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Environmental Impacts of Increased Circularity in Bicycle Sharing Service

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Abstract

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Disciplines

Environmental Sciences | Physical Sciences and Mathematics

Comments

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Spring 2022

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ABSTRACT

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Although bike-sharing services have gained tremendous popularity in China by presenting themselves as champions of sustainable urban transportation and an example of a sharing economy, the lack of a sufficient recycling and maintenance process has been pointed to as one of the main contributors to its environmental impact and has called the sustainability of bike-sharing into question. The adoption of a circular economic model for this service is proposed to remediate these impacts. This Life Cycle Assessment study will estimate the effects of a circular economy model adoption through increased recycling rates and recycling efficiency of bike-sharing services. The results find that increase in circularity of the bicycle sharing system does bring reduction to nearly all environmental impact categories; however, it is inconclusive if the rise in circularity brings an overall reduction in environmental impact. The current reduction is limited by existing recycled materials and environmental impacts caused by the recycling process. Further research is needed to confirm the finding in this study.

DEDICATION

I dedicate this work to my family, who have always supported and encouraged me to make a difference in this world

I dedicate this work to my professors, who have inspired me to pursue sustainability and the circular economy

A special thanks to Dr. Guozhu Mao, whose work laid the foundation of this research

I further dedicate this work to the millions of people out in the world who are trying to make this world better for others

Society thrives when we plant trees for our next generation to take shade under

There is always some good in the world that is worth fighting for

1 Introduction

Since 2016, dockless bike-sharing services have gained considerable popularity in China, offering new means of urban transportation that promote low-carbon and a healthy lifestyle. However, the actual sustainability of this service has been called into question. Starting in 2016, companies such as OFO pioneered bike-sharing services and were quickly followed by other companies such as Hallo Bikes and Mobikes. These dockless bike-sharing services marketed their services on convenience and sustainability. However, overproduction, poor management, and the initial lack of regulation have shown to the public that this kind of service can also be a source of nuisance and environmental hazard. It was not uncommon to have piles of bikes stacked on the street blocking pedestrians and abandoned in landfills and junkyards. Eventually, due to various reasons, such as improved logistics and improved governmental regulations and planning, the inconveniences caused by the bikes have been drastically reduced. However, the environmental impacts of bike-sharing services remain to be addressed.

In 2018, it was suggested that the circular economy model (CE), which attempts to achieve sustainability by closing the resource loop and increasing material usage to improve sustainability, should be applied to bike-sharing services (Dajian, 2018). This offers an interesting perspective and an opportunity to understand the benefit of a CE model's adoption to bike-sharing services and gain a better understanding of the relationships between the circular economy and the sharing economy represented by the bike-sharing service. Unlike the CE model, sharing economy (SE) attempts to improve sustainability by creating a market for exchanging the right to temporarily use under-utilized resources. Although past research has examined what impact bike-sharing services have and possible links and synergistic relationships between CE and SE (Chiappetta Jabbour et al., 2020; Henry et al., 2021; Mao et al., 2021), it is unclear how much the service can be improved through a circular economy. To answer this question, this research employs the use of LCA to estimate the potential environmental impacts of increased circularity through increased recycling rate and recycling efficiency within the bike-sharing system. The following section will be divided into four parts: Section 2 will provide a brief overview of CE and SE concepts and bicycle-sharing services in China. Section 3 will focus on LCA methodologies and Life Cycle Data. Section 4. will show the LCA results. And

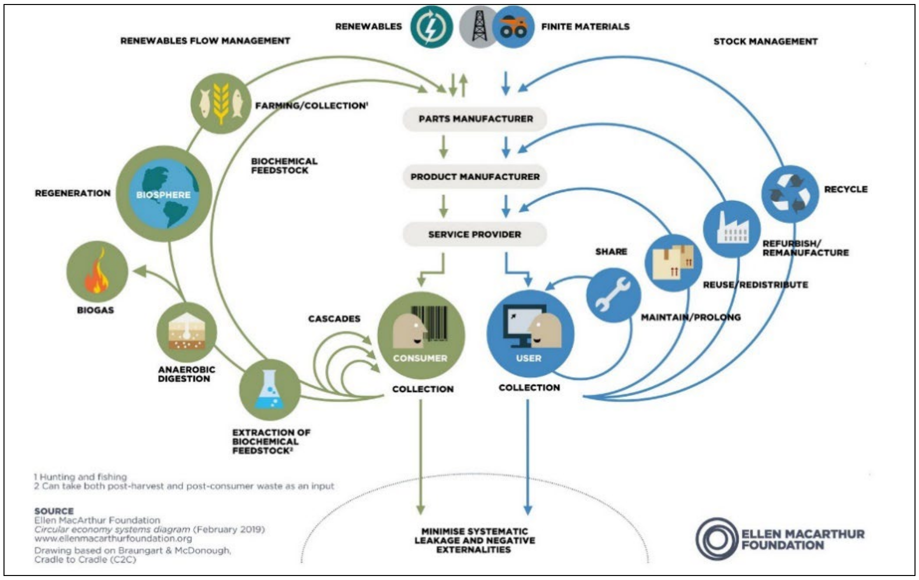
Section 5 will provide a discussion of results with potential policy and research recommendations.

2 Background Review

2.1 Circular Economy

The circular economy (CE) and sharing economy (SE) are concepts that capture the attention and interests in academia, business, and the realm of governmental policy, as both offer a pathway towards a sustainable development model for human society. CE can be generally defined as:

> "The creation of resource loops in a defined (economic) system according to the system's underlying biophysical roots to minimize waste and pollution or maximize resource utilization" (Henry et al., 2020).



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough, Cradle to Cradle (C2C)

Figure 1 The Circular Economy System Diagram. Source: Ellen MacArthur Foundation (2019)

However, the definition of CE can range from an increase in recycling to a systematic focus on *reuse and refurbishment* (Fig. 1). Among these variations, Kalmykova et al. (2017) found shared principles including stock optimization, eco-efficiency, waste prevention, and the achievements of the above goals through the "Reduce, Reuse, Recycle and Recover" principle. The root of the concept can be traced back to Boulding's (1966) publication of the Spaceship Earth and the acknowledgment of Earth as a "single spaceship, without unlimited reservoirs of anything, either for the extraction or for pollution." CE as a concept is widely popular among academic, business, and political spheres. According to Kalmykova et al., CE has been a major development focus in China since its early adoption in 2002 as a national development strategy. "The expectation was that this strategy would promote sustainable urban development in China and establish an equilibrium between the countryside and urban areas. In particular, waste elimination and reallocation of resources were regarded as good strategies for encouraging rural populations to remain in rural areas" (Kalmykova et al., 2017). Following its adoption as a development strategy, China has passed several governmental documents to promote the adoption of CE, including the *Law for the Promotion of the Circular Economy* (2008), *The Strategic Circular Economy Development and Short-term Action Plan* (2013), and *The Circular Development Leading Act* (2017). In fact, The Ellen MacArthur Foundation (2018) has published extensively on the circular economy development in China and praised the bike-sharing system as a demonstration of a circular and sustainable urban transportation model.

However, CE is not without its limitations. Geissdoerfer et al. (2017) pointed out that although CE is related to sustainable development, there are differences between these concepts. CE exhibits tendencies to create a hierarchical relationship between Economic, Environment, and Social aspects, rather the horizontal relationship of these aspects in sustainable development. CE also seems to be more focused on material flow, waste reduction, and emission output. Other limitations of this CE might include a lacking analysis of certain environmental impacts, such as biodiversity, and the social impact of CE is rarely touched upon. Of more concern is the CE rebound effect presented by Trevor Zink & Roland Geyer (2017), in which an increase in circularity may not displace the primary resource consumption and lead to an increase in environmental impact.

2.2 Sharing Economy

SE proposes to achieve sustainability through redistribution and market exchange for temporary access of under-utilized resources with aid from digital platforms. Compared to CE, SE is 20 years younger and only met wide academic interest between 2013 and 2015(Henry et al., 2021). It is believed that SE's predecessor was the idea of "collaborative consumption" proposed by Felson and Spaeth in 1978(Si et al.,2020). They believed that consumers demand the *use* of a product rather than the product itself; therefore, it is more sensible to rent and have temporary rather than permanent ownership. To realize the SE concept, a business model called product service system (PSS) was developed (Jabbour,2020). This PSS model calls for the integration of physical goods with intangible services and focuses on the sale of services rather than the sale of goods. An example of such a model will be the bike-sharing system, where the service of bicycle transportation was sold rather than the bicycle itself. Similar to CE, SE has also garnered excitement for its promise of reduced material consumption and promotion of sustainable development. For instance, Zhang & Mi (2018) calculated that the Shanghai Bike-share system presents positive environmental impacts by reducing CO2 and NOx emissions by 25000 tons and 64 tons in 2016. Meanwhile, Woodcock et al. (2014) found that bike-sharing services lead to a general increase in cycling activities, and over 10000 premature deaths can be avoided if EU cities reach 25% of all trips made by biking. Meanwhile, SE also presents its own challenges. For instance, there are concerns regarding how sharing economy platforms approach sustainability. According to Geissinger et al. (2019), there is only a limited amount of sharing economy platforms that actively refer to any type of sustainability-oriented business operations. And as we see in the example of the Chinese Bike-sharing model, there are companies that use the sustainability ideal of SE to disguise for-profit motivations and lead to a SE rebound effect.

2.3 Circular Economy & Sharing Economy relationships

The relationships between SE and CE are complex. According to Henry et al. (2021), SE and CE are both popular paradigms within the sustainable development framework; however, these two fields are not as interconnected as one might have thought. Less than one percent of the 4422 publications reviewed by Henry et al. overlap both SE and CE (Fig. 2). Furthermore, among the publications reviewed regarding China, all the literature is focused on CE, with a clear lack of study of SE implementation in the region. This shows a knowledge gap exists in the academic field regarding CE's and SE's potential synergistic relationship and combined impacts on product or service sustainability.

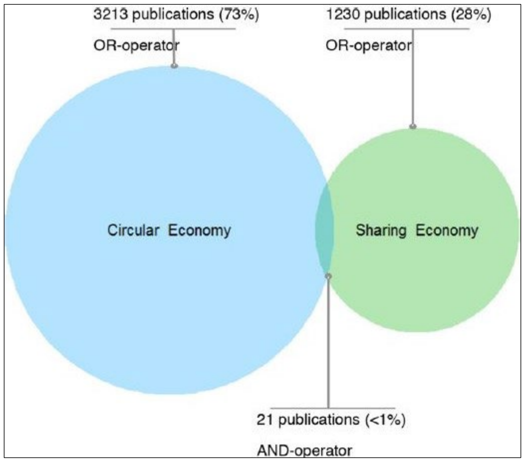


Figure 2 Literature bodies of CE and SE 1996-2018
Source: Henry et al, 2020

Despite this lack of interdisciplinary research, SE and CE are, in fact, intimately related. For instance, the sharing model of SE can be considered as a use-oriented subset system within the larger circular economic system (Henry et al.,2021; Jabbour et al.,2020). This sentiment is also present in the CE strategy database composed by Kalmykova et al. (2018), where sharing practices is listed as one of many CE strategies. Finally, research surrounding these two paradigms also have the potential to complement one another. As described by Henry et al. & Geissdoerfer et al., CE exhibits a tendency to prioritize environmental impact, material flow, waste reduction, and emission output while neglecting the social factors that also play a big role in sustainable development. Yet, social sustainability is often discussed in SE related literature. Similarly, the rebound effect is a topic not often examined within SE literature that is receiving increased attention in CE research. Therefore, there is ample space for SE and CE research to complement one other to investigate aspects that are lacking each paradigm.

2.4 Bicycle sharing services in China

Bike-sharing services have been demonstrated to provide considerable environmental benefits, as demonstrated by Zhang & Mi (2018) in terms of reduction in CO_2 and NO_x emissions and fossil fuel consumption. Using Beijing as an example, Sun & Ertz (2021) also show that the new dockless bicycles also provide a higher resource utilization rate and potential in resource conservation than the traditional station-based bike-share system.

However, these sustainability and resource conservation promises are hampered by the development history of the bike-sharing industry in China (Si et al.,2020; Ma et al., 2018; Reddick et al.,2020; Mao et al.,2021). China's first bike share system was started by the OFO bike-share company in Beijing in 2015. by June 2017, bike-sharing service users reached106 million, and the volume of shared bikes reached 16 million. In the same year, China's bike-sharing companies have put 23 million bikes into the market in total, covering 200 cities. This indicated that 7 million bikes were launched into the market in just five months. This increase in bike share volume was attributed to the huge growth in bike-share companies with the support in capital investment to nearly 70 enterprises in less than two years, with the largest two companies being OFO and Mobike. This growth period did not last. As the market got saturated, companies started to employ tactics, such as subsidies, to attract users to their platform. This started what is called a Subsidy War that lasted from 2017 to 2018. In this competitive mode, companies tried to grab market shares as quickly as possible by spending huge amounts of money to compensate for the cost of consumers so that users could ride the bikes at incredibly low prices or even for free at the beginning. It is only after beating most of the competitors in the industry that they started to raise the prices and run their business in a normal way. Consequently, those small bike-sharing enterprises with little capital support went broke and exited the competition in a very short time. Eventually, most of the previous 70 bike-sharing companies were shut down by the end of 2018. Apart from the use of subsidies, bicycle-sharing companies also tried to cut costs by deploying large quantities of cheaply produced bikes that are easily damaged and rarely maintained. Meanwhile, the large influence of investors that care more about short-term returns also disregarded long-term corporate sustainability responsibilities. Eventually, due to poor bicycle quality, lack of circular infrastructure, and the abandonment of bicycles that belongs to bankrupted companies, the bike share system eventually led to huge resource waste and the emergence of so-called "bicycle graveyards" (Fig.3). These unsustainable development patterns eventually led the Chinese government to change its initial favorable sentiment toward the bike share industry and began a period of industry regulation. In this post-subsidy war period, municipal governments like Shanghai start to impose policies that hope to regulate the market and foster a more sustainable market environment. Interestingly, it was in this regulatory period that the idea of the CE model adoption in the bike share industry was first proposed by academics. Yet, due to concerns over safety, the industrial bicycle association eventually disregarded these recommendations and insisted on a mandatory three-year replacement requirement. The increased government regulation proved to be very effective in cleaning up the streets occupied by bikes. Not all companies survived this period, as old companies like OFO eventually went bankrupt as they failed to pay off debt owned to customers and meet new regulatory standards. Mobike, the main rival of OFO, also faced its own difficulty and was eventually acquired by Meituan. Currently, the most successful bicycle-sharing company is Hellobike, which survived the subsidy war and the market regulation by improving its own user experiences and expanding to become an all-encompassing travel service provider.

Figure 3 Discarded bikes Source: Tencent Technology net, 2018

3 Methodologies

To study the impact of improved circularity rates of bike-sharing services, a comparative cradle to cradle LCA study method will be employed, and the same product system will be analyzed through multiple scenarios with different recycling rates. It is expected that the increase of the circularity rate will lead to a drastic reduction in all environmental categories.

Since this is a comparative LCA, the study will follow the guidelines and methodologies outlined by ISO 14040. According to the definition given by ISO guidelines, LCA consists of four phases, including Goal and Scope Definition, Life Cycle Inventory, Impact Assessment, and Results Interpretation. The Goal and Scope Definition step will involve outlining the direction of the research, the extent of the modeled system, and the definition of the functional unit. This is followed by Inventory Analysis, where the data collection and material flow calculation are performed. Impact Assessment will then characterize these material flows into impact categories and calculate the midpoint impact of those categories. The results will be interpreted to generate conclusions and possible suggestions. These steps will be performed, and any changes, limitations, and assumptions made during the LCA study will be documented. Furthermore, different recycling rates will be modeled to gauge their impacts.

3.1 Goal and Scope Definition

The goal of this LCA study is to determine how the increase of recycling and reuse rate (Circularity Rates) will affect the environmental impact of the addition of 75000 shared bicycles in Shenzhen, China, in 2020 (Shenzhen News, 2020).

The full life cycle will cover Raw Material Extraction, Supply Chain (Material Processing), Primary & Secondary Manufacturing, and End-of-Life Treatment. Some life cycle stages such as transportation and Maintenance and Use are excluded from this analysis for various reasons. Transportation is excluded because 1. identifying different bike parts from production location to assembly is difficult and there is a lack of data and 2. transportation of bikes caused by bike redistribution has a very limited effect on the environmental impact caused by changes in circularity rates, and thus is not relevant to the goal of this study. Although Maintenance and Use do have noticeable impacts on a bicycle's life span and are relevant to the circularity of a bicycle, these stages are excluded because the environmental damage resulting from the use of a bicycle is assumed to be minuscule, and the data surrounding the maintenance of bicycles such as the actual ride usage data and damage rate in Shenzhen are not available.

3.2 Functional Unit, System Boundary,

The Functional unit of this study is set to be one bicycle fleet that consists of 75000 bikes with a service period of 3 years. There are many different bicycle-sharing companies in China, each with its own separate bicycle models; however, this study will mainly be using the bicycle component data provided by Mao et al. (2020). The specific components, material type, weight, and percentage proportion are given in Table 1.

Table 1Bicycle Components Source: Mao et al. (2020)

Part Name	Material Type	Weight(Kg)	Proportion
Frame, front fork	Aluminum alloy	7	46.70%
Rims (including spokes)	Aluminum alloy	2.5	16.70%
Tires (inner and outer tires)	Rubber	1.5	10.00%
Front and rear brake housing	Steel	1	6.70%
Fender	Steel	0.95	6.30%
Seat steel pipe	Steel	0.7	4.70%
Foot support	Steel	0.45	3.00%
Bicycle chain	Aluminum alloy	0.3	2.00%
Seat	Rubber	0.25	1.70%
Others		0.35	2.20%

The product system boundaries are provided in Fig.4, which will include Raw Material Extraction, Material Processing, First and Secondary Production, and End of Life Treatment, and information on the specific manufacturing process and materials used are gathered from previous research (Li,2021).

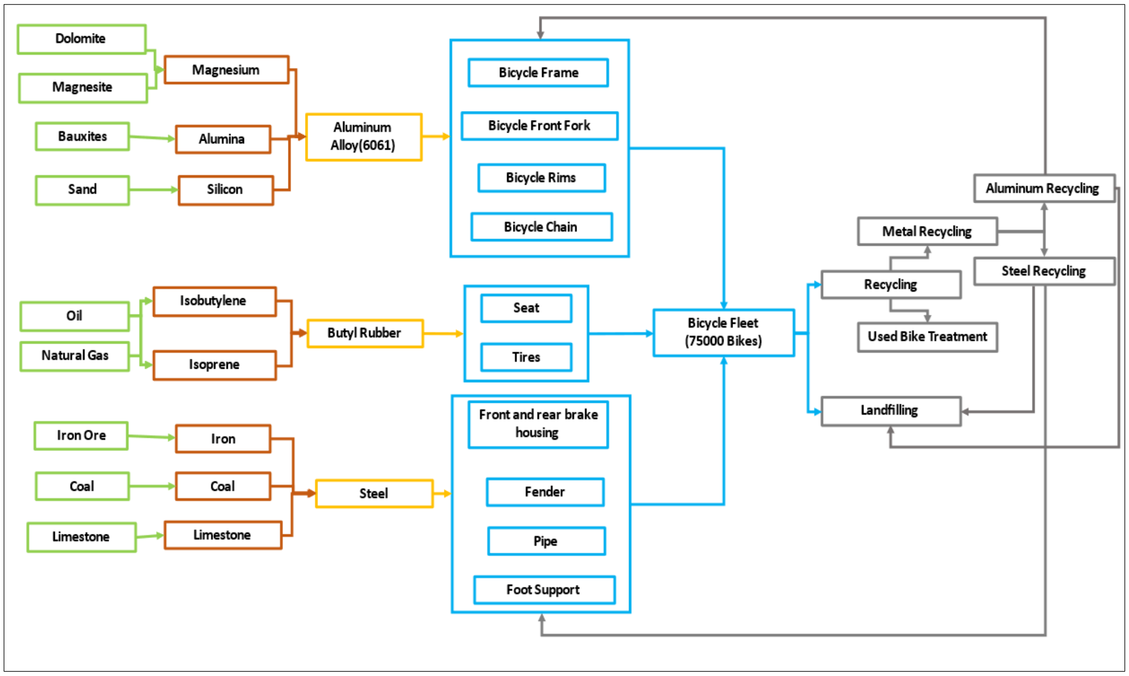


Figure 4 Bicycle Sharing Life Cycle (Green: Raw Material Extraction; Brown: Material Processing/ Supply Chain; Yellow: Primary Manufacturing; Blue: Secondary Manufacturing; Grey: End of Life treatment

3.3 Scenarios

Of particular importance to this study is the current End-of-Life treatment process of used bicycles. According to Hao et al. (2020), the current most valuable parts of a bicycle for recycling include various materials such as steel and aluminum alloy, rubber, and electronic components. But, due to the ineffective bike-share recycling system, currently only steel is economically viable for recycling. Therefore, this study will also mainly focus on metallic material recycling, including steel and aluminum alloy.

Additionally, Hao et al. (2020) have also pointed out that there is no established mature shared bicycle recycling system. This means that much of these bikes remain degraded. And because of high recycling costs and narrow profit margins, most companies choose to ignore these abandoned bikes and have no incentive to dispose of them properly. These circumstances eventually led to less than 10% of the bikes are eventually enter the proper recycling stream. As for the bicycles that enter the recycling stream, their resources are not fully reclaimed. Hao et al. estimated that the current bicycle recycling efficiency only reaches 50%. This means that of the 10% of bikes that are being recycled, only 50% of their metallic resources are reclaimed, which means that only 5% of the entire bicycle fleet's resources can reenter the production system.

To test the environmental impact of changed circularity rates, this study established four scenarios based on current and assumed future recycling rates and efficiency, presented in Table 2.

Table 2 Life Cycle Scenarios

Name	**Current Rate**	**Assumed Future Rate**
Recycling Rate of Bicycles	10%	60%
Recycling Efficiency of Metal Parts in a Bicycle	50%	100%
Scenario Name	**Modeled Recycling Rate**	**Modeled Recycling Efficiency**
Business As Usual (BAU)	10%	50%
Improved Recycling Rate	60%	50%
Improve Recycling Efficiency	10%	100%
Circular Economy (CE)	60%	100%

In the Business as Usual Scenario, the recycling rates and recycling efficiency are maintained at the present level of 10% and 50%. This scenario represents the current system and serves as the baseline to gauge the change of environmental impacts in the other scenarios. The

Improved Recycling Rate Scenario increased the End-of-Life recycling rate to 60%. This means that 60% of the bicycles are eventually collected and put into the recycling stream. The 60% recycling rate is assumed since the Chinese government aims to reuse 60% of its urban household waste by 2025(Reuters, 2021). The Improved Recycling Efficiency Scenario assumes that China will establish a formal bicycle recycling system with improved recycling efficiency of 100% for metallic materials. While the 100% metallic material recycling efficiency may be a bit idealistic, current bicycle industry leader such as ROETZ bikes are already making progress towards a fully circular bicycle (Li, 2021). Finally, the Circular Economy Scenario combines the increase in recycling rate and recycling efficiency to bring most of the used bicycles back into the production system

3.4 Data Sources, Software, and Impact Assessment Method

The data used in this study will be collected using the Ecoinvent 36 LCA database. To be representative of the technology and the location of the study, the data are collected with a preference of Chinese data sources. When Chinese data are not available, Global or Rest of the World (RoW) data are brought in as a substitute.

Table 3 Life Cycle Data Set

Life Cycle Stage		Material/Process	Name	Location
Raw Material Extraction	**Aluminum Alloy**	Bauxite	bauxite mine operation | bauxite | APOS, S	Global
		Sand	silica sand production | silica sand | APOS, S	Rest-of-World(Swiss, data are assumed to be representative of the global production)
		Dolomite	dolomite production | dolomite | APOS, S	Rest-of-World
	Steel	Coal	hard coal mine operation and hard coal preparation | hard coal | APOS, S	Rest-of-World(European)
		Iron	iron mine operation, crude ore, 46% Fe | iron ore, crude ore, 46% Fe | APOS, S	Global
		Limestone	limestone production, crushed, for mill | limestone, crushed, for mill | APOS, S	Rest-of-World(Switzerland)
	Butyle Rubber	Oil/Petrolium	petroleum production, onshore | petroleum | APOS, S	Rest-of-World
Material Processing/Supply Chain	**iron ore**	iron ore beneficiation	iron ore beneficiation to 65% Fe | iron ore, beneficiated, 65% Fe | APOS, S	Rest-of-World
	magnesium	magnesium productio	magnesium production, pidgeon process | magnesium | APOS, S	China
	Silicon	silicon production	silicon production, metallurgical grade | silicon, metallurgical grade | APOS, S	Rest-of-World
Primary Production	**Steel(6061)**	Steel	steel production, converter, low-alloyed | steel, low-alloyed | APOS, S	Rest-of-World(Data relate to plants in the EU)
	Aluminum Alloy	Aluminum Alloy	aluminium alloy production, Metallic Matrix Composite | aluminium alloy, metal matrix composite | APOS, S	Rest-of-World
	Synthetic Rubber	Rubber	synthetic rubber production | synthetic rubber | APOS, S	Rest-of-World
Secondary Production	**Bicycle**	Bicycle Production	bicycle production | bicycle | APOS, S	Rest-of-World(China for Manufacturing and Retail in EU)
End-of-Life Processing		Steel Recycling	treatment of waste reinforcement steel, recycling | waste reinforcement steel | APOS, S	Rest-of-World(Switzerland in late 1990ies)
		Aluminum Recycling	treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | aluminium scrap, post-consumer, prepared for melting | APOS, S	Rest-of-World(European Aluminum Association)
		Used Bike Treatment	treatment of used bicycle | used bicycle | APOS, S	Rest-of-World(Europe)
		Landfilling	treatment of inert waste, inert material landfill | inert waste, for final disposal | APOS, S	Rest-of-World(Switzerland in 2000)

However, these data do present some challenges and include some limitations. For example, among all data collected, only bicycle production data come from China, with the remaining data only listed as RoW or as Global. These RoW and Global data are sometimes described in the database as based on European data sources and are only assumed to be representative of global production practices. Due to these limitations, the data collected may not very well describe the production practices and environmental impact used in China. In addition, the bicycle production data is a Blackbox data that contains the production of the bicycles and the transportation to Europe for retail. Therefore, the production data does not fit the scope defined for this study and may cause an overestimation of the total environmental impact of the system. Finally, some of the data sources also contain assumptions and uncertainties due to weak data qualities on the production processes. However, the bicycle production data remains the only available data for the production stage of bicycles and is used in this study. Despite these limitations, considering the goal of the study is mainly focused on assessing the changes of environmental impact caused by shifts in circularity rates, the negative effect caused by life cycle data errors is assumed to be small and will not drastically change the result of this study.

These life cycle data will be used to calculate the environmental impact of the production system using the OpenLCA 1.10.3 in combination with the ReCiPe 2016 Midpoint Impact Assessment method under a Hierarchist perspective.

3.5 Types of Environmental Impacts

To gain a comprehensive view of the changes in environmental impacts between different scenarios, this study reviewed previous LCA studies on bicycle sharing systems and their selected environmental impact categories. This study eventually decided to include 15 of the Environmental Impact categories available in the ReCiPe 2016 methodology. These categories include both resource use and emissions and contain several themes, including global warming, land use, Ecotoxicity, eutrophication potential, fine particulate matter formation, fossil resource scarcity, mineral resource scarcity, ozone formation and depletion, and water consumption.

3.6 Grouping

To gain a more detailed understanding of the environmental impacts, this study will also use grouping to place various processes under five different life cycle stages: Raw Material Extraction, Supply Chain (material processing), Primary Manufacturing, Secondary Manufacturing, and Waste treatment. The specific grouping methodology is presented in Table 4.

Table 4Production Process Grouping

Grouping	Processes included
Raw material extraction	Silica Sand Production, Dolomite Production, Bauxites Mining, Land Crude Oil Extraction, Coal Mining, Limestone Mining, Iron Ore Extraction
Supply chain	Silicon Production, Magnesium Production, Iron Ore Beneficiation
Primary manufacturing	Aluminum Alloy Production, Rubber Production, Steel Production
Secondary manufacturing	Bicycles Production
Waste treatment	Used Bicycle Treatment, Aluminum Recycling, Steel Recycling, Landfill

4 LCA Results

As the LCA data shown in Table 5 demonstrates, there is a clear reduction in nearly all environmental impacts as the product system's overall circularity rate increases.

Table 5Scenario LCA Results

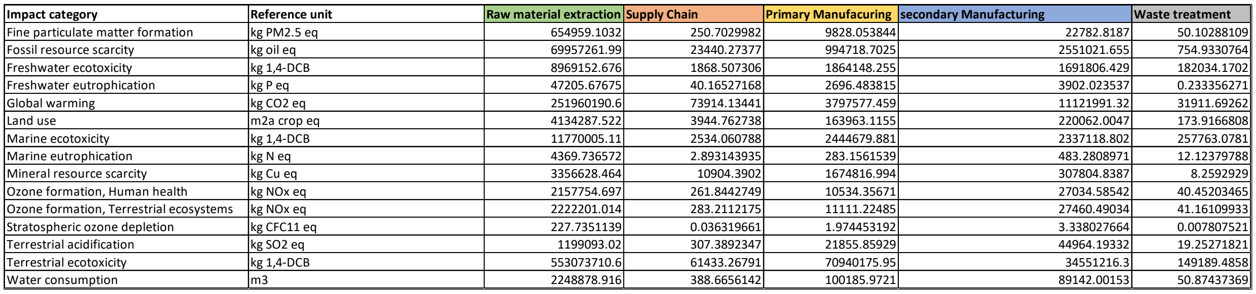
Impact category	Reference unit	Business As Usual results	Improved Recycling Efficiency Results	Improved Recycling Results	Circular Economy Results
Fine particulate matter formation	kg PM2.5 eq	687923.5779	687478.6572	685692.6484	683006.4498
Fossil resource scarcity	kg oil eq	73531827.18	73490131.24	73323650.02	73072083.18
Freshwater Ecotoxicity	kg 1,4-DCB	13041109.86	13310782.97	14319594.74	15832762.07
Freshwater eutrophication	kg P eq	53864.74353	53741.50402	53244.50514	52498.71544
Global warming	kg CO2 eq	267007836	266843892.6	266185357	265194690.6
Land use	m2a crop eq	4523530.202	4516273.352	4487338.67	4443481.359
Marine Ecotoxicity	kg 1,4-DCB	17209380.61	17520755.77	18682668.05	20425465.52
Marine eutrophication	kg N eq	5151.939758	5137.703986	5080.62074	4994.97065
Mineral resource scarcity	kg Cu eq	5355494.815	5271722.102	4935513.737	4431193.925
Ozone formation, Human health	kg NOx eq	2195681.84	2195217.416	2193364.275	2190559.636
Ozone formation, Terrestrial ecosystems	kg NOx eq	2261154.007	2260662.945	2258703.381	2255738.599
Stratospheric ozone depletion	kg CFC11 eq	233.1084301	233.0310332	232.7193715	232.2497554
Terrestrial acidification	kg SO2 eq	1266364.922	1265390.255	1261475.896	1255588.464
Terrestrial Ecotoxicity	kg 1,4-DCB	659503125.7	656619820.2	644939276.5	627410106.9
Water consumption	m3	2439224.486	2434820.677	2417145.127	2390545.512

However, looking closer, the reduction in most environmental impacts is relatively small. In fact, if we use the BAU scenario result as a baseline to calculate the percentage reduction in environmental impact the other three scenarios, as shown in table 6, then we see that most reduction is only in the tenth of a percent range. The largest reduction in impact comes from the reduction in Mineral Resource Scarcity (-17.25%), which is then followed by Terrestrial Ecotoxicity (-4.8%) and Marine Eutrophication (-3.04%). More interestingly, we can also see that compared to the BAU scenario, there is a drastic increase in the Freshwater Ecotoxicity (+21.4%) and the Marine Ecotoxicity category (+18.68%). These results are contrary to the expectation that the increase of circularity rate can lead to a drastic reduction to all environmental impacts, so the question becomes 1. How can we explain the limited environmental impact reduction? And 2. What caused the dramatic increase in Freshwater Ecotoxicity and Maine Ecotoxicity?

Table 6 Scenario LCA Impact Reduction Comparison (%)

Impact category	**Improved Recycling Efficiency**	**Improved Recycling Rate**	**Circular Economy**
Fine particulate matter formation	-0.0646759	-0.324299036	-0.714778258
Fossil resource scarcity	-0.056704628	-0.28311164	-0.62523131
Freshwater ecotoxicity	2.067869336	9.803497509	21.40655392
Freshwater eutrophication	-0.228794386	-1.151473769	-2.536033774
Global warming	-0.061400216	-0.308035532	-0.679060752
Land use	-0.16042447	-0.800072738	-1.769609988
Marine ecotoxicity	1.809333956	8.560955646	18.687976
Marine eutrophication	-0.276318681	-1.384313889	-3.046796253
Mineral resource scarcity	-1.564238523	-7.842059277	-17.25892606
Ozone formation, Human health	-0.021151722	-0.105551041	-0.233285354
Ozone formation, Terrestrial ecosystems	-0.021717332	-0.108379464	-0.239497549
Stratospheric ozone depletion	-0.033202086	-0.166900282	-0.368358489
Terrestrial acidification	-0.07696576	-0.386067697	-0.850975692
Terrestrial ecotoxicity	-0.437193606	-2.208306311	-4.866242099
Water consumption	-0.180541362	-0.905179432	-1.99567419

Table 7 Grouped Process Environmental Impacts (BAU)



Impact category	**Reference unit**	**Raw material extraction**	**Supply Chain**	**Primary Manufacuring**	**secondary Manufacturing**	**Waste treatment**
Fine particulate matter formation	kg PM2.5 eq	654959.1032	250.7029982	9828.053844	22782.8187	50.10288109
Fossil resource scarcity	kg oil eq	69957261.99	23440.27377	994718.7025	2551021.655	754.9330764
Freshwater ecotoxicity	kg 1,4-DCB	8969152.676	1868.507306	1864148.255	1691806.429	182034.1702
Freshwater eutrophication	kg P eq	47205.67675	40.16527168	2696.483815	3902.023537	0.233356271
Global warming	kg CO2 eq	251960190.6	73914.13441	3797577.459	11121991.32	31911.69262
Land use	m2a crop eq	4134287.522	3944.762738	163963.1155	220062.0047	173.9166808
Marine ecotoxicity	kg 1,4-DCB	11770005.11	2534.060788	2444679.881	2337118.802	257763.0781
Marine eutrophication	kg N eq	4369.736572	2.893143935	283.1561539	483.2808971	12.12379788
Mineral resource scarcity	kg Cu eq	3356628.464	10904.3902	1674816.994	307804.8387	8.2592929
Ozone formation, Human health	kg NOx eq	2157754.697	261.8442749	10534.35671	27034.58542	40.45203465
Ozone formation, Terrestrial ecosystems	kg NOx eq	2222201.014	283.2112175	11111.22485	27460.49034	41.16109933
Stratospheric ozone depletion	kg CFC11 eq	227.7351139	0.036319661	1.974453192	3.338027664	0.007807521
Terrestrial acidification	kg SO2 eq	1199093.02	307.3892347	21855.85929	44964.19332	19.25271821
Terrestrial ecotoxicity	kg 1,4-DCB	553073710.6	61433.26791	70940175.95	34551216.3	149189.4858
Water consumption	m3	2248878.916	388.6656142	100185.9721	89142.00153	50.87437369

To answer the first question, we need to investigate the process's contribution to the overall environmental impacts. If we group the different processes according to the grouping methodology listed in table 4, then we see that most environmental impacts are attributed to the

Raw material extraction life cycle stage (Table 7& Fig.5). This remains constant even if the system circularity rate is increased (Table 8& Fig.6). As we look closer at the individual process contributions, we can see that onshore oil production contributes the most to all environmental impact categories within the raw material extraction stage (Fig.7 & Table 9). This is important because oil is mainly used to produce industrial rubber, which is not recycled under the current Chinese bicycle recycling system. Without recycling rubber, there is no

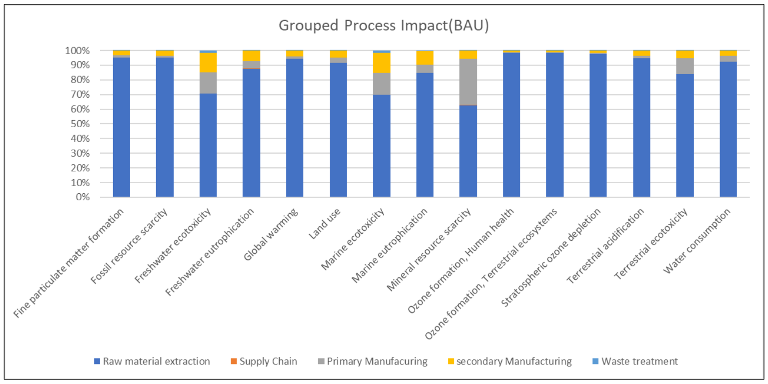


Figure 5 Grouped Percentage Process Impact (BAU)

Table 6 Grouped Process Environmental Impact (CE)

Impact category	Reference unit	Raw material extraction	Supply Chain	Primary Manufacuring	secondary Manufacturing	Waste treatment
Fine particulate matter formation	kg PM2.5 eq	654888.1066	105.5591571	4495.305685	22782.8187	734.6596614
Fossil resource scarcity	kg oil eq	69914390.78	9869.588955	535656.864	2551021.655	61144.28999
Freshwater ecotoxicity	kg 1,4-DCB	8966856.884	786.7399181	796293.802	1691806.429	4377018.219
Freshwater eutrophication	kg P eq	47131.99215	16.91169334	1192.691305	3902.023537	255.0967604
Global warming	kg CO2 eq	251929172.4	31121.7408	1793172.923	11121991.32	319232.1676
Land use	m2a crop eq	4132408.386	1660.952732	75314.86039	220062.0047	14035.15541
Marine ecotoxicity	kg 1,4-DCB	11766831.85	1066.972963	1044359.878	2337118.802	5276088.024
Marine eutrophication	kg N eq	4365.144079	1.218165867	123.7200336	483.2808971	21.60747464
Mineral resource scarcity	kg Cu eq	3340535.366	4591.322188	710894.2804	307804.8387	67368.1172
Ozone formation, Human health	kg NOx eq	2157669.642	110.250221	4921.356992	27034.58542	823.8016924
Ozone formation, Terrestrial ecosystems	kg NOx eq	2222114.366	119.2468284	5206.106147	27460.49034	838.3895687
Stratospheric ozone depletion	kg CFC11 eq	227.7193079	0.015292489	0.954591978	3.338027664	0.222535404
Terrestrial acidification	kg SO2 eq	1198917.552	129.4270462	9941.657563	44964.19332	1635.634116
Terrestrial ecotoxicity	kg 1,4-DCB	553039078.3	25866.63912	30449661.68	34551216.3	9344284.031
Water consumption	m3	2248669.705	163.6486797	45219.19282	89142.00153	7350.964458

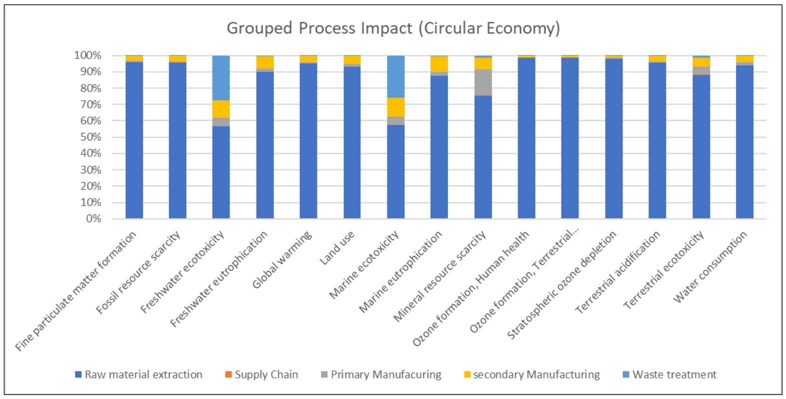


Figure 6 Grouped Percentage Process Impact (CE)

Table 7 Individual Extraction Process Impact

Impact category	Reference unit	bauxite mining	dolomite production	hard coal mining hard coal preparation	iron mine operation	limestone production	onshore well production, oil/gas	silica sand production
Fine particulate matter formation	kg PM2.5 eq	18.36458105	0.13780692	72.45177418	30.25868092	0.587010846	654836.4726	0.830679059
Fossil resource scarcity	kg oil eq	1981.275595	12.36881749	71668.71976	265.2128142	22.86449534	69883211.72	99.83473243
Freshwater ecotoxicity	kg 1,4-DCB	97.05834732	1.459837056	3834.479922	23.6793879	2.108739512	8965187.217	6.672815073
Freshwater eutrophication	kg P eq	0.57486619	0.020772866	126.4307698	0.156867193	0.011364885	47078.40334	0.078765995
Global warming	kg CO2 eq	6803.951644	54.32453955	45225.66844	1001.495029	81.76326279	251906613.8	409.5624343
Land use	m2a crop eq	70.6205375	1.213324111	3037.873167	30.96088627	2.901910339	4131041.742	102.2098597
Marine ecotoxicity	kg 1,4-DCB	147.6072974	1.929264818	5287.764369	31.27383423	2.773118576	11764524.02	9.747078975
Marine eutrophication	kg N eq	0.073987501	0.001551391	7.825654607	0.023955896	0.001478222	4361.804084	0.005860053
Mineral resource scarcity	kg Cu eq	22760.2619	0.07219875	22.81383198	5013.020517	0.31477184	3328831.295	0.68580026
Ozone formation, Human health	kg NOx eq	60.63364431	0.180208931	58.43242277	24.1943872	1.520826567	2157607.783	1.951836342
Ozone formation, Terrestrial ecosystems	kg NOx eq	61.80396875	0.182370616	59.50787909	24.64245616	1.548500731	2222051.349	1.979434816
Stratospheric ozone depletion	kg CFC11 eq	0.011281038	2.64104E-05	0.011304274	0.004341742	0.000227078	227.7078126	0.00012073
Terrestrial acidification	kg SO2 eq	48.96054765	0.248684701	234.8647227	15.97086986	0.950321293	1198789.94	2.085086475
Terrestrial ecotoxicity	kg 1,4-DCB	45717.68833	64.07489724	10469.59506	1714.906482	152.9786054	553013891.1	1700.314394
Water consumption	m3	276.7589861	0.248912613	74.87724664	4.232522289	2.499234141	2248517.551	2.747445726

displacement of raw extracted oil. Since oil extraction is one of the main contributors to the overall environmental impact of the production system, the overall reduction in environmental impact remains limited under the current recycling system.

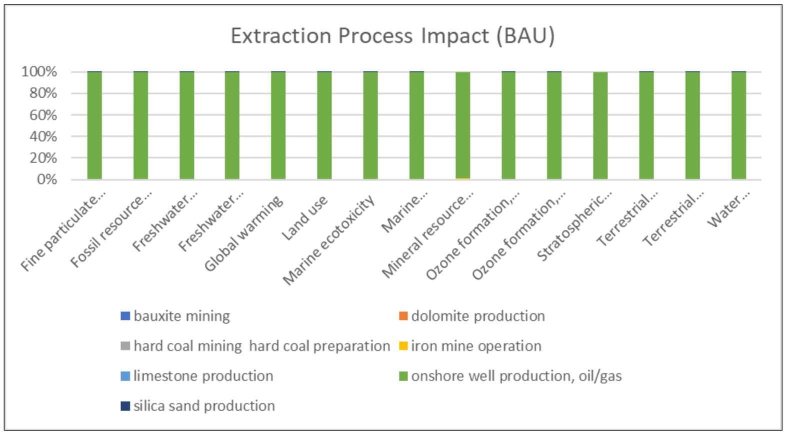


Figure 7 Extraction Process Impact (%)

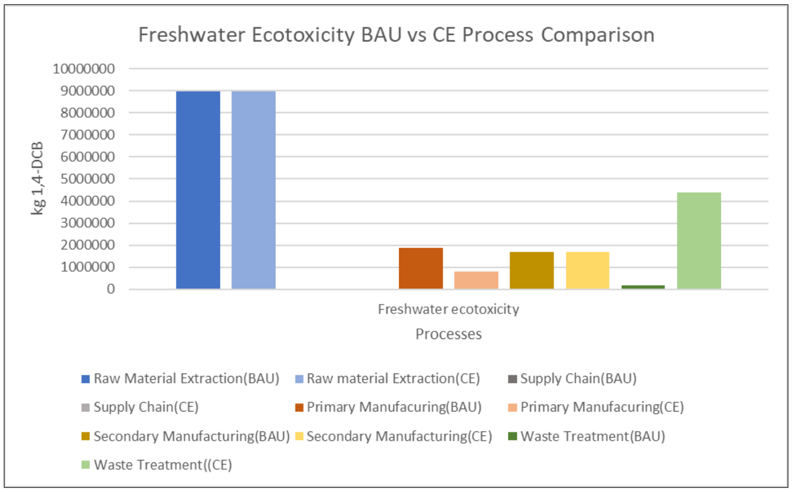


Figure 8 Freshwater Ecotoxicity BAU vs CE Process Comparison

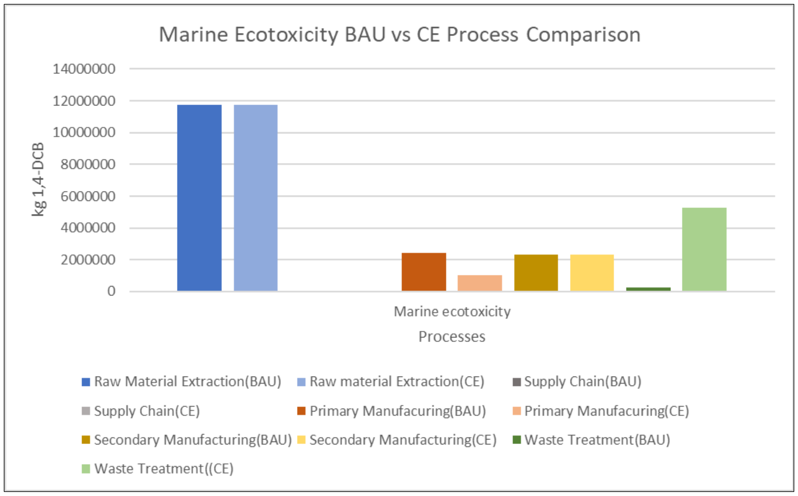


Figure 9 Marine Ecotoxicity BAU vs CE Process Comparison

But what might explain the increase in Freshwater and Marine Ecotoxicity? To answer this question, we must see the changes of environmental impact attributed to various life cycle stages under different scenarios. As shown in Fig.8&9, the largest changes in Freshwater and Marine Ecotoxicity come from the large increase of Ecotoxicity material at the End of Life treatment stages. And if we refer to Fig.10&11, then we will see that the aluminum scrap treatment process contributes the most to both Freshwater and Marine Ecotoxicity. By diving deeper, we see from data that the copper ion emission to ground water during the aluminum scrap process contributes the most to both Marine and Freshwater ecotoxicity. All this means that as we increase in circularity by increasing the metals recycled, we are also increasing the environmental impacts of the recycling process. This is a good reminder that recycling also comes with environmental impacts that need to be considered and ensure that the increased impact of recycling does not outweigh the reduction in raw material extraction.

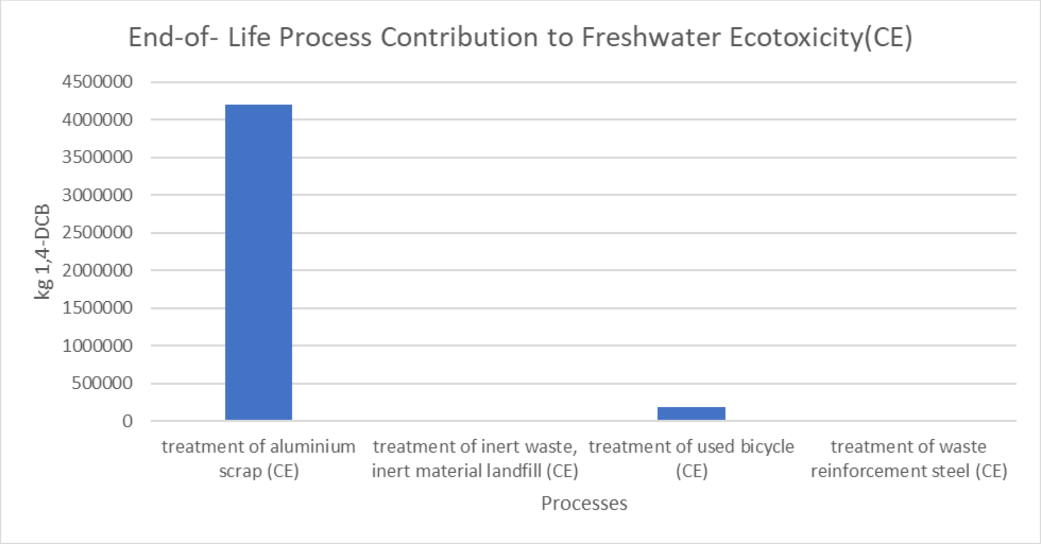


Figure 10 End-of-Life Process Contribution to Freshwater Ecotoxicity (CE)

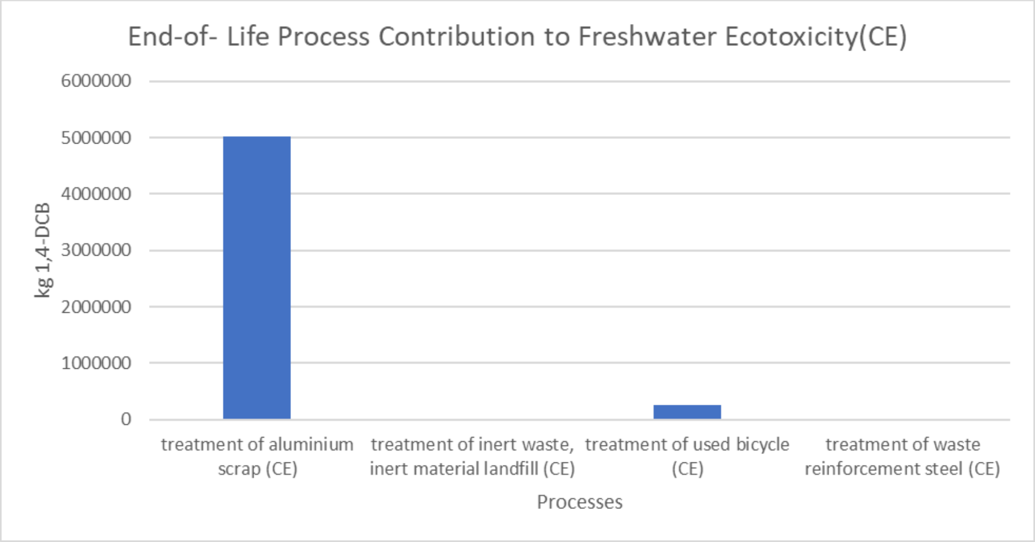


Figure 11 End-of-Life Process Contribution to Freshwater Ecotoxicity (CE)

5 Discussion

From these results, we can reach a few conclusions. Firstly, improving recycling rates and recycling efficiency does have a positive impact on the reduction of environmental impacts for the bike-sharing product system. In general, reduction of environmental impact follows a BAU>Improved Recycling Efficiency>Improved Recycling Rate>Circular Economy pathway. This is maybe useful to the government, and bike-share service providers, as it can help them to prioritize recycling policies. It is recommended to increase both recycling rate and recycling efficiency if it is possible but considering the increase in recycling efficiency may be more difficult since it requires improvements in recycling technologies, it is best to first increase the current recycling rate from 10% to 60% as outlined by the Chinese government. Apart from being more easily implemented, it is also comparatively an action that brings the most reduction in environmental impacts. To improve the recycling rate, the government may consider fostering a formal bicycle recycling system and engage with industry to push circular economy as an industry standard by setting up policies that encourage companies to construct a reverse logistical system and set legal producer extended responsibilities.

However, the reduction in environmental impacts is not as impressive as we might think. This is mainly due to the materials that are currently being recycled and the environmental impact of the recycling process itself. As we see in the previous section, onshore oil extraction contributes the most to the overall environmental impact of the product system. Unfortunately, due to current recycling system limitations, oil-based components such as rubber tires are not being recycled. Thus, even if the recycling rates and efficiency increase for metallic resources such as steel and aluminum, the overall reduction in environmental impacts is limited. Additionally, we also see a drastic increase in freshwater and marine Ecotoxicity as the circularity rate increases. This is attributed to aluminum recycling processes, and the increase of aluminum being recycled. All this shows that there is a great need to expand and improve the current recycling system beyond just recycling rate and recycling efficiency. Recycling metallic resources such as aluminum and steel can only improve the system's environmental impact by a marginal amount. To make a difference, the bike share industry needs to incorporate industrial rubber recycling into the circular supply chain. Furthermore, there should also be an effort to improve the current aluminum recycling process to reduce the increase in Freshwater and Marine Ecotoxicity.

It is difficult to say for certain from these results if an increase in recycling rates and efficiency is, in general, environmentally beneficial. Does the relatively moderate decrease of environmental impacts in most impact categories compensate for the drastic 21% and 18% increase in freshwater and marine Ecotoxicity? This is a question that needs to be further researched, or rather it is an environmental trade-off that different companies and governments approach differently depending on local circumstances. Related to this question is the fact that this study mainly focused on recycling, which is a low priority in circular strategies. Other circular strategies, such as remanufacturing and refurbishing, may yield considerably better results as these circular strategies doesn't require the materials to be completely broken down. Apart from these questions, several others also warrant research. Firstly, the data used in this research is limited to general global production data and contains uncertainties related to specific processes. It is advised that more detailed research using more specific and local data be conducted to confirm the findings in this study. Additionally, this study did not consider the maintenance and life span of individual bicycles. As discussed in section 2.4, there were talks of prolonging shared bikes' life span to gain better resource efficiencies. It may be interesting to investigate further the effects of a stronger bicycle design and material used on the product system's environmental impact. Moreover, does the rebound effect in both circular economy and sharing economy system play a role within the bike share system and its recycling system? Finally, there are new materials such as bamboo that are starting to replace steel as the main materials for bicycles that promise strength and environmental sustainability. How might these new materials fit into the circular bicycle sharing system?

6 Conclusion

The study investigated the current recycling system of shared bicycles in China and uses a cradle to cradle LCA method to analyze the reduction in environmental impacts under different scenarios with different recycling rates and recycling efficiency. The study finds that, in general, an increase in circularity does lead to a reduction of environmental impacts with an increase in recycling rate having more effects on environmental impacts than recycling efficiency. However, the study also finds that the current recycling system is limited in how much it can reduce the environmental impact of the product system. This limitation is mainly because the most environmentally impactful process is oil extraction, which is used to produce industrial rubber. However, industrial rubber is not recycled under that current system which means that oil production is not reduced. Additionally, the study result also shows that an increase in circularity leads to an increase in Freshwater and Marine Ecotoxicity caused by current aluminum recycling processes. The result of the study is inconclusive regarding if increased circularity brings a reduction in general product system environmental impacts and requires further confirmation. However, the results do show there is a line of preference between the increase in recycling rate and recycling efficiency. It also clarifies directions for future research, including improving industrial rubber recycling and improving the aluminum recycling process. Additional future research questions may include the effects of prolonged product life span, rebound effect impact on circular bicycle-sharing economy, and new sustainable bicycle material such as bamboo on the circular bicycle system.

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