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Life cycle analysis of bike sharing systems: A case study of Washington D.C.

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ABSTRACT

In the past few years, shared bicycles have become a major form of green transport. There are two types of shared bicycle systems: pile-based and pile-less. These two types of systems have different carbon emission profiles when it comes to manufacture, operation and maintenance, and disposal. This research explicates these trade-offs through a thorough life cycle assessment of Capital Bikes' shared bikes in Washington D.C., USA. Our research indicates that while the installation of platforms and docks is the primary source of carbon emissions for dockless bikes, fleet management and maintenance are the primary sources of emissions for these vehicles. This is significant because the literature has shown that both dockless bikes and piling systems boost the resilience of transportation networks during pandemics or transport outages, albeit in different ways, when consumers may choose to utilize dockless bikes for exercise or to avoid using public transport. Planners should encourage proactive maintenance and fleet management to boost environmental advantages, as manufacturing operations generate five times as much carbon emissions as disposal activities. This study contrasted the Total Normal Environmental Impact (TNEI) of a dockless system with that of a piling system in our case study. The manufacturing process of a shared bicycle produces the largest amount of carbon emissions. The carbon dioxide emissions saved by a bicycle are about 0.07 kg per day. We also demonstrate that a net decrease in emissions in the Capital Bikes case study requires that each bike be utilized for a minimum of 591 days. In order to guarantee that the carbon emissions produced by shared bicycles are optimised, travelers should be incentivized to ride for longer and firms should strive to extend the usable life of their equipment.

1. Introduction

Rapid urbanization over the past two decades has placed considerable strain on urban transportation networks, markedly increasing levels of congestion and pollution (Liu and Su, 2021; Elgendy and Abaza, 2020; Gokasar and Karaman, 2023). The transportation sector's rapid development has required massive resource consumption and generated significant carbon emissions, as both the construction and operation of transport networks are energy-intensive with adverse environmental impacts (Caulfield et al., 2017). However, not all transport modes contribute equally to the problem. Automobile trips powered by fossil fuels (diesel, petrol) contribute to both air pollution and greenhouse gas emissions; substitution with alternative forms of transport, especially bicycles, makes a significant reduction to carbon dioxide emissions and air pollutants that are released into the environment, while also promoting a healthier lifestyle (Henriksson et al., 2022). It was against this backdrop that the advent of commercially viable shared bicycling systems in the mid-2010s enjoyed the rapid embrace of both planning authorities and the general public (Faghih-Imani and Eluru, 2014; Faghih-Imani and Eluru, 2016).

Comparing shared bicycles to private automobiles, however, represents two extremes of within the transport mix, as most urban systems offer public transport options that are suitable for commuting and recreational use. Studies comparing the carbon emissions associated with public buses with those of shared bicycle systems also found in favor of shared bicycles as producing significantly less emission of greenhouse gases (Zheng et al, 2021a). Quantifying the extent of the contribution of bike sharing, as well as other sharing economy ventures, to urban sustainability, however, requires rigorous empirical studies which employ life-cycle assessment to consider not only the carbon footprint but also the embodied carbon in bike sharing enterprises, as well as alternative transport forms (Mi and Coffman, 2019; Tukker, 2000). Over the past

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few years, a large literature has emerged considering employing a variety of LCA tools to quantify greenhouse gas emissions of both piling and dockless bike sharing systems (Coelho and Almeida, 2015; Luo et al., 2019; Mao et al., 2021; Cheng et al., 2022). Perhaps one of the most surprising findings, counter-intuitive to many, is that the greatest shares of lifecycle greenhouse gas emissions for dockless bikes occur during the operational phase, largely as the result of fleet operations (redistributing bicycles or recovering them) and maintenance (Mao et al., 2021). Other scholars have recommended extensions that offer rigorous comparisons of the value-added from technology improvements and product updates versus those involved in the premature disposal of retired bicycles (Bonilla-Alicea et al., 2020; Sun et al., 2023). Recent studies have taken a more nuanced approach to understanding the options available in the final stage, comparing recycling, burning, and disposal in landfills (Zhu and Lu, 2023), though many of the details of these methods vary by locality.

Meanwhile, using a variety of methodological approaches, both qualitative and quantitative, these investigations were widened to consider co-benefits of bike sharing such as air pollution reduction, or contribution to the resilience of transport networks to planned and unplanned outages (Cheng et al., 2021) and pandemics (Jobe and Griffin, 2021; Chen et al., 2022; Kim and Cho, 2022). When roads in a metropolitan area are blocked to traffic, Bi et al. (2022) discovered that shared bicycles may be a useful supplemental means of transportation. Planners can do this by giving careful thought to the allocation and relocation of subway stations, shared bicycle stops, and their capacity and utilization. This should make urban transit networks more resilient while maintaining activity uniformity. Despite an increase in average travel length (from 13 min to 15 min) and lower decreases in patronage (71% vs 90% ridership, 50% ridership ratio), the BSS is more robust than the metro system. It takes 19 min one trip (Teixeira and Lopes, 2020). Two highly cited studies (Cheng et al., 2021; Chen et al., 2022) use Capital Bikes data, but neither of them considers questions of environmental efficiency.

Research conducted during the pandemic often combined LCA analysis with operations research to understand not only the optimal transport mix, but also how the architecture of urban transport networks could maximize efficiency gains and improve overall transport network resilience (García-Palomares et al., 2012; Hu et al., 2021). Integrating subway/rail, bus, and shared-bicycle systems emerged as the best approach, where possible, to encourage low-carbon development while respecting commuter choices (Tamakloe et al., 2021; Zhang et al., 2021a, 2021b; Tavassoli and Tamannaei, 2020). These studies generally all made use of the 'smart feature' of BSS, that is that the systems record GPS data, which can be used to investigate where rides start and end, often the routes taken, and duration of rides.

Our study aims to draw together recent innovations in LCA, in order to compare dockless and piling systems more rigorously, and to provide a single measure that estimates how long a shared bicycle should be used to compensate for the carbon emissions produced during the production, operation, and eventual disposal of the asset. Such a measure is needed to help planners make better understand the trade-offs involved in step-scale expansions of the use of shared bicycle systems within a wider transport mix and with technology upgrades that entail replacing bicycle stock, so that environmental efficiency does not come at the expense of resilience, or vice-versa. This, in turn, fits within the New Urban Agenda's wider strategy to cast cities and their networks as enablers of sustainable societies, by promoting strategic planning objectives such as energy and resource efficiency, urban resilience, the growth of smart cities, and better urban governance, while recognizing that realizing these aims requires recognizing the trade-offs embedded in them (Coffman and Mi, 2024).

2. Methodology

2.1. Data collection and case study

Life cycle analysis is used to analyze the effect of the various factors and major attributes that drive energy consumption in bike sharing and to refine our model for the accounting of carbon emissions over the whole life cycle of the shared bike system. The data for this study on bike sharing systems came from Capital Bike, a company operating in the metropolitan region of Washington, DC. Through analysis of the primary data, we discovered that there is a correlation between the time of year and the total number of bicycles available for shared use. For instance, the vast majority of commuters would rather use BSS during the warmer months of the year (Fig. 1). This computation considers total number of bike trips that were shared between the years 2018 and 2021. Each data point has a bike trace, along with a unique cycle ID, start and end timings expressed in seconds, longitude and latitude coordinates, and trip length stated in meters.

The following procedures were carried out so that the raw data could be cleaned up and made ready for use. When a journey does not have a final destination, we refer to the place at which the journey begins or ends as the O/D location. Trips fewer than ten seconds, or shorter than ten meters were not regarded as legitimate. The great majority of the erroneously entered data had a trip duration or distance of zero seconds or zero meters, while just a small number of trips (0.01%) had recorded trip durations (or lengths) greater than 0 but below 10 s (or 10 m).

A shared bike goes through three phases in its life cycle: the phase of manufacture, the phase of operation and maintenance, and the phase of disposal. The terms 'production,' 'operation,' and 'disposal' refer, respectively, to the three components that make up each phase in the process. The maker of the bicycle is the best source of information on the amount of energy and materials that were used during the manufacturing process. As proof of concept, researchers were able to construct a roadworthy shared bicycle in its whole by purchasing from Maruishi all of the essential components; in addition to the lightweight materials of steel, aluminum, and plastic, as well as other materials, each bike weighed 25 kg (Gu et al., 2019). The production of a single automobile requires 0.85 cubic meters of natural gas, 0.37 kW-hours of electricity, and 0.001 cubic meters of water in the manufacturing process.

As the frequency of use increases, so does the number of shared maintenance windows, particularly the replacement of bicycle components, which is an important component of LCA for the maintenance phase. In some instances, the primary structure of the bicycle will also be recycled, rather than merely replacing component parts (Francart et al., 2021). On average, after the seventh repair, the bicycle is often beyond repair. Statistics for the amount of energy used during the disposal process were derived from the relevant IPCC guidance (IPCC, 2006).

Recovery incineration and spontaneous degradation are the two methods that are involved in the disposal process. In the scenario of recycling incineration, the non-recyclable parts of shared bikes are incinerated as municipal garbage while the recyclable parts of the bikes are recycled. The majority of the recyclable components of a bicycle are the frames; thus, the majority of the municipal solid waste (MSW) is found outside of the frame, and it is composed of 1.45 kg of rubber and 1.105 kg of plastic (Table 1). At the stage of disposal, the average distance travelled by each bike during transit is four kilometers. In natural degradation, the shared bicycles are disposed of in a landfill without any attempt being made to reclaim or disassemble them. The majority of Capital Bikes' retired shared bicycles are disposed of throughout undeveloped landfills outside of the city.

The coordinates, in both longitude and latitude, of each Capital Bike located in a specific place. We collected these the data, and performed the investigations required to arrive at an estimate of the normal daily riding distance and the amount of time spent on a bike with the assistance of the Application Programming Interface for Maps. According to

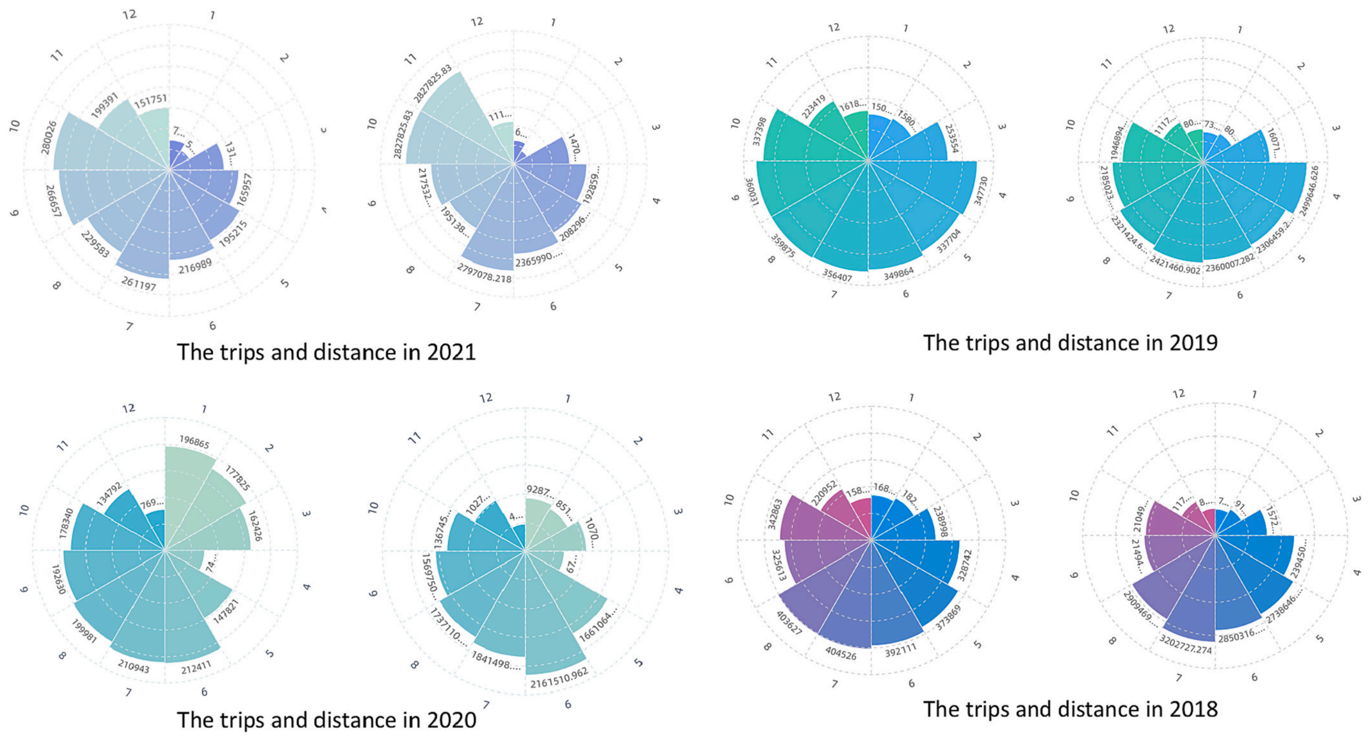


Fig. 1. The trips and distance from 2018 to 2021 (unit: km).

Table 1
Key parameters and fundamental values of Life cycle carbon emissions.

Stage of the Life Cycle	Energy Consumption	Weight	Unit	Carbon emission factor	Unit
Bicycle production	Natural gas	0.850	m^3	2.000	$kgCO_2/m^3$
	Electricity	0.370	kwh	0.703	$kgCO_2$/kwh
	Water	0.001	m^3	0.911	$kgCO_2/m^3$
Solid waste incineration	Rubber	1.450	kg	0.470	$kgCH_4$/kg
	Plastic	1.105	kg	1.105	$kgCH_4$/kg

Castro et al. (2019) on average, 9.8%, 50.8%, 32.1%, and 7.3% of the users of Shared bikes ride for less than 10 min, for 10–30 min, for 30–60 min, and for more than 60 min, respectively. These percentages are based on the length of time that riders spent on their rides. According to the data, an average ride for a cyclist lasts for a duration of thirty minutes. Despite this, there are riders whose total time on the clock is fewer than ten minutes, and there are others whose total time on the clock is more than sixty minutes. Even though the average distance travelled by bike sharing users is just 0.356 km, the local population appears not to drive their own bicycles alongside using the bike sharing system. We collected ride data to determine the average travel duration. The usual distance travelled in a single day using a shared bike is 0.356 km, and the average number of times a shared bike is used in a single day is 4.552.

The Capital Bike Sharing company in the city of Washington is the primary focus of the research presented in this article. The key parameters that will be used in the computation are determined by looking back at previous methods. These fundamental values will be used in the analysis. After this, the last three stages of a shared bike's life cycle are accounted for carbon-wise. A cap has been set to safeguard carbon resources. Carbon emissions will be tracked using the Capital Bikeshare system during the phase where they build the shared bicycles.

2.2. Accounting method

As noted above, the development of a shared bike consists of four basic steps: the fabrication of the raw materials, the processing of those materials, frame spraying, and the assembly of the bike frame. The manufacture process of the raw materials has a significant impact on the amount of energy used during the whole life cycle.

The energy consumption of a vehicle is calculated as

$$N = \begin{cases} \dfrac{d \bullet p_1 \bullet \rho_1}{\lambda_{e1} \bullet \lambda_{t1}} \\ \dfrac{d \bullet p_2 \bullet \rho_2}{\lambda_{e2} \bullet \lambda_{t2}} \end{cases} \tag{1}$$

N is the vehicle's energy output, d is the travel distance in kilometers, and L/km is the unit of measurement. Unit: litres per km and describes the amount of diesel used by the bus for its travel. It amounts to the quantity of petrol consumed by private vehicles as a function of the distance driven to and from work each day. We include the vehicle density of gasoline (in kilogrammes per litre) and the bus density of diesel oil (in kilogrammes per litre). Diesel oil's extraction and transportation efficiency are expressed above. One way to represent the effectiveness of petrol transportation is with the sign. The following formula is used to determine the emissions of CO_2 and NO_x, which are the primary focus of this study. E is the CO_2 and NO_2 emission factor, and it represents the emissions from the fuels used in vehicles, including gasoline and diesel (Chen et al., 2021).

$$E = \begin{cases} d \bullet p_1 \bullet \rho_1 \bullet f_i \\ d \bullet p_2 \bullet \rho_2 \bullet f_i \end{cases} \tag{2}$$

Using ISO 2050:2008, a standard for calculating the carbon emissions of different raw materials is achievable. ISO 2050:2008 is a standard for measuring the greenhouse gas emissions that a product generates throughout its life cycle. The following is the formula that should use while computing:

$$ME = \sum_{1}^{i} EC_i * EF_i \tag{3}$$

ME is a formula used to compute carbon emissions in the manufacturing process, where *EC* is the energy consumption of making bikes, and *EF* is the *i* th carbon emission factor of creating bikes. When it comes to operations procedures (*OP*), carbon emissions during maintenance are included into the equation.

Operations processes (*OP*) is a formula that represents carbon emissions during maintenance, and *MEj* denotes the maintenance probability of the *j*th parts.

$$OP = \sum_{1}^{j} EC_j * EF_j * ME_j \tag{4}$$

Recycling and stacking deterioration are the two most popular procedures for getting rid of shared bikes. As a result of the fact that the carbon emissions produced by a bicycle throughout its disposal stage are calculated depending on the actual disposal situation, this study has resulted in the development of two unique disposal scenarios.

Scenario 1: The first potential result takes into account the scenario in which non-recyclable parts of shared bikes are removed and disposed in the same manner as other forms of municipal solid waste (MSW). According to the findings of our research, the most recyclable parts of a bike are the frames; as a result, the municipal solid waste is mostly found outside of the frames. A calculation that takes into account of the emissions of greenhouse gases caused by the burning of municipal solid waste is used to determine how to dispose of the amount that cannot be recovered. The following formula is then used to ascertain carbon emissions:

$$DE_{S1} = \sum_{1}^{n} (MW_n * EF_n) \tag{5}$$

EF_n is the carbon emission factor of incinerating type *n* component of bicycle in the formula DE_{S1}. MW_n is the weight of municipal solid waste (kg) of type *n* component.

Scenario 2: Stacks of borrowed bikes are left to rot. The use of heavy equipment, such as cranes and tractors, should be accounted for while implementing this disposal approach. Different carbon emissions are computed for each section of the bike based on its material properties during the natural deterioration stage. Tires are a kind of macromolecule elastic material that is not melting or refractory. Tires will not harm soil or plant development for hundreds of years, while plastic portions are progressively photolyzed and other components are damaged by the recharge of nitrate in the soil. Green gas emissions will be created in significant concentrations in this procedure. In addition to CH_4, chemical oxygen demand (COD), and other pollutants, bicyclists are likely to create. Firstly, the quantity of the above pollutants discharged is determined; next the discharge duration is computed, and lastly the aforementioned emissions are tallied as carbon dioxide emissions. In this study, the calculating technique is as follows:

$$DE_{S2} = \sum_{1}^{m} (MW_m * EF_m) \tag{6}$$

An important measure of the rate at which something deteriorates over time is the natural degradation weighted time coefficient (*NDWT*). To make things easier to understand, we use the IPCC (2006) technique to calculate a final *NDWT* of 0.915. It is possible to compute the average time that Shared bikes' emissions have been in the atmosphere over the course of a century by using the calculation above. TE_{Si} is Carbon dioxide consumption in the whole life cycle

$$Time_{ET} = DE_{S2} * NDWT \tag{7}$$

$$TE_{Si} = ME + OP + DE_{Si} \tag{8}$$

If the bike sharing system comprises a substantial number of bikes in addition to a large number of stations and docks, the findings of the LCA will be affected in a different way (Liu et al., 2015). There were 30.5 million journeys taken on station-based bike-sharing systems in 2020, down 24% from 2019's total of 40 million rides. There were only 47 million rides on station-based systems in 2021, although that was 18% higher than it had been before the outbreak. Cities continued to invest in station-based systems thanks to strong cooperation with operators that kept devices available throughout the epidemic (NACTO, 2022). In a similar vein, the number of riders is increasing. This suggests that the environmental performance of a bike sharing system at the program level is reliant on the particulars of each scenario. This is because bike sharing system are designed to work together. Calculations were done to determine the number of stations per bike-kilometer, docks per bike-kilometer, and bikes per kilometer (km) that are required to service 1 bike-kilometer. This was done so that systems may be compared with one another. For the purpose of developing a base station-based scenario in the United States, the average values of eight station-based bike sharing system were used (Kou and Cai, 2019). Because of their high and low efficiency, respectively, the New York and Seattle bike sharing system were chosen as the best-case and worst-case scenarios for analyzing the environmental implications of various bike sharing system types. This was done in order to compare and contrast the various bike sharing system kinds. The compilation of the basic, best, and worst examples for the dockless system was accomplished using the same manner. An individual set of operating parameters was generated for each of our many test scenarios.

The conclusions of the LCA will be impacted in the event that the bike sharing system has a significant number of stations and docks in addition to a big number of bikes. The number of passengers is likewise growing. This indicates that the environmental performance of a bike sharing system at the program level is contingent on the particulars of each unique scenario. As a result, the number of stations per bike kilometer, docks per bike kilometer, and bikes per kilometer that are required to serve 1 bike kilometer has been established. This was done so that comparisons may be made across different transportation systems. The average values of eight station-based bike sharing system in the United States were used to construct a base station-based scenario (Kou and Cai, 2019). The same method of generating hypothetical scenarios was used to compile the 'base' example, 'best' example, and 'worst' example of the dockless system. It devised a unique configuration of operating parameters for every one of our test scenarios.

3. Results and discussion

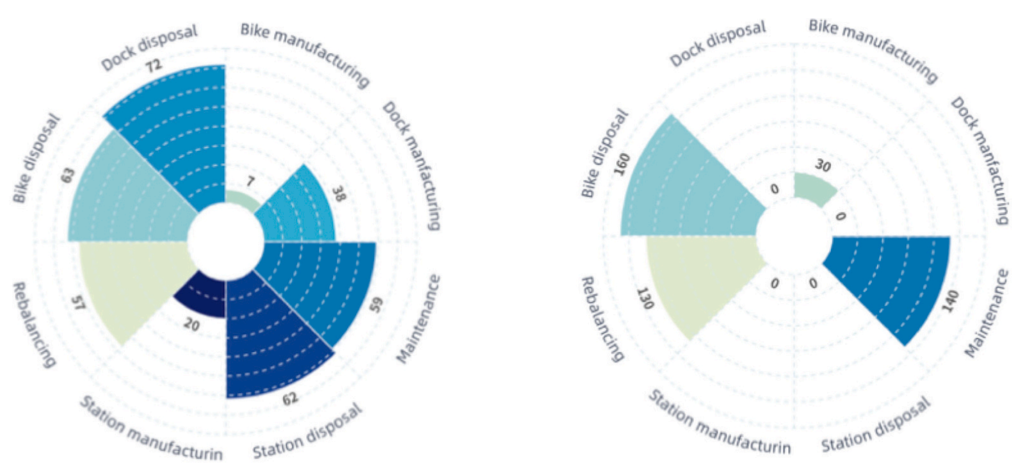
3.1. Greenhouse gas emissions

In this section, the preliminary findings of the LCA testing for docked and station-based bike sharing system are provided. The study does not take into account the switching between different modes of transportation that takes place while utilizing a bike sharing system. To examine the environmental ramifications of each system from two distinct vantage points: the emissions of greenhouse gases, and the total nuclear energy input that is required because to the restricted space. Both of these perspectives will be taken into consideration. In addition, we analyze the points at which the two bike sharing systems reach financial neutrality, as well as the levels of sensitivity shown by significant components, in order to determine the degree to which alterations in system design and operational methodology have an effect on the findings. This allows us to determine the extent to which changes in system design and operational methodology have an effect on the findings. The next item that to do is conduct an analysis of the ways in which the overall results of green gas emissions and total normalized environmental impact (TNEI) are affected by the different transportation mode substitution scenarios. The station-based system is responsible for producing 65 g of CO_2-equivalent emissions for every kilometer of bike riding in a typical scenario. It emits between 7 g (the best-case scenario) and 160 g (the worst-case scenario) of CO_2-equivalent for every bike-kilometer travelled, depending on the situation. When using a dockless bike system, a user will produce between 30 g and 140 g of CO_2-equivalent for every bike-kilometer to travel, with a base rate of 115 g CO_2-equivalent for every bike-kilometer travelled. This range is derived by the average CO_2-equivalent created per bike-kilometer. If the station-based system is not created and run successfully, it is possible that it will not be much more ecologically beneficial than the dockless alternative. The re-balancing of bicycles by transporting them by truck (fleet management) is responsible for 57 g CO_2-equivalent and 130 g CO_2-equivalent, respectively, of the total emissions of the combined emissions that are caused by the combined emissions. This is the driver that is responsible for the greatest amount of emissions of greenhouse gases (Fig. 3). To account for the unpredictability of the input data and to identify the primary contributors to the greenhouse gas emissions, we carried out a sensitivity analysis on the company's greenhouse gas emissions. This allowed us to identify the factors that are most responsible for these emissions.

Multiple challenges may arise when infrastructure is upgraded frequently, for example, because of a change in contractors, due to poor station maintenance, or because there are duplicate station locations (Chrisafis, 2018). It is likely that the impact dockless bikes have on rebalancing may be mitigated if they were distributed more evenly around the city. The quantity of CO_2 equivalent emissions created by cycling may range anywhere from 7 g to 160 g CO_2-equivalent grammes per kilometer, depending on the kind of terrain and the weather (ideal or worst-case). Dockless bike sharing program are quickly becoming more widespread in cities all over the globe, and will soon be the norm rather than the exception. The fact that dockless systems and station-based systems are so comparable gives support to the idea that dockless systems are better for the environment than station-based systems. The rebalancing of bicycles in vehicles is responsible for 36% of the emissions of greenhouse gases in autos, and 73% of the emissions in bicycle transportation systems overall. Unless significant efficiency gains in fleet management can be made, perhaps using green routes established for other logistics operations (Pamučar et al., 2016), a dockless bike system will have a greater demand for rebalancing than a typical docked bike system. Due to limited data, we calculate only the carbon emissions generated by maintaining different materials in this calculation. These results will be used to calculate carbon emissions from trucking for maintenance workers. In the baseline scenario, station-based systems are responsible for the emission of 65 g of CO_2-equivalent for every bicycle kilometer travelled (Fig. 2). When a distance of one kilometer is travelled by bicycle, it will produce between 26 g and 147 g of CO_2-equivalent (ideal and worst-case). With dockless bike systems, the lowest emission rate is 78 g CO_2-eq per bike-km, while the highest emission rate is 160 g CO_2-eq per bike-km. Dockless bike systems release an average of 118 g CO_2-eq per bike-km of emissions. It is very improbable that the station-based method will be less harmful to the environment than the dockless option due to the overlap between the two. Cycling inside automobiles is responsible for the majority (36%) and majority (73%) of all of the greenhouse gas emissions that are produced by these two systems, respectively. Because the weight distribution of each bike required constant adjustment, we anticipated that rebalancing would be necessary whenever more bicycles were added to the dockless system. Compare the total green gas emissions produced by a station-based and dock-free bike sharing system throughout the course of their life cycles, as well as by individual phases. The best and worst case scenarios for this emission rate are, respectively, 391 g CO_2-eq per bicycle (Station-based). For the system without docks, each bike may travel up to 456 g CO_2-eq.

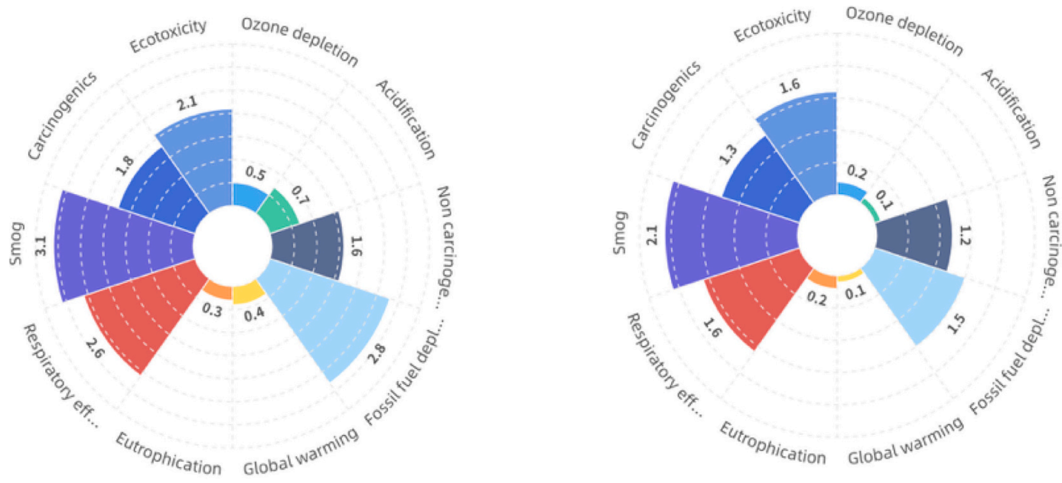
3.2. Total normalized environmental impact (TNEI)

It is feasible to compare the TNEI of one system to that of another system with a range of environmental consequences by normalizing and summing the effects from each of the numerous categories. Fig. 4 shows that the TNEI for the dockless system is 1.49E-04 unit/bike-km, which is 54% higher than the TNEI for the station-based system, which is 2.30E-04 unit/bike-km. This difference can be seen by comparing the two systems' TNEI values. When looking at the TNEI of the station-based system, the substances that cause cancer have the most significant impact on people's health. Smelting generates chromium VI, a powerful carcinogen that is the major source of carcinogenicity. Chromium VI is the principal cause of carcinogenicity. These procedures are carried out during the production of aluminum and steel respectively. When compared to the dockless bike sharing system, the production process for the stations (which use 38.5 kg of aluminum and 45.4 kg of steel per station) and docks (13.6 kg of aluminum and 67.8 kg of steel per dock) uses much more aluminum and steel than the dockless system. As can be seen in Fig. 4b, which can be accessed via this link, the TNEI is awarded advantages at each stage of its life cycle. Docks and stations in station-based systems account for 61% and 23%, respectively, of the overall environmental damage created by these facilities due to the emission of carcinogenic substances. This is the case since these facilities cause the



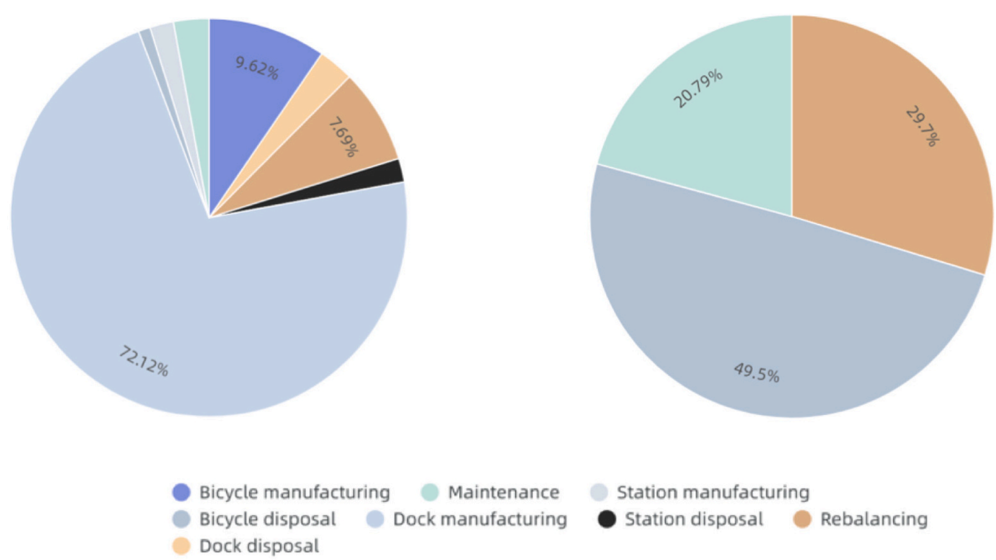
(a) Station-based (b) Dockless

Fig. 2. Life cycle greenhouse gas emissions (g CO_2-eq/ bike-km) of the station-based and dockless bike sharing system.



(a) Station-based (b) Dockless

Fig. 3. Total normalized environmental impact (TNEI).



(a) Station-based (b) Dockless

Fig. 4. Contributions to TNEI from different life cycle stages.

discharge of these compounds. The production of bicycles provides the vast majority of the total TNEI for the dockless system. This is owing to the fact that there is a significant need for this mode of transportation, which necessitates the production of bicycles so that there can be enough of them to meet demand. The solar panel and other electrical components that have been added to the dockless bike contribute to its TNEI impacts. During the rebalancing phase of the dockless system, the TNEI takes into account a variety of impact categories, including pollution, ozone depletion, SO_2, and others. This is equivalent to 39% of the whole sum. In the station-based system, the TNEI spans 6.71E-05 to 4.09E-04, but in the dockless system, it spans just 1.30E-03 to 2.16E-02. This is due to the fact that the TNEI value takes into consideration both the best-case scenario and the worst-case scenario simultaneously. Because of the overlap, it would seem that the station-based system would have a lower TNEI if the service could be provided with fewer docks and stations, although reducing the number of docks and stations near public transport hubs will reduce the contribution of BSS to urban transport resilience (Cheng et al., 2021). As a consequence of this, the design and operation of bike sharing system in various cities may provide conclusions that are in conflict with one another about whether kind of system, station-based or dockless, has a lower TNEI. Station-based bike sharing systems need much more aluminum and steel for the stations, manufacture, respectively, than dockless systems.

The manufacturing process, which includes the gathering of raw materials and their subsequent treatment, accounts for the bulk of shared bicycles' carbon footprint. This research estimates that a shared bicycle produces 34.56 kg of carbon dioxide annually (incineration after recycling). Its natural decay produces 40.12 kg of carbon dioxide. Energy use during manufacturing accounts for 63% of all carbon emissions from raw materials. So, the primary contributor to the greenhouse gas impact of shared bikes is the energy used to produce the bikes' components (Fig. 5). In a system without docks, the TNEI would be lower,

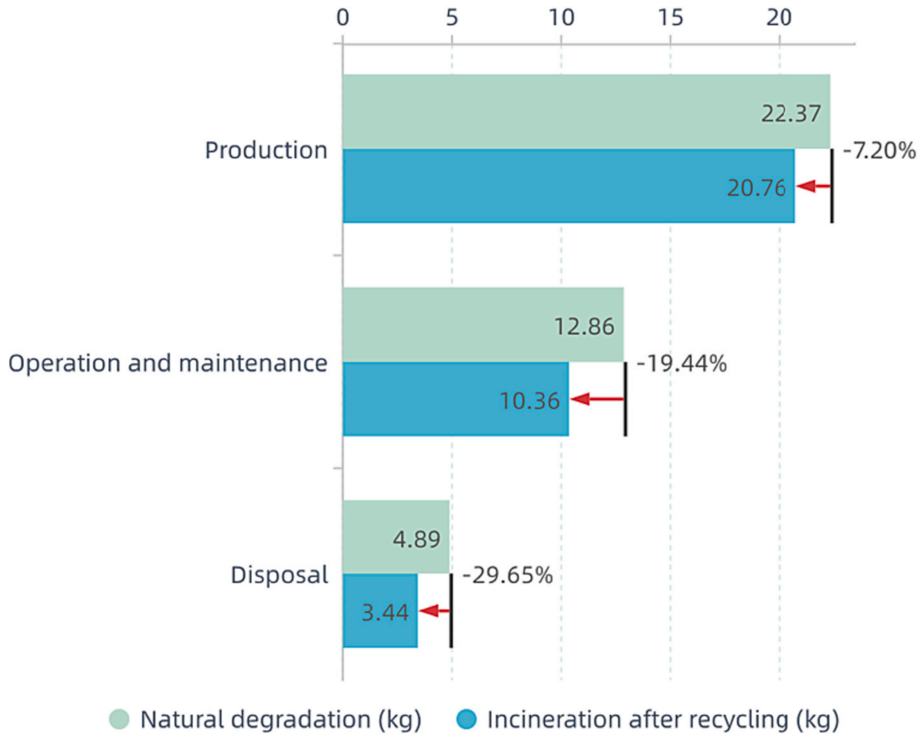


Fig. 5. The main contribution of shared bike carbon emissions is in the production stage.

but this would only be the case if the total number of docks could be reduced by 40 % without negatively impacting the quality of the service. It would be necessary to ensure that the design of the system include an impractically low number of unoccupied ports. In the event that the total number of journeys that are handled is expanded, the docking infrastructure needs to have a longer life expectancy. This will result in a reduction in the overall number of docks that are necessary since it will reduce the number of docks that are needed to service a certain amount of bike kilometers. There are trade-offs involved in the upgrading of dockless stations and repairs, versus replacement. It is possible that the shared infrastructure's estimated lifespan of 10 years might be extended to 15 years provided sufficient maintenance is performed on it. As can be shown in Fig. 5, the TNEI for the dockless system has the potential to be higher than that of the station-based systems in the event that it is determined that a greater number of bicycles are required than was first anticipated. This is due to the fact that dockless bikes are more susceptible to vandalism than station-based bikes. Because the operator will need to continue adding bicycles to fulfil demand, selecting a figure that suggests a bigger number of bicycles per bike kilometer is vital. This is because the operator will need to continue adding bicycles. The station-based system has a TNEI that is 52.6% greater than the dock-free system.

3.3. Different processing results

Landfills are responsible for a far higher level of carbon emissions than incinerators, which burn waste to generate power via the process of gasification. Even though recycling results in lower levels of carbon dioxide emissions than natural breakdown, it is still required before incineration can take place. Would the recycling of the steel from Capital Bikes' bicycle, which weighs 15.35 kg, be enough to reduce the amount of carbon dioxide that is produced by combustion? When organic matter breaks down, it releases greenhouse gases like carbon dioxide and methane into the atmosphere. These gases contribute to global warming. The warming potential of carbon is twenty-five times that of methane (Boucher et al., 2009). It has been estimated that the natural breakdown of a bicycle that has been shared would result in the production of 48.62 kg of carbon dioxide. The poisoning of water supplies and the deterioration of land are both made worse when natural resources are used up. This is a vicious cycle. It is estimated that the machinery used in the process of extracting methane would release 42.51 kg of carbon dioxide into the surrounding environment. In the United States, neither bio composting nor recycling the rubbish that is generated by landfills are now common practices. In addition, the typical use rate of shared bicycles is somewhere in the vicinity of 40 %. It is anticipated that riding a bicycle for transportation will result in the production around 45.56 $kgCO_2$ for the whole of the bicycle's life cycle. When garbage is burnt for energy generation rather than being buried in landfills, there is a 6.11 kg reduction in the amount of carbon dioxide that is released into the environment. In a landfill, it will take another 27 years before a bicycle has completely broken down into its component parts. Through calculation, it is known that an average bicycle is ridden for approximately 180 min every day. The carbon emissions saved by a bicycle per day are 0.07 kg. Therefore, the most current figures indicate that each bicycle would need to be used for at least 591 days before there would be a net decrease in emissions. This is the minimum amount of time required.

4. Conclusion

The purpose of this research was to assess the impact that station-based and dockless bike sharing systems have had on the environment in their respective locations in order to understand the trade-offs with urban resilience. Dockless bike sharing systems result in higher levels of greenhouse gas emissions compared to station-based systems. This is due, in part, to the fact that the balancing criteria for dockless systems are more stringent, which encourages better fleet management. Break-even points and sensitivity analyses of parameter values are both useful tools for assisting with this. Within every bike sharing system, the performance of greenhouse gas emissions is the most sensitive indication of whether or not rebalancing is required.

The results of a study conducted by TNEI comparing the two distinct systems indicate that station-based systems perform better than dockless systems do, which provides evidentiary support for their inclusion in the design of resilient urban transport networks. This remains the case despite the fact that dockless systems have become more popular in recent years, and were especially popular during the pandemic, where they added resilience to urban transport networks. With docked or piling systems, the majority of the extra environmental damage is generated by the downstream impacts of the manufacturing of port infrastructure, which includes the use of aluminum and steel components. This may be broken down into two categories: direct and indirect consequences. Among these downstream impacts are the emissions of cancer-causing chemicals that result from the processing of metals. In a dockless system, the biggest factors to the influence that the system has on the environment are the manufacturing of bicycles and the labor needed in rebalancing them. Experiments involving breakeven points and parameter sensitivity showed that the TNEI performance for both station-based and dockless systems is heavily influenced by the number of docks and bicycles required to satisfy a particular demand. This was the case irrespective of whether the systems relied on docking stations or operated station-free.

Second, TNEI analysis shows that the strategies for extending the service life of the stations and the usage rates of the bikes will be the most influential factors in determining whether the system should be station-based or dockless. Disparities have been observed between docked bicycles and dockless bicycles with regards to user requirements and travel paths. Bicycle lanes are often used for purposes such as commuting to work or educational institutions, engaging in recreational travel, and pursuing leisure activities. Hence, it is essential for urban planners to engage in a systematic and logical approach when designing bicycle infrastructure, including the allocation of pathways and parking facilities. Given proper funding by public authorities, increased preferential policies, including discounts, coupons, and tax rebates, can be employed by shared bicycle companies to encourage passengers to choose bike sharing over higher carbon transport modes. Firms can also incentivize riders to encourage proper handling of bicycle equipment, both when in use and when stored. The selection of dockless versus docked shared bicycles by cyclists is often influenced by the locations of their starting and ending places, thereby emphasizing the need of urban planning pertaining to docked bike stations. In order to promote urban resilience, effective urban design needs careful consideration of established transportation networks, particularly in relation to docked bicycles (Zhang et al., 2021a, 2021b). Furthermore, it may be necessary to implement governmental subsidies in order to help bike sharing firms internalize the positive externalities associated with urban resilience of both varieties of bike sharing systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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