The Circular Economy and Industrial Symbiosis Potential of the Bicycle Industry

Yansong Li
University of Pennsylvania

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Yansong Li

8/2/2021
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Introduction

Widely acknowledged as the symbol of sustainable transportation, bicycles have gained increased attention from the public. In 2016, around 12.4% of Americans cycled regularly. The number of cyclists in the US increased over five years from 43 million to 48.88 million in 2019. And the estimated size of the US bicycle market has grown to $6.2 Billion as of 2015. It can be expected that biking will play an essential role in the future transportation system as society becomes increasingly sustainability-conscious as we face environmental challenges. This transition period has given the Biking industry an opportunity to reevaluate our business model and discover opportunities to improve our sustainability. Although biking is far more sustainable than many other modes of transportation, it also faces environmental challenges. One of the most important challenges that face us is resource limitations. The bicycle industry mostly operates in a Linear Economic model, in which resources are used in an extract, use, and discard manner. On a planet with finite resources, this model of production is obviously unsustainable. Organizations such as the Ellan McArthur Foundation have proposed a transition to Circular Economy to resolve this problem.

Circular Economy

A circular economy (Fig 1) creates a resource loop in an economic system, and such a system is regenerative by design, minimizes or eradicates waste and pollution, and maximizes resource utilization. By transition to a circular economy, the biking industry will have the opportunity to 1. Ensure Sustainable development of the industry 2. Reduce cost 3. Enhance reputation 4. Uncover new products/approaches/marketing claims 5. Enhance supply chain 6. Appeal to customer base.

Figure 1 The Circular Economy System Diagram. Source: Ellen MacArthur Foundation
To adopt a circular economy will also require the industry to rethink product design, material choices, supply chain management, product manufacturing process, logistics, day-to-day operations, and relationship with other industries.

**Industrial Symbiosis and Ecology**

As part of the circular economy framework, industrial symbiosis and industrial ecology focus on products and manufacturing interconnections. As explained previously, a circular economy seeks to drastically reduce, if not wholly exterminate the concept of waste. To achieve this goal, producers need to rethink waste as by-products that can be used in other manufacturing processes rather than useless materials to be disposed of. A typical example of this change in mindset involves the numerous by-products produced in the petroleum industry that are redirected and sold as raw materials in the manufacturing process of other products. It will also require manufacturers to carefully examine the current manufacturing process to derive more efficient approaches to reduce material and energy usage and reduce environmental impacts.

To assist the Bicycle industry in identifying potential circular economy implementation options and becoming a more sustainable industry, this report will first examine the standard bicycle materials and design, then assess the industry supply chain, including raw material extraction, supply chain, primary production, and secondary production, for sustainability and industrial symbiosis improvements. The report will then examine corporate sustainability and circular economy implementation opportunities. In conducting this research, multiple industry-leading companies, and their efforts to improve their circularity are examined. The companies examined are listed in Table 1.
Table 1. Benchmark Companies

<table>
<thead>
<tr>
<th>Company Name</th>
<th>Location</th>
<th>Corporate Sustainability and Circular economy Efforts</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROETZ</td>
<td>Amsterdam, Netherland</td>
<td>Circular Economy, Social Enterprise, and High Quality</td>
</tr>
<tr>
<td>TREK Bike</td>
<td>Waterloo, WI, US</td>
<td>Green Facilities, Waste Reduction, Restoration, Packaging</td>
</tr>
<tr>
<td>Bjorn Bikes</td>
<td>Canada</td>
<td>Sustainable Materials and design</td>
</tr>
<tr>
<td>Cannondale</td>
<td>Connecticut, US</td>
<td>Sustainable Packaging</td>
</tr>
<tr>
<td>REVEL Bikes</td>
<td>US</td>
<td>Sustainable Packaging</td>
</tr>
<tr>
<td>Boomer Bikes</td>
<td>West Africa and North America</td>
<td>Innovative and sustainable materials</td>
</tr>
</tbody>
</table>

Bicycle Design and Materials

A bicycle consists of several main components, including Breaks, Chains, Derailleurs, Frame, Wheels, and Saddle. A simplified list of materials used to create each part is shown in Figure 2. After carefully reviewing the current literature, available recycling technology, and existing industry examples, we believe the most essential Bicycle component, including the frame, the seat, the handlebars, and the wheel, presents the highest redesign and material choice improvement opportunities.

Bike Frame

The Most Common materials used to produce Bike frames include Steel, Alloy Steel, Aluminum, Carbon Fiber, and Titanium. Currently, steel and aluminum are the most widely used materials in the industry. Aluminum frames are relatively cheap to manufacture, have an excellent strength to weight ratio, and are corrosion resistant. However, it is also difficult to repair, somewhat fragile, and less durable compared to steel, thus making it less appealing to steel when the circular economy and product durability is considered. But steel has the weakness of corrosion and rust, leading many manufacturers to apply anti-corrosion coating on the outer layer. From reviewed companies, the 4130 Chromoly steel seems to be the most common choice for bike manufacturers, and this material provides the beneficial quality of being lightweight, durable, strong, and recyclable. Steel’s recyclability is quite well known with both energy and resource benefits. 60% of Iron and steel produced in
the US is manufactured using steel scrap in an electric arc furnace or EAF. The production process using recycled steel requires 60% less energy, 40% water and reduces mining waste by 97%. The use of recycled steel is vital for the biking industry. As mentioned above, the resource limitation of the earth dictates that any currently used resources can be depleted if we cannot transition to a circular economy. For steel production, the most vital resource used is Iron ore. The current estimation of the global Iron reserve is 180 billion Tons (2020), with a worldwide extraction rate of 2.2-2.3 billion tons a year and a recycling rate of 27.8%. Table 2 presents the years remaining before the iron resource is depleted if we counties our current linear production method.

Table 2. Iron Reserve Limits with a growing population (27.8% recycling rate)

<table>
<thead>
<tr>
<th>Extraction rate (with growing world population)</th>
<th>Years Remaining before resource depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020 population extraction rate</td>
<td>82 Years</td>
</tr>
<tr>
<td>2040 population consumption rate</td>
<td>71 Years</td>
</tr>
<tr>
<td>2060 population consumption rate</td>
<td>68 Years</td>
</tr>
</tbody>
</table>

However, steel is 100% recyclable, so if perfect circularity can be achieved by maximizing the recycling rate to 100%, then the reserve limit can be prolonged by 30 to 50 years, as shown by table3 and demonstrating there should be an increased effort to improve steel scrap recycling in the steel manufacturing supply chain.

Table 3. Iron Reserve Limits with a growing population (100% recycling rate/ The + represents time gained)

<table>
<thead>
<tr>
<th>Extraction rate (with growing world population)</th>
<th>Years Remaining before resource depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020 population extraction rate</td>
<td>122 Years (+51)</td>
</tr>
<tr>
<td>2040 population consumption rate</td>
<td>107 Years (+36)</td>
</tr>
<tr>
<td>2060 population consumption rate</td>
<td>102 Years (+34)</td>
</tr>
</tbody>
</table>

Additionally, other materials are also showing promise. Although Carbon Fiber has not been chosen to be the material used for frame production, there are promising developments in that area. Some companies start using recycled carbon fiber in their production and use recycled carbon fiber to build prototype bicycles when creating new bicycle designs. Carbon Fiber has the advantage of being extremely light, stiff, and durable. Its most significant benefit is for manufacturers to manipulate it in endless ways, offering high customization. However, its
cost of manufacture is high; therefore, bikes with carbon fiber frames are often on the higher
end of the market. Carbon Fiber recycling is still in relatively early stages in circularity and
environmental impact, but it does show promises. Virgin carbon fiber is 14 times as energy-
intensive to produce as steel. However, recycled carbon has a 95% reduction in energy than
virgin carbon (roughly 0.7 times virgin steel’s energy). Comparing to steel and aluminum,
carbon fiber also does not degrade, rust, or fatigue, which leads to a longer lifespan.

Additionally, Carbon Fiber is also about five times lighter than steel. This means less
energy spent on transportation. Production location can also impact manufacturing materials.
For example, in China, the steel scrap to crude steel production rate is about 21.7% back in
2019 comparing to 60% in the US. Therefore, it is vital to examine the share of recycled
materials used in steel production by the material suppliers. Overall, there should be an
increased effort to incorporate steel scraps into the steel manufacturing supply chain. Other
more unconventional materials such as Bamboo have also been used for bike frame designs.
Companies such as Boomers have innovated and utilized this renewable resource to construct
durable and biodegradable bike frames. Unlike metallic materials, Bamboo is renewed rapidly,
leading to less concern over resource limits (although sustainable agriculture must be
considered in its cultivation). However, from our research, it seems that bamboo material does
not currently have any options for material circularity. Therefore, it is recommended to invest
in R&D efforts on this topic.

**Grips and Seats**

The vegan leather material is used for grip and seat manufacturing, and some models of
seats will also involve using materials such as nylon and plastic. Still, this study will mainly be
focusing on vegan leather. It is often chosen for its weather-resistant ability and with
consideration of animal welfare. Vegan leather can be made from various raw materials, the
most common being PVC or Polyurethane (PU), and both are derived from crude oil. This means
that both traditional PVC and PU are not sustainable. The estimated global reserve of oil is
1497.98 billion barrels in 2018, and 10% of oil goes to plastic, so the global oil reserve for plastic
production is 149.798 billion barrels. The world’s current oil extraction rate for plastic
manufacturing is around 3.59 billion barrels per year, and the consumption rate is 3.578 billion barrels per year. Finally, the current recycling rate for plastic is 8.7%, with an additional 15.8% incinerated. From these numbers, the study leads to the following oil reserve limits estimation.

Table 4 represents the estimation if the current 8.7% recycling rate is maintained with no future improvements. In comparison, Table 5 present the estimated results if the recycling rate is increased to 24.5% by recycling the currently incinerated portion. Finally, Table 6 gives the estimation of if a 100% recycling rate for plastic is achieved.

**Table 4. Oil Reserve Limits with a growing population (8.7% recycling rate)**

<table>
<thead>
<tr>
<th>Extraction rate (with growing world population)</th>
<th>Years Remaining before resource depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020 population extraction rate</td>
<td>42 Years</td>
</tr>
<tr>
<td>2040 population consumption rate</td>
<td>36 Years</td>
</tr>
<tr>
<td>2060 population consumption rate</td>
<td>35 Years</td>
</tr>
</tbody>
</table>

**Table 5. Oil Reserve Limits with a growing population (24.5% recycling rate/ The + represents time gained)**

<table>
<thead>
<tr>
<th>Extraction rate (with growing world population)</th>
<th>Years Remaining before resource depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020 population extraction rate</td>
<td>52 years (+10)</td>
</tr>
<tr>
<td>2040 population consumption rate</td>
<td>46 years (+9)</td>
</tr>
<tr>
<td>2060 population consumption rate</td>
<td>43 years (+8)</td>
</tr>
</tbody>
</table>

**Table 6. Oil Reserve Limits with a growing population (100% recycling rate/ The + represents time gained)**

<table>
<thead>
<tr>
<th>Extraction rate (with growing world population)</th>
<th>Years Remaining before resource depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020 population extraction rate</td>
<td>84 years (+42)</td>
</tr>
<tr>
<td>2040 population consumption rate</td>
<td>73 years (+37)</td>
</tr>
<tr>
<td>2060 population consumption rate</td>
<td>70 years (+35)</td>
</tr>
</tbody>
</table>

The estimation shows that even with a perfect recycling rate, the oil reserves will likely be depleted within the middle of the century. Therefore, the bicycle industry must find alternative materials to replace traditional petroleum-based PVCs vegan leather. Some of these materials are already available. For example, renewable ethylene feedstock-based PVC developed by Omnexus produces PVC material offers a more sustainable material option while reducing greenhouse gas emissions by 90% compared to traditional PVC. Another company
called Dessert has created a cactus-based vegan leather widely used in furniture and the fashion industry. It claims to have a reduced energy demand, greenhouse gas emission, eutrophication potential, and water use compared to PU vegan leather. The company also claims to operate under a carbon-negative farming method. Finally, one of the benchmark companies reviewed for this study, TREK bike, has utilized 100% recycled post-industrial TPE plastic to create its lock-on grip. This simple lock-on design makes it easy to install and remove, while the increased modularity makes it easier to recycle, repair, and upgrade.

**Wheels (Tires and Tubes)**

The bike tires are primarily made of two parts: Tires and tubes. The Inner tube is what riders pump gas into, and the outer Tire is more like a cover for the loop. The inner tube is made of butyl rubber, a form of plastic derived from petroleum with added chemical additives. The outer Tire is a combination of rubber, chemicals, and multiple layers of different materials. The layer of the Tire (Fig 3) includes an inner layer with beading along the wheel rim, a middle woven fabric base, and an outer layer made of rubber coating with treads. Since raw materials used to create butyl rubber includes petroleum, it is fundamentally not sustainable. A detailed assessment and estimation of global oil reserves resource limits are shown in Tables 4, 5, and 6.

Tubes and Tires recycling is possible but difficult due to their complex components. Most municipal recycling plants can only handle pure substances, so tubes and tires are beyond their capability. Since the tube is made of plastic, landfilling can lead to the breakdown of plastic and result in microplastic. It is here recommended that the biking industry consider simplifying the material used in the production of bike tubes and tires. Generally, the combination of multiple materials, or Monstrous Hybrids, often create difficulty in recycling and reincorporation of resource back into the economy. It is suggested that the industry invests in
R&D efforts to replace currently selected materials with renewable and recyclable materials. Another R&D opportunity exists for more modular and easily separable bike tires designs that can be recycled easily. An industry example is the Schwalbe tire company, which has established its inner tube recycling system and devoted R&D efforts to develop a recyclable inner tube design and implement a used Inner tube collection and recycling system. They have claimed that their tubes are 100% recyclable, and each of their new tubes uses 20% recycled butyl rubber materials. This has led to a drastic energy input reduction of 80%. Bicycle companies can also collaborate with companies with existing inner tube recycling systems. For example, Alchemy Goods has a tube upcycling program where customers and individual bike shops can send in collected inner tubes to upcycle. There are tubeless bike tires where the tires are filled with filling liquids instead of gases. This method does eliminate the inner tube, but the environmental impact and the sustainability of the filling liquid still require examination. Unfortunately, this report does not include such examinations.

Supply Chain Improvements and Industrial Symbiosis Opportunities

The supply chain maybe once just considered to be about lowering costs, Just-in-time delivery, and shrinking transportation time, however as sustainability becomes more important for industry development, the environmental cost of these networks is becoming one of the new major focuses when considering supply chain management. Supply chain sustainability is a new measurement of logistics management profitability. The examples of sustainable supply chain management set by world-renowned companies like Wal-Mart has demonstrated that extending the sustainability evaluation to the entire supply chain and carefully crafted relationship with suppliers provides advantages for continual corporate development. In terms of circular economy, the supply chain offers one of the greatest opportunities to minimize waste production by establishing industrial symbiotic relationships. In the following section, the report will provide a brief overview of the life cycle of bikes and then detail the potential for improvements to improve the energy and material consumption of each material. The report will also discuss the potential to establish industrial symbiosis relationships.
Bicycle Life Cycle

A Brief overview of a bicycle’s life cycle is shown in Figure 4. It starts with extracting raw materials such as iron and coal for steel and petroleum for PVC and butyl rubber. These materials are refined in the primary manufacturing stage to become the feedstock for secondary manufacturing, including components manufacturing and assembly. The finished products are packaged and distributed to customers through various channels. When the product reaches its end-of-life stages, it will either be discarded or, as in the case of a circular economy, be introduced back into the supply chain as resources via the reverse logistics pathway.

Steel Production

The production of steel involves the use of pig iron, which is derived from Iron Ore, Coal, Coke (heated coal to almost pure carbon), sinter (lesser grade and finely divided iron ore, roasted with coke), and limestone (or lime). Iron Ore, Coal, and limestone are extracted with Open-pit or Shafts and Tunnel Mining. In open-pit mining, the surface is removed with heavy machinery and expose to the ores beneath. Still, in cases when it is not economical to remove the surface, shafts are dug into the earth, with side
tunnels to follow the layer of ore. After the extraction process, the iron will be going through an 8-step process of refinement to become processed Iron Ore (Fig 5).

Apart from Iron ore, coal and limestone are also needed. Like iron ore, they will both go through refining processes. For Coal, this means that it will be crushed, sorted, purified, and dried into processed coal (Fig 6). Some of these coals will then be used to create coke (Fig 7). The limestone will go through two crushing steps before being screened. The lime with desired quality stone will then be washed and be transported to kilns, where it will be heated to roughly 1000°C to become lime (Fig 8).

The final component for pig iron is sinter, which is produced by combining coke, limestone, coal, lime, water, and processed iron ore. These materials will be mixed and burned until they are transformed into sinters. These sinters will then be cooled, crushed, and sorted (Fig. 9).
After these processes, the materials will be used to produce pig iron, which is used as feedstock for steel manufacturing. In pig iron production, iron ore, sinter, coke, and lime are added to the blast furnace. The hot air will be blasted from the bottom of the blast furnace, and under immense heat, lime will combine with impurities to form a layer of slags on the top. Molten pig iron will sink to the bottom. Latter molten iron will be drawn from the furnace, and the slags will be discharged (Fig 10).

However, pig iron isn’t used in all cases in steel manufacturing procedures. There are currently two production methods: Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF). BOF takes scrap metal and molten pig iron as feedstock, while EAF uses only scrap metals. BOF operates similarly to the blast furnace used for pig iron production. Scraps and molten iron are charged into the converter, where high purity oxygen will be blown into the charge. Limes will be added to help combine carbon and other unwanted elements to form slags, and scrap metal will be used to control temperature. CO2, argon, and nitrogen can also be added during the refining process. The produced steel will go through a secondary steel-making process before being cast to form the final product.
EAF uses high electricity to convert recyclable scrap metal into steel. In this process, the scrap metals are used as charge and melted by electrodes. Lime and fluorspar are added to combine impurities to form a slag that will be later discharged. The produced steel will also undergo a secondary steel-making process and casting to form the final product (Fig 12).

**Steel Manufacturing Improvements and Industrial Symbiotic Opportunities**

Coal, Iron, and Limestone mining operations always produce mining waste such as tailings, rocks, and wastewater. These materials should be either treated or reused. For example, waste rocks can be used for simple on-site construction, backfilling voids, and reconstruction of terrain to prevent soil erosion. Depending on the chemical composition of tailings, they can be used to produce bricks, paint extenders, roads, insulation, and agroforestry. They can also be used for further mining, but this option is not always economical. Wastewater produced is at high risk of polluting local water sources and thus requires thorough treatment before discharge. It is also recommended to use eco-friendly equipment for the mining operation. For example, Mining companies can switch to electric-powered equipment or simply adopt tires with higher ROI in rock-strewn environments. Companies can also reduce environmental impact by using biosolids, waste rocks, and large-scale reforestation schemes to rehabilitate mining sites.

In terms of material production, the study recommends promoting the use of EAF for steel production. Virgin iron and coke are both required for BOF steel-making, but their mass balance is not favorable. Iron ore is only 25% iron, thus making its estimated mass balance very low at only 24.775%. Additionally, coke conversion is only about 40% efficient, leading to a 60% loss. This means that almost ¾ of extracted iron and 3/5 of materials are wasted.
Additionally, using virgin pig iron to produce steel in the BOF is estimated to result in 400kg of by-products comparing to 200Kg of EAF. The energy requirement for producing the same amount of steel (1KG) is also lower for EAF (6-15Mj/Kg) comparing to BOF (20-50Mj/Kg). Thus, the mass and energy balance is also more favorable for EAF. From these numbers, it can be seen that utilizing steel scrap and the EAF for steel production is much more energy and material efficient than using virgin iron and BOF. EAF also fits the goal of transitioning to a circular economy by encouraging the use of metal scrap than extracting virgin materials from the environment. If virgin materials need to be used, this study recommends the following improvements for coal processing. First, Reduce Particulate Matter (PM) generation using water wetting, cyclones, fabric filters, venturi scrubbers, and mist eliminators. Additionally, research and develop a way to capture and reuse exhaust heat from the thermal drying process.

During the production of steel, several by-products are created. Meanwhile, by-products are also created by other industries that can be used in the steel-making industry as well. To transition to a circular economy, these by-products should be utilized as resources in the original manufacturing process or as feedstocks for other processes, and thus forming an industrial symbiotic relationship. By doing so, companies minimize waste production and reduce the cost of waste disposal and gain additional revenue from by-product trading. Table 7 have listed the observed by-products created by the steel industry and by-products that can be used in the steel industry. It is encouraged that the biking industry to assist in finding more by-products to strengthen the industrial symbiosis.

Table 7 By-products produced and used in the Steel Industry

<table>
<thead>
<tr>
<th>By-products Used in Steel Industry</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-containing materials (Biomass, residues from food companies, plastic, and rubber)</td>
<td>Used as a partial substitute for fossil materials</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main By-product of The Steel Industry</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel slags</td>
<td>Construction sector</td>
</tr>
<tr>
<td></td>
<td>Harmful Chemical removal</td>
</tr>
<tr>
<td></td>
<td>Waste Heat Recovery</td>
</tr>
<tr>
<td></td>
<td>Ceramic Tile</td>
</tr>
<tr>
<td></td>
<td>Biomedical Application</td>
</tr>
<tr>
<td></td>
<td>Optoelectronic application</td>
</tr>
</tbody>
</table>
PVC Vegan Leather Production

PVC leather is produced from Ethylene and Chlorine, which are derived from petroleum and Industrial rock Salt. The common way to extract petroleum is through Drilling and pumping method, but more recent and uncommon extraction method includes oil sand and horizontal fracking processes. The extraction of industrial rock salt will employ the drilling of shafts in salt mines and use explosives to excavate the rock salt.

Industrial rock salt and petroleum are first used to produce a compound called VCM, which is the feedstock of PVC. After excavation, rock salt and petroleum will first go through numerous refining processes. Rock salt will be crushed and cleaned. It will then be diluted in water and go through the Chlor-alkali process to produce chlorine. Petroleum will be distilled to produce naphtha, and naphtha will then be further processed to produce ethylene. Chlorine and Ethylene are then combined to

Mitigating Acidic soils
Fertilizers
Metal Recovery

H₂ Energy Generation
Ammonium sulfate Can be used as fertilizer
CO₂ Used in BOF
CO Used in BOF
BTX (benzene, toluene, and xylene) Plastic Production and Foam Production
Coal Tar Used to Produce electrodes in the aluminum industry
Coal Gas Illuminating and heating
Naphthalene Used to Produce electrodes in the aluminum industry
Used to produce refined chemicals and coal-tar products (ex. coal-tar pitch)
Mill scale Serve as a filler or partial substitute (up to 40%) for sand
EAF (Electric Arc Furnace) dust Zinc oxide production/Zamak alloy production
Zinc sludge (produced in some steel-making facilities) zinc ingots
create a compound called EDC, which will be thermally cracked to form VCM (Fig 13). Afterward, VCM goes through the suspension polymerization process to create PVC (Fig 14). However, it is likely not all VCM are reacted; thus, the PVC will be stripped, and the unreacted VCM will be reintroduced back into the feedstock. It is also likely that some PVCs will be mixed in the water used in the reaction. Thus, a water treatment process is needed to purify the water and recover PVCs. Both recovery process helps to improve process efficiency and reduce waste.

**PVC Manufacturing Improvements and Industrial Symbiotic Opportunities**

Apart from the above shown VCM and PVC recovery process, there are newly developed technologies to improve ethylene and chlorine production processes. For example, the new advanced catalytic olefins (ACO) process can produce ethylene from naphtha at a lower 700C temperature. The process is claimed to reduce energy needs by 20%, initial investment costs by 30%, and reduce carbon dioxide emissions. And for chlorine production, the new catalyst Pt1/CNT can help replace old catalysts made with large amounts of precious metals such as ruthenium and iridium while having better efficiency. Another improvement to the chlorine production process would be to capture the hydrogen gas currently vented into the atmosphere by these gases and reuse them to generate steam used on-site. Additionally, the current conversion rate of EDC to VCM is about 50%. It is also recommended that research should be conducted to improve this conversion process.

The PVC industry also produces a wide range of by-products in its manufacturing process, like hydrogen gas, which can be used internally. In contrast, many others can be used as feedstocks for other industries, as shown in table 8.
Table 8 By-products produced by the PVC industry

<table>
<thead>
<tr>
<th>By-products produced by the PVC Industry</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caustic Soda</td>
<td>Manufacture of pulp and paper, alumina, soap and detergents, petroleum products, and chemical production</td>
</tr>
<tr>
<td>Hydrogen Gas</td>
<td>Chlorine production, Energy generation</td>
</tr>
<tr>
<td>Chlorine Gas</td>
<td>Water treatment, Disinfectant</td>
</tr>
<tr>
<td>Isoprene</td>
<td>Butyl Rubber</td>
</tr>
<tr>
<td>Toluene</td>
<td>Foam, improve octane rating, Produce benzene, Solvent in painting and coating, Synthetic fragrances, Adhesives, Inks</td>
</tr>
<tr>
<td>Butadiene</td>
<td>Synthetic Rubber, Carpet backing, Plastic</td>
</tr>
</tbody>
</table>

Butyl Rubber Production

Butyl Rubber is a synthetic rubber material that is produced from Isobutylene and Isoprene. Isoprene is currently mainly produced as a by-product of the ethylene production process, which is already discussed above and will not be toughed here. Isobutylene is made from bio-products such as corn. The Bio-products are first processed into starch and then go through enzymatic hydrolysis to produce glucose. Glucose is fermented to produce Isobutylene (Fig 15). Isobutylene and Isoprene are then converted to Butyl Rubber in the cationic vinyl polymerization process, in which Isoprene is reacted with Isobutylene and chemical catalyst under a low-temperature environment. Unfortunately, information on this process is limited, making a detailed examination of this process very difficult.
Butyl Rubber Manufacturing Improvements and Industrial Symbiotic Opportunities

Although the information is limited, the estimated mass balance for isoprene production is about 39.27%. This low rate means that most resources are wasted in the conversion process, and additional research is needed to improve Isoprene’s production process efficiency. Additionally, there should be an effort to disentangle Isoprene production using petroleum, and there is ongoing research to use bio-ethanol as a raw material for Isoprene. If successful, this will change the entire supply chain of Isoprene, as it is currently mainly produced in the US as a By-product of Ethylene. As for Industrial symbiosis, the current Isoprene supply chain is the product of by-product utilization, although it is important to keep in mind that the base of this symbiotic relationship is petroleum and is unsustainable.

Bicycle Production

PVC, steel, butyl rubber, and other materials such as foam will enter the secondary production phase in which bicycle components will be assembled to build a bicycle.

The production process of bike components, including seats, tires, and wheels, are shown in Figures 16,17 and 18. Afterward, these components will be transported to the bike factory for final assembly.
The final bike assembly process will also involve the production of bike frames. The Steel Pipes will be cut into specific lengths and curved into the proper shape by a milling machine. The pipes will then be welded together to form the frame before being painted. Finally, all the bicycle components, such as the rear fender, forks, wheels, seats, chains, and handlebars, will be attached to the frame (Fig 19).

Bicycle Manufacturing Improvements and Industrial Symbiotic Opportunities

During this production process, some waste might be generated. This waste may include unused foam and leather scraps used in bike seats production and rubber in tire production. The data used to estimate the mass balance of bikes comes from the Ecoinvent LCA database. The data showed that a total of 184.5193KG of Materials are used as inputs, and assuming a bike weighs around 17Kg; the estimated mass balance is around 10%. However, this data includes the material used for manufacturing an average bicycle (Aluminum) and the disposal of a bicycle. It also assumed the manufacturing takes place in China, and the finished products are transported to Europe. Therefore, it is safe to say the low mass balance is an overestimation. The estimated mass balance is between 75% to 90%, but providing a more detailed and accurate mass balance that includes only the bike manufacturing remains challenging due to a lack of data.

There are some interesting developments in the bike production process. For example, a RIT Student thesis describes a new bike frame production system that uses 3D printed connection parts to join the different steel tubes instead of welding. The printing time for all the connection parts is about 56 hours. Using the most common 3D metal printers, they reduce the estimated energy consumption to 135W, about 20 times less than welding an aluminum frame. Additionally, some benchmark companies reviewed for this study, such as the Bjorne
bike company, said it uses diamond wire to cut the steel tubes and claims to minimize waste. Trek Bike said its upgraded robotic paint system led to a 90% reduction in carbon footprint. Another company called Tout-Terrain said it uses a powder coating system that uses electricity to reduce waste powder paint.

**Industrial Symbiosis**

To look at industrial symbiosis, this study examined a case study from Brazil, Netherland, India, and China. While each country is different due to local political and cultural conditions, there are some commonalities and ways to facilitate industrial symbiosis.

1. Reclassify certain materials as non-hazardous to encourage the exchange
2. Make it easier for exchangers to obtain the required license to handle the waste
3. Help to invest in circular infrastructures
4. Use eco-industrial parks to relieve logistical difficulties for long distances
5. A more open and communicative industry culture can help companies in finding industrial symbiotic opportunities
6. Social capital
7. Hold government-industry discussion to better understand the need for exchangers

**Packaging**

The packaging does play a role in the transition to a circular economy, and it is not as simple as using recycled materials. In general, packaging for bikes will use materials like Plastic Tapes, Plastic Bags, Foams, PVC, Staples, and Zip ties. In fact, the traditional bike box came with 20 liters of landfill waste as most of the plastic used was non-recyclable. A simple suggested order of precedent for packaging, in decreasing order of preferences, is

- No packaging
- Minimal Packaging
- Consumable, returnable, or reusable packaging
- Recyclable packaging
There can be several reasons for overpackaging. Maybe the producer is overly cautious about product protection; maybe it is to deter theft, or maybe just because the logistical company requires a certain level of packaging. These challenges require us to rethink packaging and collaborate with our supply chain. In the following sections, the report will present four examples of sustainable packaging for benchmark companies and the challenges they face.

Reduce Unrecyclable Materials (Trek Bike)

Trek bike has been very active in reducing the amount of non-recyclable materials in their packaging. They have reduced the number of non-recyclable pieces from 22 to 12, with a future goal of only two plastic parts and eventually going 100% recyclable and plastic-free. They have estimated these packaging changes eliminated 50,000 lbs. of plastic waste in a single year. Additionally, they have also created a recycling guide on their website. Their current packaging materials include paper, polypropylene, nylon, LDPE, ethylene-vinyl acetate (EVA), and rubber.

100% Recyclable Materials (Cannondale)

Cannondale has successfully transitioned to a 100% recyclable and plastic-free packaging scheme. Their previous packaging ships with 15 L of non-recyclable materials per bike. Switching to this packaging has reduced landfills by 4500 cubic meters while also providing better protection for their product. Their current packaging materials include 20% FSC-Certified cardboard, 80% recycle carton, plant-based inks, and rice paper tape (Fig 21).
Returnable/Reusable Packaging (Revel Bike)

Revel Bikes are shipped in reusable travel cases. Each case retails for more than $500, and they buy in bulk to reduce the price. If the customer doesn’t want the case, they can return it with a covered shipping back cost. In return, the customer receives a credit to use in future purchases. They have also collaborated with its supply chain to push for sustainable production.

Challenges

These and other biking companies have described several challenges, including:

- **Shipping Service Requirement**
  - For example, cannot get insurance coverage from freight companies without specific plastic reinforcements

- **Limited Demand for sustainable packaging**
  - Resulting in factories not wanting to adjust their current processes. It’s not the cost of the product, but the cost of changing their supply chain
  - But some factories are interested in this effort

- **Training of components distributor**
  - A distributor not aware of the environmental impact of packaging may train the next generation of the distributor to be as unsustainable

- **Psychology of Bike=Green can let the bicycle industry ignore the environmental impact of bicycle packaging**

- **Market competitiveness and a secretive culture**
  - Like industrial symbiosis, a secretive industry culture can become a roadblock for sustainable designs to be more widely implemented

Reverse Logistics and Product Stewardship

Reusing used products is one of the cornerstones of circular economy, which has led to the creation of reverse logistics. Reverse logistics is an effort to recover used production and put these used products back into the supply chain. This can mean taking in your own and maybe even other’s used production into the recovery stream. Reverse logistics ensure the right materials and qualities for your supply chain while reducing landfills and maximizing
material efficiency. Reverse logistics can have carried us by your own internal recovery system or be outsourced to a third party. You can also use the recycling marketplace to conduct reverse logistics. One example of reserve logistics is the returnable packaging of REVEL bikes and the Schwalbe Inner tube recycling system, as discussed in the previous section. Another highlighted example in this section would be the ROETZ bike company of the Netherlands. ROETZ bikes have Integrated circular economy into their business model by reworking the frame of discarded bikes and up-cycling materials to produce new bikes and accessories and has achieved 40% circularity with current models. They have currently three reverse logistic systems:

- Customer collecting approach
- Directly discarded bike collecting
- GPS bike return for reuse/recycle (Currently under development)

Under a customer collecting approach, buyers can receive a discount on their purchase if they bring their old bike to ROETZ for reuse and recycling. ROTEZ also has its direct collecting system, where they will locate and bring discarded bikes to their factory for cleanup and sorting. Some components are reused to produce new bicycles while the others are recycled. Their new GPS bike collecting system will attach a GPS to every sold bike and ensure that every bike sold can be located and recovered in the future and achieve 100% circularity.

Additionally, a company can employ methods of product stewardship to reduce the environmental impact of products. This will involve the collaboration of the entire supply chain. A good example will be the trek bike packaging, where detailed instructions of the recycling process of the packaging material are available online for customers to follow and help in recycling. However, this method may not be as effective as other methods such as extended producer responsibility (EPR), which designated the producer solely responsible for the product’s environmental impacts. Companies must also inform the public to participate in the stewardship operation.
Operations and Business Models

Daily operation, workspaces, and business models are as important for product manufacturing and logistics for corporative sustainability. For example, since the COVID-19 pandemic, more companies are starting to see remote working as part of the norm rather than a temporary anomaly. This change in mindset offers new opportunities for companies to rethink their operation models. Does every employee have to work in one place? Does the company truly require as much workspace as the industry previously thought? These are questions that impact not just the corporate operational structure but also the corporate environmental footprint. With more people engaged in an online working environment, daily commuting can be reduced, and previous workspaces can be vacated to companies that truly need them.

Other options to create a more circular and sustainable workspace may be to reduce waste by removing single-use items such as disposable cups and plastic drink bottles from the office and increase recycling of office materials such as used paper and composting of food waste. Furthermore, companies might reconsider their office equipment. Does every piece of equipment need to be brand new? And what to do with discarded office equipment? Will they be recycled? Or allow an employee to take home for free? With robotics taking over many manufacturing facilities, manufacturers can also reconsider the lighting and cooling option for their operations. Companies can also create a more sustainable building refitting according to LEED certifications. These actions can greatly improve the marketability and recognition of the company while also lead to cost savings. However, it is necessary to keep in mind that to become truly carbon-neutral, a building must generate more energy than it uses in its operation and construction to offset its carbon emissions.

Business Models

Transitional to a circular economy will require companies to rethink and restructure some components of their current business models. Some aspects of sustainable business
models are already discussed above, such as reverse logistics. Other areas and questions to reconsider may include:

- **Material Inputs**
  - What kind of material should be used in manufacturing? Is it sustainable? Easily Recyclable? Or Reusable? What is its impact on the environment and society?
  - Are the materials sourced sustainably? Does it have to be Virgin Material? Can your products build upon discarded bikes?

- **Supply Chain**
  - What kind of relationship does a company should have with its suppliers? Is it a short-term arrangement or a longer commitment? It can be seen in some examples presented above, engagement with suppliers and supply chain management with a sustainability focus is beneficial and essential for sustained corporate development.

- **The design of the product**
  - As discussed in the material section, a sustainable and circular design is often modular, repairable, and easily recyclable. The idea of the “Right of Repair” can also play a part in the design of an area.

- **How and where do you make a product?**
  - As the world saw in the recent COVID-19 pandemic, long and distant supply chains can be easily disrupted. Long transportation also means higher GHG pollution. Perhaps it is time for producers to start considering relocated manufacturing to a more local area.
  - Is the manufacturing outsourced or self-owned? In either case, a company should conduct audits to ensure humane treatment of workers and ensure a safe working environment. If outsourced, engagement with suppliers is necessary.
  - Robotics and AI are also replacing workers in the manufacturing areas. This leads to questions about retraining the workers for other occupations and the employment of local communities.
• Sales and Marketing
  o How to market your sustainable product and communicate with the customers about your sustainability actions? Perhaps through an annual report or social media?
  o Are the products sold online or at local bike shops? Or perhaps the company is operating or experimenting with new systems such as bike renting? Bike renting and sharing do play into the circular economy by reducing the material consumed by society.

• Distribution and Packaging
  o Do the bikes need to be distributed? Or can it be picked up without using the use of vehicles?
  o If the products need to be transported, what form of transportation will the company employ?
  o What packaging material will the product employ? Is the material reusable, recyclable, and renewable? Will the product need packaging at all? And how to minimize the need for packaging material?

• End-of-Life and Product Stewardship
  o Will the company establish reverse logistics and product stewardship schemes?

• Business Operations and Employees
  o Does the company need a particular facility? Can the work be conducted remotely?
  o Can the company help to reduce employee’s environmental impact by offering sustainable transportation methods such as free bikes or carpools?
  o How to make employees feel empowered by their work? For example, the ROETZ bike lets the buyer of a bike meet with the bike’s manufacturer, creating a personal connection between the customer and craftsman.

Conclusion
The biking industry will play an increasingly important role in our society’s effort to become more sustainable. Although biking is one of the most sustainable modes of
transportation available, there are areas that the industry can still improve. By looking at the supply chain, examine material and product design choices, and engaging with suppliers, the industry can find new opportunities to improve our operation. And through the adoption of a circular business model and working on transitioning to a circular economy, the biking industry not only ensure the sustainable development of society and the betterment of customers, but also reduces its operational cost, improve material efficiency, reduce the biking industry’s environmental impact, and sustain the continued development of the biking industry.
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