Environmental Impacts of Fuel Cell Assisted Bicycles in a Sharing Scheme

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In recent years, bicycle sharing systems have become increasingly popular in our society as an environmentally friendly mode of transportation. In this study, we discuss the bike sharing system in terms of the mitigation of eco-burden and/or biomass energy use (e.g., sewage sludge). Here, biomass energy use indicates that the bicycle’s fuel cell (FC) system is powered by H2 from the biomass. In other words, the bicycle is assisted with an FC and H2 storage as an alternative to the conventional Li-ion battery. Note that the H2 fuel is purified through the fermentation process and metal hydrides (MHs) are used for storing H2. In our study, we selected Sendai city as the model area. Our objective was to estimate the eco-burdens of our proposed bicycle using life cycle assessment methodology. We estimated the environmental impacts of the bicycles in the target area, considering their FC performance over a period of 10 years. Consequently, bicycle sharing using FC bicycles can reduce abiotic depletion potential by 15% and global warming potential by 10% compared to conventional bicycle sharing systems.

Key Words
Bio-Hydrogen, Life Cycle Assessment (LCA), Metal Hydride, Fuel Cell, Bicycle Sharing

1. Introduction
Biomass is any organic matter—wood, crops, seaweed, and animal waste—that can be used as an energy source. As biomass is carbon neutral, it is an attractive energy source that contributes to the abatement of environmental impact. In urban areas, sewage sludge is easier to collect than other biomass and is often available where energy demand is expected. Bio-hydrogen (Bio-H2) synthesized from biomass feedstock through fermentation or the gasification process is an eco-friendly fuel that can be used for fuel cell (FC) applications.

In recent years, bicycle sharing systems have become increasingly popular. The spread of bicycle sharing systems has reduced the number of cars used and enables more environmentally friendly traffic solutions. Furthermore, it has a positive impact on health and leads to a sustainable compact city. In Sendai city, located in the Tohoku region of Japan, prior research on the implementation of a bicycle sharing system was conducted in 2010. Sendai city is a government-designated city with a considerable population and well-developed public transportation, but there is still a strong dependence on car movement. In this study, we...
focused on Sendai city to reduce the number of cars used by promoting the bicycle sharing system.

Here, we propose a hydrogen-FC bike (H-bike) for the bicycle sharing system, using a polymer electrolyte FC (PEFC). For H₂ fuel, we used Bio-H₂ synthesized from sewage sludge. For all systems, we analyzed the environmental impact using life cycle assessment (LCA) methodology to compare our H-bike to conventional electric bikes (E-bikes), which use a Li-ion battery. In addition, the LCA assumes long-term 10-year use in Sendai city. Our purpose is to estimate the effect of installed bicycles in addition to its performance.

Regarding charging/filling, energy can be supplied at the cycle port, i.e., bicycle parking. This means that there is no additional driving required for charging/filling.

High-pressure gas tanks are mainly used for FC vehicles to store H₂; however, the use of high-pressure gas is considered dangerous, and there are some regulations for handling gas. Metal hydrides (MHs) are attracting much attention because they do not use high-pressure gas and are considered less dangerous. By replacing the current MH cartridges with new ones, H₂ can be supplied easily. Cartridges can be installed in a variety of places, including convenience stores. MH can be used for small vehicles with limited installation space because MH has a high H₂ volume density. The amount of H₂ that can be stored in MH per volume (kg/L) is 1.11 mass%, which is higher than that of the high-pressure gas tank (70 MPa). In view of these aspects, a storage method using MHs is assumed.

From the perspective of FC mounting on a bicycle, a lanthanum-rich misch metal nickel alloy (LmNi₄.73Mn₀.12Al₀.15) will be used, which can supply H₂ at room temperature (25°C) and normal pressure (0.1 MPa). The maximum pressure in an on-site H₂ purification system is 0.4 MPa and the system produces H₂ at a pressure of 0.4 MPa. Because this pressure is equal to the storage pressure for MH, no compressor will be needed in the storage phase.

There are challenges in using H₂ in terms of cost. However, research should be conducted in anticipation of declining H₂ prices in the next few years because using H₂ is attracting attention from an environmental point of view. In addition, according to the Fifth Basic Environmental Plan, creating and producing a model that uses H₂, as in this study, is considered a cost-reducing effort. The development of FC-powered vehicles has advanced to the practical stage: Pragma Industries is commercially marketing FC-assisted bicycles, and Asia Pacific Fuel Cell Technologies Ltd (APFCT) is developing an alloy-fueled scooter that meets Taiwan Vehicle Safety Certification.

As a part of an LCA impact analysis, we consider the abiotic resource depletion potential (ADP) and global warming potential (GWP) as important indices. ADP is used to evaluate the utilization of resources. It is defined as the ratio of the annual production and the square of the ultimate (crustal content-based) reserve for the resource, divided by the same ratio for a reference resource (Sb). The GWP assesses the impact on global warming, using carbon dioxide as its reference substance, and taking into account the impact over 100 years.

The rare metals, Pt and/or Ni, and others, used in FC systems also impact the ADP index. In addition, according to previous research, ADP and other environmental impact categories are similar in terms of platinum placement in each impact category. In other words, Pt can be a representative indicator of other impact categories. Therefore, ADP is considered as an indicator here. In addition, the use of FC and the spread of the bicycle sharing system are attracting attention as they contribute to the mitigation of global warming; hence, GWP is also considered.

2. Experimental Methodology

2.1 Case study in Sendai

First, the data obtained from our bicycle sharing experiment are shown in Table 1. This experiment was conducted in Sendai city in 2010, and was continued over 30 days (20 weekdays and 10 holidays), utilizing 10 cycle ports and 100 bicycles. There was no usage fee, and all participants were aged 18 and over, except for high school students. Next, the amount of annual sewage sludge available in Sendai City from 2018 is 16,619 t-DS. The sludge subsystem energy production used to support the bicycle FC is fully explained in 2.5.2.

2.2 Life cycle assessment (LCA)

In this study, we evaluated the environmental impact of each battery through LCA, an environmental impact assessment methodology based on ISO 14040 and 14044. The environmental impacts were assessed using Simapro software Ver.8.5.0.0. The background data were derived from Ecoinvent 3 and a CML model was used as an environmental impact assessment method.

| Table 1 | Experimental data in Sendai city |
|---------|----------------------------------|
| average utilization time | 29 min/1 bicycle |
| average use frequency per day | 596 times/100 bicycles |
2.3 System boundary and functional unit

The bicycle evaluation was divided into two phases: battery production and energy production (see Fig. 1). In this study, we argue the following two cases: the conventional assisted bicycle (E-bike) and the FC assisted bicycle (H-bike). The E-bike was analyzed for Li-ion battery production and the electric power production based on the average Japanese electricity mix data. The H-bike was analyzed for both FC and H₂ production, which were synthesized from sewage sludge. FC battery production is divided into two manufacturing aspects: the MH for storing H₂ production and FC unit production. Note that in the material recycling in each part, disposal is not taken into consideration.

The functional unit of this study is 1.54×10⁷ km traveled, i.e., the total travel distance for 10 years by bicycle sharing using 100 bicycles, which was calculated using the following formula:

\[ TD = tNv \times 365 \times 10 \]  

Where:
- \( TD \): The traveling distance for 10 years [km/100 bicycles]
- \( t \): The average utilization time observed listed in Table 1 [min/1 bicycle]
- \( N \): The average use frequency per 1 day listed in Table 1 [times/100 bicycles]
- \( v \): The average bicycle speed [km/min]

The functional unit is determined with reference to Table 1. Note that the average bicycle speed is 14.6 km/h ¹⁴.

2.4 Bicycle specifications

Table 2 shows the bicycle specifications in this study ¹⁵ ~ ¹⁹.

The rated output and battery weight are the values for the bicycles used in this experiment. Regarding the candidates for MH, we selected the components with respect to the operating conditions. In the assisted bicycle, the temperature is close to atmospheric conditions. Therefore, we selected LmNi₄.73Mn₀.12Al₀.15 for MH to be installed in the bicycle frame.

Conversion efficiency refers to the charging / discharging efficiency of each battery. Regarding the H-bike, we considered both the conversion efficiency and also the H₂ storage efficiency. The definitions of the H₂ storage efficiency are as follows:

\[ \eta = \frac{H_d}{H_s} \]  

Where:
- \( \eta \): H₂ storage efficiency
- \( H_d \): H₂ output
- \( H_s \): H₂ input

| Table 2 Bicycle specifications |
|-------------------------------|
| **E-bike (Li-ion)** | **H-bike (FC)** |
| Rated output | 240 W | 240 W |
| Conversion efficiency | 0.95 | 0.50 |
| H₂ storage efficiency | - | 0.93 |
| Lifetime per 1 bicycle | 24,000 km | 120,000 km |
| Energy capacity | 1.10 MJ | 3.27 MJ |
| Battery weight | 2.12 kg | 5.08 kg (FC+MH) 0.93 kg (except MH) |

Note: H₂-LHV is 10.8 MJ/Nm³.

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**E-bike**

- Resources Mining
- Transport / Storage
- Material Production
- Parts Manufacturing
- System Manufacturing
- Transport / Storage
- Li-ion Battery
- Electricity

**H-bike**

- Resources Mining
- Material Production
- Parts Manufacturing
- Fuel Production
- Transport / Storage
- Power Generation
- Hydrogen
- Fuel Cell
- Metal Hydride
- Biogas Production
- Reforming
- 2-step PSA
- Wastewater
- CO₂ eq
- Used Catalyst
- Wastewater
- CO₂ eq
- Electricity
- Adsorbent
- Catalyst
- Electricity
- Air
- Water
- Electricity
- Adsorbent
- Sewage sludge
The amount of H\(_2\) discharged from MH [NL]

H\(_2\): The amount of H\(_2\) stored in MH [NL]

Regarding the storage performance, we estimated the relationship between the MH weight, and the amount of H\(_2\) stored and discharged in our previous experiment \(^7\). In this experiment, varying MH weight of 26.61, 55.75, 102.90 and 211.12 g, we measured the storage performance using mass flow controllers. The initial flow rate was 1000 cc/min, and the measurement was continued until the flow rate was 10 cc/min (see Fig. 2). Consequently, we confirmed that MH can charge and/or discharge H\(_2\) at a pressure of 0.4 MPa and the atmospheric temperature. Then, the amount of H\(_2\) stored, the amount of H\(_2\) discharged, and H\(_2\) storage efficiency are calculated.

Energy capacity refers to the amount of energy that the battery can provide per charging. The energy capacity of the E-bike is based on the bicycle’s specifications targeted in this experiment, and the H-bike is defined from the amount of H\(_2\) that can be stored in MH.

To evaluate environmental impacts using LCA, the energy demand for each bicycle was determined (see Table 3). The input energy for each bicycle was obtained from the fuel economy in each case. Note that the fuel economy was evaluated by the road test using a conventional assisted bicycle. In addition, in this experiment, we confirmed that the weight gain (e.g., approximately 3 kg) is not affected by the fuel economy. This means that the fuel economy loss due to the weight gain of the MH for H\(_2\) storage is negligible.

2.5 Inventory analysis

2.5.1 Subsystem of battery manufacturing

The background data on Li-ion batteries, FC batteries, and MH in the manufacturing phase are based on the database Ecoinvent 3. Referring to the previous study, we applied the Six-Tenth Factor Rule to the data from Mizuho Information & Research Institute, Inc., and the specific material data to determine the FC batteries production \(^7\) \(^2\) \(^9\). Foreground data for the manufacture of a single battery are shown in Table 4.

2.5.2 Subsystem of energy production

The input energy for charging batteries is as follows: the input energy is conventional electricity in the case of the E-bikes, and H\(_2\) for the H-bikes. Bio-H\(_2\) production by sewage sludge is used for the H\(_2\), and the inventory data is based on the process design using the Aspen Plus Ver9.1 \(^1\) process simulator. The entire system involves three processes: biogas fermentation, methane reforming, and H\(_2\) refinery through 2-step pressure swing adsorption (2-step PSA). A two-step PSA was considered to reduce the energy consumption of H\(_2\) purification. Note that the concentration of H\(_2\) was assumed to be 99.99 vol. %. In addition, the inventory data of auxiliary energy consumption was considered, while the material data of plant facilities was ignored. We did this because the impact values of materials are negligible in comparison to the energy values. In this process design, the sewage sludge required to produce 1 Nm\(^3\) of H\(_2\) is 1.84 kg-DS. Foreground data for a 1 km bike

![Fig. 2 H\(_2\) Storage and Discharge](image)

### Table 2 Performance parameters in travelling

|                | E-bike(Li-ion) | H-bike(FC) |
|----------------|----------------|------------|
| Specific travel distance (/1 charge) | 106 km | 314 km |
| Fuel economy   | \(1.10 \times 10^2\) MJ/km | \(2.22 \times 10^2\) MJ/km |
| Output         | 42.2 W         |            |
| Output energy  | \(1.04 \times 10^{-2}\) MJ/km |            |

### Table 3 Performance parameters in travelling

|                | Li-ion battery manufacturing | FC battery manufacturing |
|----------------|------------------------------|--------------------------|
| Perfluorosulfonic acid-based electrolyte membranes | 0.0610 kg/unit | 0.0013 kg/unit |
| Perfluorosulfonic acid-based electrolyte resin | 0.00434 kg/unit | 0.00246 kg/unit |
| Carbon fiber | 0.274 kg/unit | 0.00114 kg/unit |
| Platinum | 0.00217 kg/unit | 0.00217 kg/unit |
| Carbon black | 0.00217 kg/unit | 0.00217 kg/unit |
| Synthetic graphite | 0.717 kg/unit | 0.00114 kg/unit |
| Phenolic resin | 0.180 kg/unit | 0.00114 kg/unit |
| Silicone rubber | 0.0456 kg/unit | 0.00114 kg/unit |
| Steel | 0.407 kg/unit | 0.00114 kg/unit |
| Lanthanum-rich misch metal nickel | 415 kg/unit |
ride are shown in Table 5. Note that the greenhouse gas emission factor for electricity is 0.699 kg-CO$_2$/kWh.

2.6 Evaluation of environmental indicators

In this study, the environmental impact of a long-term bicycle sharing scheme is measured. To make our evaluation meaningful, we set up the following two scenarios: Scenario 1: Impact analysis on bicycle manufacturing. Scenario 2: Impact analysis on long-term use (10-years) of the bicycle sharing scheme in Sendai city.

In Scenario 2, we indicate the number of batteries estimated, energy demand, and traveling distance for 10 years (see Table 6). "Number of batteries estimated" is the number of batteries corresponding to the inventory data per functional unit (10-years mileage: 1.54 × 10^7 km). Note that we assume that shared bicycles will be used in equal measures. The number of batteries estimated for 10 years was calculated as follows:

\[ NE = \frac{TD}{LD_E} \]  
\[ NH = \frac{TD}{LD_H} \]

Where:
- \( NE \): The number of E-bike batteries estimated for 10 years
- \( NH \): The number of H-bike batteries estimated for 10 years
- TD: The traveling distance for 10 years [km/100 bicycles]
- \( LD_E \): The lifetime driving distance of E-bike listed in Table 2 [km/10 years]
- \( LD_H \): The lifetime driving distance of H-bike listed in Table 2 [km/10 years]

Here, we note that the amount of sewage sludge in Sendai city is sufficient: the amount of sewage sludge required for a 10-year sharing cycle is 58.7 t-DS from Section 2.5. From Section 2.1, the amount of sewage sludge produced over 10 years is 166,000 t-DS, which is 2830 times more than the amount required in the 100-bicycle share cycle.

3. Results and Discussion

3.1 Results of Scenario 1

Fig. 3 shows the LCA results of Scenario 1. Both ADP and GWP of H-bikes were impacted more than those of E-bikes. Considering ADP, H-bikes had a stronger impact due to the precious metal used in the application.

3.2 Results of Scenario 2

Fig. 4 shows the LCA results of Scenario 2. Both impact values of H-bikes were smaller than those of the E-bikes because the number of Li-ion batteries required is 5 times that of FC batteries. Considering the lifetime of each battery, with a lifetime that is 5 times longer, the distance that can be driven per bicycle will be 5 times longer, and the number of bicycles needed to meet the driving demand will decrease. In the case of the H-bikes, the environmental impact of fuel is also lower. This result implies that the promotion of a bicycle sharing scheme using H-bikes achieves an ADP mitigation of 15% and GWP abatement of 10% in comparison to the E-bikes case.

It should be noted that this study focuses on assessing both ADP and GWP and uses Ecoinvent 3 for background data. However, it does not take into account changes in global warming potential over a 10-year period.

| Table 5 | Foreground data per 1 km travel |
|---------|--------------------------------|
|         | E-bike                        | H-bike                        |
| Electricity | 3.04 × 10^-3 kWh/km         |                               |
| Hydrogen    | 2.07 × 10^-3 Nm^3/km        |                               |

| Table 6 | Data about bicycle sharing for 10 years |
|---------|----------------------------------------|
|         | E-bike (Li-ion) | H-bike (FC) |
| Number of batteries | 640 units/10yrs | 128 units/10yrs |
| Energy demand | 1.68 × 10^5 MJ/10yrs | 3.44 × 10^5 MJ/10yrs |
| Traveling distance | 1.54 × 10^7 km/10yrs | |

Fig. 3 Results of ADP and GWP (Scenario 1)
4. Conclusions

In this study, we argued for the promotion of a bicycle sharing scheme. In particular, regarding the potentiality of FC assisted bicycles, we estimated the environmental aspects on the basis of an LCA. As a result, we found that our proposal has good potential in terms of environmental protection through road tests by an assisted bicycle and/or the performance tests of FC applications, even while FC assisted bicycles are still being developed. In other words, more environmental benefits will be obtained with long-term usage, such as a sharing scheme. In future research, we will carry out R&D on the H2 refinery system, including H2 storage using two-step PSA and impurity removal technology.

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