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Environmental Impacts of Fuel Cell Assisted Bicycles
in a Sharing SchemeEmi HOSOBUCHI^{※1†}, Chiharu MISAKI^{※1}, Noboru KATAYAMA^{※2}, Yin LONG^{※1}, and Kiyoshi DOWAKI^{※1}

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In recent years, bicycle sharing systems have been increasingly promoted 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 H_2 from the biomass. In other words, the bicycle is assisted with an FC and H_2 storage as an alternative to the conventional Li-ion battery. Note that the H_2 fuel is purified through the fermentation process and metal hydrides (MHs) are used for storing H_2 . 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.

近年、環境負荷の小さい交通手段として、コミュニティサイクル(シェアサイクル)が注目を集めている。本研究では、環境負荷低減や、バイオマスエネルギー(下水汚泥等)由来の水素燃料の利用を考慮した、自転車シェアリングシステムを検討する。従来のコミュニティサイクルには、リチウムイオン電池を搭載した電動アシスト自転車を用いられているが、本研究ではその代替システムとして、航続距離の延長と環境負荷低減を目的に、燃料電池(FC)を搭載したシステムを想定した。なお、 H_2 はメタン発酵工程を経て精製されることとし、水素貯蔵には水素吸蔵合金(MH)を用いることとする。また、仙台市をモデル地域とし、提案する自転車の環境負荷を、ライフサイクルアセスメント(LCA)を用いて評価した。FC自転車の性能を考慮し10年間の環境負荷を試算した結果、自転車シェアリングにFC自転車を用いることによる環境負荷の低減が示唆された。従来のコミュニティサイクルと比較して、非生物資源枯渇領域において15%、地球温暖化領域において10%、環境負荷を低減することが明らかになった。

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- H_2)

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 city¹⁾. In Sendai city, located in the Tohoku region of Japan, prior research on the implementation of a bicycle sharing system was conducted in 2010²⁾. 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

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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 H_2 fuel, we used Bio- H_2 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 H_2 ; however, the use of high-pressure gas is considered dangerous, and there are some regulations for handling gas³⁾.

Metal hydrides (MHs) are attracting much attention because they do not use high-pressure gas and are considered less dangerous⁴⁾. By replacing the current MH cartridges with new ones, H_2 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 H_2 volume density. The amount of H_2 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)⁵⁾. 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 ($LmNi_{4.73}Mn_{0.12}Al_{0.15}$) will be used, which can supply H_2 at room temperature (25 °C) and normal pressure (0.1 MPa). The maximum pressure in an on-site H_2 purification system is 0.4 MPa and the system produces H_2 at a pressure of 0.4 MPa⁶⁾. Because this pressure is equal to the storage pressure for MH, no compressor will be needed in the storage phase⁷⁾.

There are challenges in using H_2 in terms of cost. However, research should be conducted in anticipation of declining H_2 prices in the next few years because using H_2 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 H_2 , as in this study, is considered a cost-reducing effort⁸⁾. 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^{9) 10)}.

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 category¹¹⁾. 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^{8) 12)}; 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 2010²⁾, 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-DS¹³⁾. 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

	Value
Average utilization time	29 min/1 bicycle
Average use frequency per 1 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:

$$TD = tNv \times 365 \times 100 \quad (1)$$

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/h¹⁴.

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 LmNi_{4.73}Mn_{0.12}Al_{0.15} 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:

$$\eta = \frac{H_d}{H_s} \quad (2)$$

Where:

η : H₂ storage efficiency

Table 2 Bicycle specifications

	E-bike (Li-ion)	H-bike (FC)
Rated output	240 W	240 W
Conversion efficiency	0.95	0.50
H ₂ 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

E-bike

H-bike

Fig. 1 System boundary

H_d : The amount of H_2 discharged from MH [NL]

H_s : 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 experiment⁷⁾. 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) 20)}. 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 Ver9.1¹⁶⁾ 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 Nm³ of H_2 is 1.84 kg-DS. Foreground data for a 1 km bike

Fig. 2 H_2 Storage and Discharge

Table 3 Performance parameters in travelling

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

Table 4 Foreground data for producing a battery

Li-ion battery manufacturing	
Li-ion battery	2.12 kg/unit
FC battery manufacturing	
Perfluorosulfonic acid-based electrolyte membranes	0.0610 kg/unit
Perfluorosulfonic acid-based electrolyte resin	0.00434 kg/unit
Carbon fiber	0.274 kg/unit
Platinum	0.00217 kg/unit
Carbon black	0.00217 kg/unit
Synthetic graphite	0.717 kg/unit
Phenolic resin	0.180 kg/unit
Silicone rubber	0.0456 kg/unit
Steel	0.407 kg/unit
MH manufacturing	
lanthanum-rich misch metal nickel	4.15 kg/unit

Table 5 Foreground data per 1 km travel

E-bike	
Electricity	3.04×10^{-3} kWh/km
H-bike	
Hydrogen	2.07×10^{-3} Nm ³ /km

ride are shown in Table 5. Note that the greenhouse gas emission factor for electricity is 0.699 kg-CO₂/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:

$$NE = \frac{TD}{LD_E} \quad (3)$$

$$NH = \frac{TD}{LD_H} \quad (4)$$

Where:

NE: The number of E-bike batteries estimated for 10 years

NH: The number of H-bike batteries estimated for 10 years

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	

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.

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

Fig. 4 Results of ADP and GWP (Scenario 2)

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 addition, if Bio-H₂ from sewage sludge generated in the city area (e.g., apartments, food shops, restaurants, etc.) will be promoted, the energy generation would be the basis of increased bicycle rental. 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.

References

- 1) Ministry of Land, Infrastructure, Transport and Tourism, https://www.mlit.go.jp/road/ir/ir-council/cyclists/pdf7/04jitensha_shiryou3.pdf (Last access: September 5, 2019)
- 2) Sendai city, http://www.city.sendai.jp/jitensha/kurashi/machi/kotsu/jitensha/torikumi/documents/komisaikokka_1_1.pdf (Last access: September 5, 2019)
- 3) Yoshihide, S., *Safety Engineering*, **44**(6), 427-434 (2005)
- 4) Itsuki, U., *Hydrogen Energy System*, **25**(2), 8-18 (2000)
- 5) Shimizu, T., *J. Surf. Finish. Soc. Jpn.*, **56**, 189-193 (2005)
- 6) Kako, S.; Seo, Y.; Dowaki, K.; Kameyama, M., The 14th Conference on Biomass Science (the Japan Institute of Energy), 137-138 (2019)
- 7) Yamate, S.; Fujiwara, Y.; Tadokoro, H.; Katayama, N.; Seo, Y.; Kameyama, M.; Dowaki, K., *J. Jpn. Inst. Energy*, **97**, 336-341 (2018)
- 8) Ministry of Economy, Trade, and Industry, <https://www.meti.go.jp/press/2018/03/20190312001/20190312001-1.pdf> (Last access: September 5, 2019)
- 9) Pragma Industries, <https://www.pragma-industries.com/light-mobility> (Last access: August 15, 2020)
- 10) Asia Pacific Fuel Cell Technologies, Ltd., <http://www.apfct.com/en/technology/fuel-cell> (Last access: August 15, 2020)
- 11) Duclos, L.; Lupsea, M.; Mandil, G.; Svecova, L.; Thivel, P. X.; Laforest, V., *J. Clean. Prod.*, **142**, 2618-2628, (2017)
- 12) Ministry of the Environment, <https://www.env.go.jp/guide/budget/h26/h26-gaiyo/058.pdf> (Last access: September 5, 2019)
- 13) Miyagi Prefectural Government, <https://www.pref.miyagi.jp/soshiki/gesui/55-odei.html> (Last access: August 20, 2020)
- 14) Makoto K., Japan Institute of Country-ology and Engineering, The 20th Japan-Korea Construction Technology Seminar, http://www.jice.or.jp/cms/kokudo/pdf/reports/act/20th/nikkan2009_05.pdf (Last access: July 26, 2019)
- 15) Yamaha Motor Co., Ltd., <https://www.yamaha-motor.co.jp/pas/owner-support/manual/pdf/X0T-28199-JG.pdf> (Last access: October 3, 2019)
- 16) Saw, L. H.; Ye, Y.; Tay, A. A., *J. Clean. Prod.*, **113**, 1032-1045 (2016)
- 17) Mellino, S.; Petrillo, A.; Cigolotti, V.; Autorino, C.; Jannelli, E.; Ulgiati, S., *Hydrogen Energ.*, **146**, 5 (2016)
- 18) NEDO, <https://www.nedo.go.jp/content/100106566.pdf> (Last access: October 3, 2019)
- 19) Shanghai Re-Fire Technology Co., Ltd, <http://www.re-fire.com> (Last access: October 3, 2019)
- 20) Mizuho Information & Research Institute Inc., Survey on Lifecycle Evaluation of Stationary Fuel Cell System and Fuel Cell Vehicle (2008)