooters produced in China have higher emissions than an average mid-sized electric car. The scooters produced in UK and Sweden however have lower emissions than a public bus in the UK but still higher than trains, e-bikes, and bicycles. An increase in lifespan will help scooters produced in these countries emit lower CO2 emissions than public UK trains which would definitely be a dream scenario. Thus, this shows that the fundamental idea behind e-scooters in sharing services – to replace short distance car journeys with e-scooters, is possible with production in Sweden, UK and maybe even other European countries.

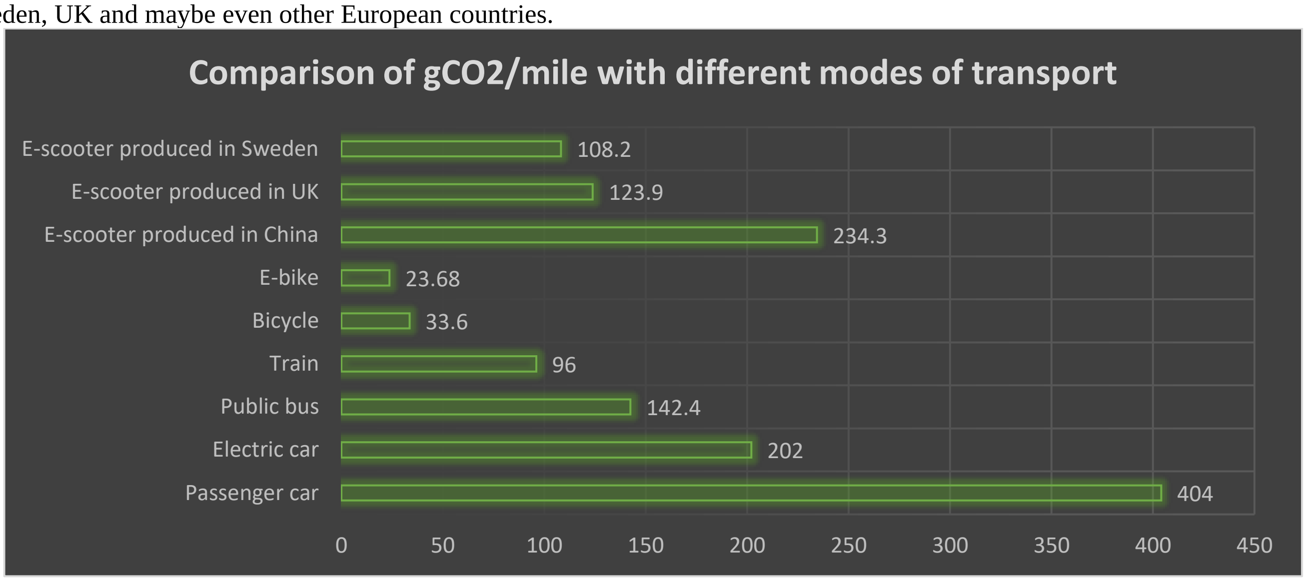

Figure 9 comparing the per mile emissions of the e-scooters from different production locations with other modes of transport – refer to sources [37] for figures on e-bikes and bicycles, [38] for figures on public buses and trains in the UK and [31],[30] for figures on electric and passenger cars.

The UK's electricity grid is getting greener with every passing year. About 24% of the UK's grid electricity in 2020 was powered by wind turbines [39]. It would be interesting to know how a fully wind powered electricity grid would pan out in the context of LCA of e-scooters. However, this scenario would not be possible until 2035 as the UK plans to establish 40GW of offshore wind capacity which would suffice 80% of UK's energy consumption [40]. Therefore, although it is possible to visualize the effects of a fully wind powered grid on the LCA of an e-scooter, the results would only give answers to e-scooter production in 2035 and would be futile as we are searching for answers right away. Hence, in this final section, we assume that the e-scooters use wind power purely for charging purposes and are not produced using wind power.

The literature for greenhouse gas emissions for wind power varies dramatically but the results of Weidmann et.al's calculations on wind power in coastal Germany offers the closest resemblance to offshore wind farms in the UK. Their comprehensive analysis shows carbon emissions of 45 gCO2/kWh for wind turbines considering different sizes, locations and mode of operation. This translates to a reduction of 65% carbon emissions per kWh from the currently grid intensity (0.2773 kgCO2/kWh). Again, we consider a lifespan of 90 days and an electric vehicle for the collection and distribution process. From Figure 9, we see that emissions decrease by 10g/mile for both the cases when compared to Figures 5 and 6. When produced in Sweden, the best scenario's emissions is only slightly above that for a public train in the UK at 98.8 gCO2/mile. These figures would no doubt be even lower if the entire lifecycle of the scooter was powered by wind electricity. Severengiz et.al observed a similar reduction when solar energy was simulated for charging purposes. A grid intensity of 0.08 kgCO2/kWh was considered for solar energy and reductions close to 20% was observed from the optimal scenario.

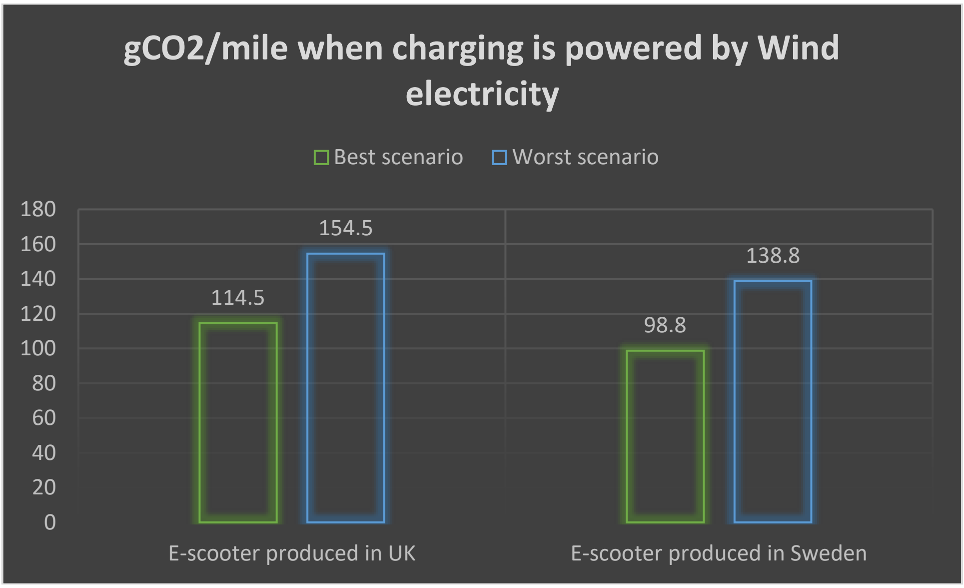

Figure 10 representing GHG emissions if e-scooters were charged using wind electricity.

The results were calculated for a charging scenario using 100% solar electricity and the results were surprisingly very similar. This is because solar electricity generation emits 38 gCO2/kWh which is very close to the numbers of wind electricity generation [42]. Nevertheless, when an e-scooter is charged strictly using solar electricity in the UK, it yields a reduction of 0.2% in GHG emissions compared to wind electricity making it the ideal scenario.

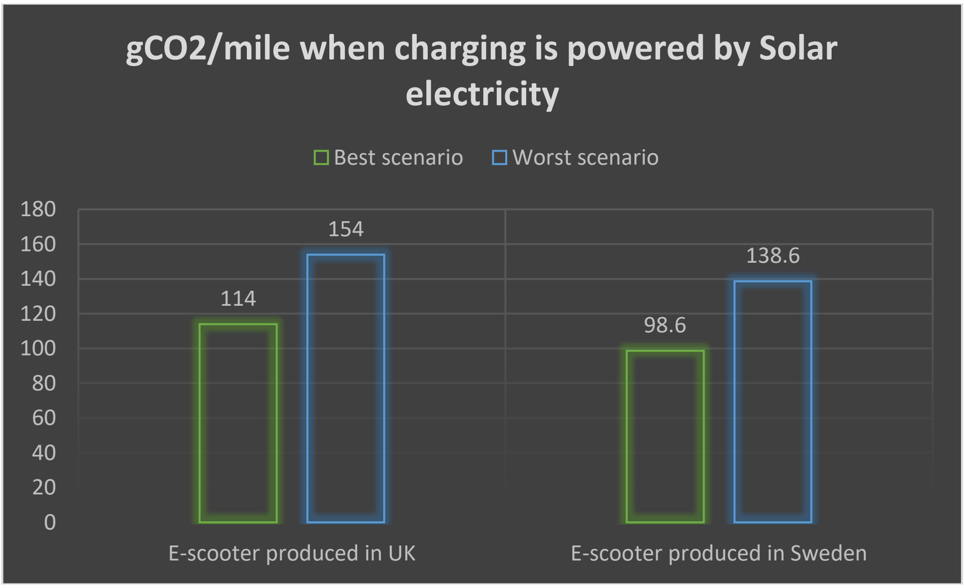

Figure 11 representing GHG emissions if e-scooters were charged using solar electricity.

4.5 HUMAN HEALTH IMPACTS

Emissions due to toxic gases from vehicles either during use or during production have continued to decrease year-on-year, owing to the contributions made to make transport greener and the environment healthier. But it is important to understand that the reason behind effecting such change is to ease the burden on human health. Nearly 5 million people die each year because of air pollution related diseases [43]. There is a large number of evidence that links vehicle pollutants to human health diseases such as respiratory problems and cardiopulmonary diseases. The main greenhouse gases from road transport that cause human health problems are Carbon di oxide (CO2), Methane (CH4), and nitrous oxide (N_2O). It is understood that CO2 affects human health even when exposed to very low levels causing problems such as inflammation, reduced cognitive performance, kidney and bone problems [44].
Combustion engine vehicles emit a very harmful substance called Particulate Matter ($PM_{2.5}$). These are very fine particles, about 1 or 2 microns in width emitted along with other harmful gases through the vehicle's exhaust. It has been found that these fine particles travel deep into the respiratory tract and lodge there worsening conditions such as Asthma and heart diseases. With electric vehicles,

there are no Particulate Matter emissions because of zero tailpipe emissions. According to Spengler et.al, reducing gas-powered vehicles with electric vehicles in cities could reduce air pollution dramatically.

It is predicted that electric vehicles will dominate the market only sometime after 2035. Until then, fossil fuel powered vehicles would be the popular choice. But what can be done during that time is the implementation of more 'last-mile' ride vehicles such as e-scooter sharing services. The number of e-scooters on the road will directly translate to a reduction in $PM_{2.5}$ and other harmful compounds. Perhaps the best example to display the positive health impacts of e-scooters is to compare the GHG emissions from an e-scooter and a gasoline powered car for an average journey in the UK. 50% of car journeys in the UK are under 2 miles [45]. From the above sections, emissions from an e-scooter produced in UK is 123 gCO2/mile and 404 gCO2/mile for an average gasoline powered vehicle [30]. For 2 miles, they would release 246 gCO2 and 808 gCO2 respectively. This stark difference in amount of CO2 emitted demonstrates that they might be extremely beneficial to human health in the long run.

5. CONCLUSION AND FUTURE WORK

E-scooters are a necessary solution to solve urban congestion and last mile problems. But what is perhaps more necessary is to understand the environmental impact of this new mode of transport. In this study, we compared the greenhouse gas emissions in terms of amount of CO2 emitted per mile for e-scooters produced in China, United Kingdom and Sweden considering a cradle-grave system boundary. We also compared impacts of collection and distribution for charging using more eco-friendly methods such as electric and fuel cell vehicles under 2 scenarios – best and worst. The results dictated a resounding drop in manufacturing emissions by 41% for e-scooters produced in UK and 58% for e-scooters produced in Sweden compared to an e-scooter produced in China. This is attributed to the production of electricity predominantly using coal-powered plants in China which results in a higher carbon emissions per kWh. Also, the main hindrance for e-scooters in sharing services is a short lifespan. A range of lifespans between 3-6 months were simulated in the model and for all the 3 case studies, we noticed an inversely proportional relationship between an e-scooter's lifespan and the greenhouse gas emissions i.e., emissions decreased with an increase in lifespan.

Electric vehicles seem to offer the best option in terms of sustainability for the e-scooter rebalancing process. Although electric vehicles and fuel cell vehicles emit 200 and 276 gCo2/mile, the difference in overall lifetime emissions per mile of the scooter always stayed within 2-3 gCO2/scooter mile. However, when the same figures are compared with a huge fleet of 50 or 100 scooters, the benefits of using electric vehicles can be seen clearly. The two scenarios in question - best and worst represent the collection process in urban and sub-urban areas. A combination of the best scenario (travelling 4 miles to collect 20 scooters) and an electric vehicle without a doubt offers the best reduction in emissions. The worst scenario (travelling 10 miles for 5 scooters) can be used in future works as a threshold and as a general idea to researchers on what the range of emissions from the collection and distribution process could be.
Overall, considering a lifespan of 90 days in the best scenario, and using an electric vehicle for the distribution process,

1. E-scooters produced in China emit between 234 and 274gCO2/scooter mile,
2. E-scooters produced in UK emit between 122 and 162 gCO2/scooter mile, and
3. E-scooters produced in Sweden emit between 108 and 148gCO2/scooter mile.

Production in Sweden therefore offers the best reduction in lifetime emissions even with emissions due to transportation from Sweden to London. But the transportation emissions were negligible and also, the grid carbon intensity is so low that it is able to offset the emissions from transportation comfortably. Finally, we observed that e-scooters manufactured in UK and Sweden emit lesser emissions than gasoline cars, electric cars and even public buses in the UK thereby giving e-scooters in sharing services a real advantage. The whole idea of an e-scooter sharing system is to give people the option of a sustainable form of transport. If production is established at scale across Europe, this would be a viable option to reduce the carbon footprint by a huge margin. We also looked at e-scooters charged using wind and energy which offered the best emissions output by far at 98.6 gCO2/mile. This could be promoted by charging the e-scooters during peak renewable energy production and by collaborating with electricity operators to supply renewable energy to a specific charging depot.

Another idea is to transport the e-scooters from Stockholm to London via ferries. This is because there is no direct rail that links the two cities and emissions associated with unloading and loading the cargo at 4 different locations (Stockholm, Copenhagen, Brussels and London), together with the rail emissions might be much higher than transport by ferries. Using recycled aluminium consumes 90% less energy than primary aluminium and widespread use of recycled aluminium would certainly reduce the environmental impacts even if produced in China. The likes of TIER and VOI have already started to equip their fleet of e-scooters with swappable batteries. What this does is indirectly increase the number of e-scooters that can be collected, thereby increasing the ratio of distance travelled by a vehicle to pick up e-scooters to the number of e-scooters picked up. But perhaps what will help the cause of LCA even more is if the lifespan of e-scooters in sharing services is able to increase. The university of Warwick is conducting a project that aims to increase the lifespan from 3 months to 3 years [39]. This would be a significant improvement and would put the overall emissions of e-scooters in direct competition with bicycles and e-bikes.

Future work in this field could include :

- Conducting a techno economic analysis on potential e-scooter production locations in Europe and the UK to identify production sites, and to conduct an LCA and economic analysis in setting up such sites.
- A complete lifecycle analysis on the vehicles used for the collection and distribution process.
- Analyzing impact of using recycled aluminium and other renewable energy sources such as solar for charging.
- Lastly, a research on alternative materials that can be used to improve the reliability and durability of e-scooters in sharing systems.

6.ABBREVIATIONS

a) GHG – Green House Gases
b) EV – Electric Vehicles
c) LCA – Lifecycle Analysis
d) CO2 – Carbon di oxide
e) kWh – kilo watt hour
f) t-km – ton-km

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