Article

Improvement of Power Capacity of Electric-Assisted Bicycles Using Fuel Cells with Metal Hydride

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Abstract: Hydrogen is an alternative fuel that is currently being used in fuel cell (FC) applications. This study focuses on electric-assisted bicycles (electric bicycles) powered by FCs and aims to determine the configuration of an FC system based on power demand. Metal hydrides (MHs) were used in the investigation to facilitate the containment of FC systems with improved hydrogen storage capacity. The flow performance was evaluated in our previous study; thus, here we focused on understanding the hydrogen flow characteristics from storage and the weight gain of the cartridge. Through experiments performed on existing electric-assisted bicycles, the relationship between the load weight and the power demand was evaluated. Furthermore, the power capacity of Li-ion batteries and FC systems was compared. No loss in performance was observed up to an additional payload weight of 8 kg. Combining the FC unit with an auxiliary battery offers up to 6.81× benefits with a significant weight capacity (8 kg). It is inferred that the current MH tank design does not support the required amount of hydrogen. The hydrogen flow could be supported by the exhaust heat of the FC to the MH.

Keywords: electric bicycle; fuel cell; metal hydride; electric demand; weight; sizing power distribution; auxiliary power

1. Introduction

Recently, Daud et al. [1] indicated that fossil fuels cannot satisfy the world energy demand and, even if they could, they adversely impact the environment. In East Asia, there is already a sense of crisis due to the dependence on oil and natural gas imports [2]. In this context, renewable energy has appropriate potential to provide solutions; however, the renewable energy sources also have certain limitations. For example, the electricity generated by photovoltaics or wind turbines is currently inadequate for the general grid owing to the uncertainties in climatic conditions. However, hydrogen, an energy source that can be used to produce electricity, is being considered as the most promising fuel. This power generation system refers to a fuel cell (FC) that obtains electricity by chemically reacting hydrogen as a fuel with oxygen in the air without any CO₂ emission. In general, FC technology can generate this energy with high efficiency. Moreover, the conventional methods and technologies of extracting hydrogen from oil and natural gas are already in use, indicating that the renewable resources derived from biomass feedstocks and water can be utilized using processes such as fermentation, gasification, and electrolysis. Furthermore, hydrogen can be stored regardless of external factors and can be used on demand [2]. The expected hydrogen demand is approximately 10 EJ in 2020 and is estimated to be 78 EJ in 2050 [2]. In particular, China is projected to have the largest hydrogen demand. Additionally, CO₂ emissions can be reduced by up to 2.7% in East Asia with the expansion of the

hydrogen market [2]. Considering the contribution required towards the mitigation of greenhouse gas emissions, the necessity of extracting hydrogen energy from renewable resources and the development of FC applications with high efficiencies are imminent [3].

By 2020, an expanding market was expected to facilitate the commercialization of FCs [3]. Although light-duty FC vehicles (FCVs), such as scooters [4] and bicycles [5], have been developed since 2000, FC buses and/or railway trains have not been promoted extensively in our society [2,4].

In Japan, efforts are being made to reduce the cost of major elemental technologies so that the price of FCVs will be about the same as EVs in the future. In addition, in the hydrogen supply chain, a hydrogen production project using lignite is being promoted to reduce the price of hydrogen [6]. In 2019, major convenience stores in collaboration with Toyota started a project to utilize small FC trucks, FC generators, solar panels, rechargeable batteries, and building energy management systems (BEMS) in convenience stores to reduce the environmental burden [2]. Toyota is aiming to build a hydrogen supply chain based at a railway station to introduce FC technology to the railways [7]. In addition, Toyota has developed a maritime FC system, operated by combining renewable energy and an in-vehicle system that produces hydrogen from seawater [8].

Recently, rising interest in electric-assisted bicycles has been observed. In China, there is an increasing demand from residents in areas with poor public transport, women carrying children, and high-income earners [9]. Maruyama et al. [10] evaluated the environmental impact of electric-assisted bicycles, scooters, passenger cars, and light trucks as short-distance transportation. That study found that electric-assisted bicycles have a low environmental impact even when evaluated by various indicators, such as service life and number of passengers. In 2020, COVID-19 led to restricted contact between people, resulting in increased use of electric-assisted bicycles as a sustainable means of transportation [11]. In addition, the installation of a bicycle lane results in the cars running next to the bicycle lane driving at a lower speed and the amount of exhaust gases being reduced [11], better ensuring the safety of cyclists [12]. However, it should be noted that pedestrians of different genders, ages, and regions are uncomfortable with the width of the bicycle lane and the road design policy for sustainable traffic changes [13]. According to Nikiforiadis et al. [13], women are generally less satisfied with the transportation infrastructure than men. In addition, young people are less satisfied with the transportation infrastructure than older people. In Japan, approximately 30% of the CO₂ emissions in the transportation sector is from household vehicles [14]. Moreover, the proportion of personal users who commute within 5 km using their own vehicles stands at approximately 40%. Therefore, the Japanese government suggested an alternative, such as a bicycle and/or public transportation [4]. Recently, a bicycle-sharing system using electric-assisted bicycles has been implemented [15]. According to Hosobuchi et al. [16], the distance traveled per bike per day by shared bicycles is approximately 43 km in Sendai, Japan. It is nearly 60 km in Taipei, where the shared cycle program is primarily for commuting [17]. Thus, FC technology is expected to be employed on a large scale for e-bikes.

FCs can generate electricity sourced from hydrogen and oxygen and emit only water. Therefore, from the perspective of life-cycle assessment—from the cradle to the grave—FCs are considered as an eco-friendly technology alternative to Li-ion batteries because of their longer lifetime [18]. In addition, the energy conversion efficiency (40–50%) of FCs is higher than that of coal-fired power generation systems [19]. Azadeh et al. [20] reported an efficiency of 35% for powered bicycles, and Folkesson et al. [21] stated that the hybrid polymer electrolyte membrane (PEM) fuel cell concept bus exhibited an efficiency of 40%. In the proposed project, the use of renewable hydrogen fuel was considered under FC technology.

The FCs are produced through the biomass gasification process of woody materials, sewage sludge, and so on. The promotion of this technology would solve numerous environmental issues and create new business schemes that contribute to the improvement of economic conditions. Currently, there are six main types of FCs: alkaline, phosphoric acid, molten carbonate, solid oxide, polymer electrolyte membrane FCs (PEMFCs) (also called proton-exchange membrane FCs), and direct

methanol FCs (DMFCs). Among these, PEMFCs and DMFCs can operate at low temperatures (e.g., room temperature) [19], but DMFCs have lower efficiency than PEMFCs and can have polluting byproducts [19]. Additionally, PEMFCs can operate at light mass and high power density, making them the most promising FC technologies. They are used not only in stationary devices, but also in portable devices [1]. However, there are four known problems in promoting PEMFCs. The first issue is the stable supply of high-purity hydrogen. Dowaki [22] reported that H_2S (hydrogen sulfide) contamination degrades the performance and lowers the voltage of PEMFCs [22]. The second issue concerns the spatial accommodation of PEMFC systems. Ulrich et al. [23] reported that the high-pressure storage configuration in FCVs is designed in consideration of space and weight, which are significantly attributed to the performance, and that inadequate conditions worsen the performance. The third issue involves the improvement of efficiency and storage capacity of the FC battery. This is related to the fourth problem of PEMFCs comprising the socioeconomic issues related to the establishment of hydrogen infrastructure [24] (e.g., hydrogen fuel stations and safety measures), which costs a few hundred billion dollars [3,24].

Thus, to solve the second and third problems, this study focused on hydrogen storage using a metal hydride (MH). The storage method is primarily based on chemical adsorption [23]. The volumetric density of MH is higher than that of compressed hydrogen, and the operating pressure at room temperature (25–30 °C) is relatively lower. The amount of hydrogen can be changed in accordance with the user demand [25]. Comparing the storage capacities of MH (Japan Metals & Chemicals Co., Ltd.) and Li-ion batteries (Yamaha Motor Co., Ltd., Shizuoka, Japan), Li-ion has a storage capacity of nearly 150 Wh/kg and 200 Wh/L [26], and MH ($LaNi_5$) has a storage capacity of approximately 120 kg- H_2/m^3 (4033 Wh/L), i.e., approximately 1.0 mass% (336 Wh/kg) [27]. This high energy density enables the system to operate for a longer time. Hara et al. reported that the negative environmental impact of an e-bike with hydrogen compression is worse than that with an MH [28].

Several studies have been conducted on FC and MH-powered light vehicles. Kendall et al. [29] developed an FC-powered electric motorcycle with 2.4 kWh of hydrogen storage, extending the driving range from 25 miles on lead-acid batteries to about 160 km. This design used a high-pressure tank (350 bar) for hydrogen storage; MH storage was also examined, but was rejected because of weight and heat problems. In addition, Kheirandish et al. [30] developed an electric-assisted bicycle equipped with FC and MH. They reported that the hydrogen storage medium should be changed to high-pressure gas because of the inability to provide a stable supply of hydrogen from MH during the operation. However, they did not anticipate an appropriate power demand during operation. If an appropriate power demand could be estimated, the amount of hydrogen supplied by the MH would change and, hence, the configuration of the system would change. In addition, the energy density per weight of MHs (including the MH cartridge) is smaller than that of Li-ion batteries; thus, the change in power demand in terms of weight change when MHs are replaced would also need to be considered. Therefore, this study focused on electric-assisted bicycles using FCs with an MH storage cartridge. As an alternative to the conventional assisted bicycle (e-bike), assisted bicycles mounted with FCs having an MH cartridge (h-bike) were discussed. If this h-bike is developed, the bike can travel a longer distance on a charge than a conventional e-bike. Shuguang et al. [31] argued that, if the demand for e-bikes increased in the future, the batteries had to be recharged. However, h-bike will surely gain the battery capacity. Therefore, the user can reduce the recharge time of the battery. That is, without any inconvenience, they can ride an h-bike, by which the eco-friendly mobility scheme would be achieved. The objective of this study is to determine the power demand of an h-bike and predict the steady state for standardized running schedules.

First, the operational performance of a conventional e-bike was investigated. Thereafter, the power demand for the supposed running conditions was estimated using the measured results in a physical simulation. The rated power of the FC was introduced after the estimations of power demand in steady states were completed. In addition, a battery or an ultra-capacitor can be used as an auxiliary power source during peak power demands [21]. Furthermore, the total weight of the FC unit in

comparison with the conventional Li-ion battery should be considered to optimize performance and energy consumption. Therefore, the additional weight of the FC device and MH cartridge is a concern with regards to the performance. For this reason, the performance differences of an h-bike using the test data under varying weight conditions were analyzed. Finally, the hydrogen loading time from the MH tank was investigated to determine the effectiveness of the h-bike in use.

2. Materials and Methods

2.1. Experiment on Power Demand for e-Bike

The amount of electricity required to run an e-bike was investigated by running tests, conducted using a conventional electric-assisted bicycle (PAS ami PA26A, Yamaha, Shizuoka, Japan), which comes loaded with a conventional Li-ion battery having a nominal voltage of 25.5 V and electricity capacity of 12.3 Ah (Figure 1). The following measurement tools were built into the e-bike: a voltage logger (LR8515, Hioki, Nagano, Japan), an anemometer (WS-02, Custom, Tokyo, Japan), and a rotational speed sensor (FT3406, Hioki). In addition, the measurements were recorded considering various road conditions.

Figure 1. Schematic of the electric bicycle.

The speed of the e-bike was estimated by the number of wheel rotations at a sampling interval of 1.0 s. The voltage and current were simultaneously measured using the voltage logger at an interval of 0.1 s. In addition, the wind speed was measured as it is a significant factor—besides the speed and total load weight of the e-bike—affecting the power demand.

To specifically understand the estimated results, the travel distance and road conditions of both flat and gradient roads were tracked on Google Maps. The difference in the average slope angle in a gradient road was 0–5.71° in the running tests conducted in the present study.

It was assumed that the conventional Li-ion battery was replaced with an FC battery having an MH cartridge. Yamate et al. [32] showed that the energy density of an FC battery with MH cartridge is smaller than the energy density of Li-ion batteries when considering the weight of the entire FC system; thus, the weight of the FC battery would be higher than that of the Li-ion battery. In addition, an auxiliary battery was used to meet the demand of the bike and prevent the deterioration of the FC. Therefore, it was essential to evaluate the relationship between the load weight and the power consumption of the bike because the additional load weight affects the bike performance.

Here, the average speeds and power consumption of the e-bike were measured in the running tests at various additional load conditions of 0 kg, 3 kg, 5 kg, and 8 kg to indicate the change in power demand owing to the weight gain. Table 1 presents the average speeds with variation of load weight used for estimating the power demand of the e-bike. The experiments were conducted multiple times under each loading, resulting in variations of wind and bike speeds. Specifically, the wind speed was a natural phenomenon and could not be controlled, resulting in its variation. Further, the bike speed varied as a result of a mixture of slope running and flat road running. Note that the running tests were conducted on a flat road using a plastic bottle placed in the front basket (Figure 1).

Table 1. Average speed with variation of load weight.

Load Weight [kg]	Slope Angle [°]	Relative Wind Speed (Average) [m/s]	Bike Speed (Average) [m/s]
0.0	0.00–5.71	0.833–3.69	0.600–4.52
3.0	0	2.06–4.73	3.98–4.12
5.0	0	3.98–4.12	3.98–4.19
8.0	0.00–5.71	0.733–5.00	1.16–4.27

2.2. Dynamic Model for Bicycles

Based on the experimental results, a simulation model was developed to estimate the power demand under various road conditions. The relationship between the measured demand of the e-bike and the dynamic simulation model was expressed by the physical model (Figure 2). Following Newton's second law, the balance equation of power is shown as

$$Ma(t) = M \frac{d^2x}{dt^2} = F_p - (R_r + R_s + R_w(t)), \quad (1)$$

where M is the combined mass of the bicycle and the rider [kg], $a(t)$ is the acceleration of the bicycle at a certain time [m/s²], x is distance [m], t is time [s], F_p is propulsion force [N], R_r is rolling resistance [N], R_s is gradient resistance [N], and $R_w(t)$ is wind resistance at a certain time [N]. The rolling resistance coefficient (C_r) shown in Table 2 was used to calculate the rolling resistance (R_r). The wind resistance, R_w , can be expressed as

$$R_w(t) = \frac{1}{2} \cdot C_d \cdot \rho \cdot A \cdot (v_g(t) + v_w(t))^2, \quad (2)$$

where ρ is the density of fluid (e.g., 1.2 kg/m³ for air at standard temperature and pressure) [kg/m³], C_d is the drag coefficient, A is the characteristic frontal area of the body [m²], and $v_g(t)$ and $v_w(t)$ are ground speed and wind speed at a certain time [m/s], respectively. Therefore, the primary power of the bicycle (P_{total}) [W] is estimated using Equations (1) and (2) as

$$P_{total}(t) = (Ma(t) + R_w(t) + R_s + R_r) \cdot v_g(t). \quad (3)$$

The parameters of the e-bike are listed in Table 2.

Figure 2. Longitudinal components of the forces acting on the e-bike.**Table 2.** Model parameters.

Model Parameter	Value
A [m ²]	0.4 [33]
ρ (air) [kg/m ³]	1.225 [34]
C_d	1.0 [33]
C_r	0.014 [33]

2.3. Predicting Power Demand for Running Schedule

The standardized running schedule proposed by the public organization of Japan was used to estimate the performance of the FC battery with MH for an h-bike in comparison with an e-bike [23] (Table 3). Based on this schedule, the power demand of an e-bike was estimated and the experimental results were compared for validation. In this study, it was assumed that no power was supplied on the downhill because no pedaling was involved.

Table 3. Standardized running schedule.

Road Condition	Distance [km]	Speed [km/h]	Gradient [°]	Wind Speed [m/s]	Rider Weight [kg]
Flat road	1	15	0	0	55
Gradient road	1	10	4	0	55
Flat road	1	15	0	0	55
Gradient road	1	20	−4	0	55

2.4. Evaluation of Power-Source Scale for the h-Bike

The dynamic power demand for an e-bike was evaluated based on the standardized running schedule. This was used for the physical simulation of both the steady state and the experimental value in the transient state. Meanwhile, the scale of the power source was fixed to satisfy the FC battery and the auxiliary power source. The battery and ultra-capacitor were candidates for auxiliary power devices.

Here, the battery was used because its energy density was higher than that of the ultra-capacitor. Figure 3b shows the system schematic for the h-bike. The FC battery provides electricity to the battery [35] to ensure that the battery does not run out.

Figure 3. System schematic for an (a) e-bike and (b) h-bike.

Moreover, both operation forms are compared as follows: in the conventional e-bike (see Figure 3a), the battery is recharged in each user. The battery is just connected to the plug for power supply. However, the longer recharge time would be inconvenient.

On the other hand, in the h-bike (see Figure 3b), the basic scheme is an MH cartridge replacement system. In this case, the user is assumed to constantly possess a few cartridges, which are delivered individually from the energy company. The empty one is returned to be refilled. The advantage of this scheme is a reduction of recharge time.

The available energy in the storage device against the power demand was estimated using the Ragone plot theory of the battery (Equations (4) and (5)) [35,36]. We drew Figure 4 by the applicable mathematical model (Equations (4) and (5)).

$$e_b(p) = \frac{1}{2} \frac{p}{1 - \sqrt{1-p} + 2R/R_L} \quad (4)$$

$$p = \frac{4RP}{U_0^2} \quad (5)$$

where $e_b(p)$ is the energy [Wh], p is power [W], R is internal resistance [Ω], R_L is leakage resistance [Ω], P is load power [W], and U_0 is cell voltage [V]. Figure 4 shows the specific power density and specific energy density, which is calculated by dividing the energy ($e_b(p)$) by the cell weight. In this study, the energy capacity and power covered by the battery are calculated by Equations (6)–(10). The energy density and power density are used as testing parameters so that the energy can be used up during the test run time and the battery weight is minimized.

Figure 4. Ragone plot of the MR2100AA1 Golden power.

Consequently, the energy density, power density, weight of the battery, and rated power of the FC battery were evaluated (Figure 4 and Equations (6)–(10)).

$$P_{bat}(t) = \begin{cases} 0 & (P_{demand}(t) \leq P_{FC}(t)) \\ P_{demand}(t) - P_{FC}(t) & (P_{demand}(t) > P_{FC}(t)) \end{cases} \quad (6)$$

where $P_{bat}(t)$ is the battery output [W], $P_{demand}(t)$ is specific power demand for the e-bike [W], and P_{FC} is the FC battery output [W]. The output of the FC battery ($P_{FC}(t)$) for the road conditions (flat or gradient road) was determined. Note that the load-following capability of the FC battery is inadequate. The charge capacity (E_{pos} [Wh]) and discharge capacity (E_{neg} [Wh]) of the battery were calculated using Equations (7) and (8), as follows:

$$E_{pos} = \frac{1}{3600} \int_0^t \{P_{FC}(t) - P_{demand}(t)\} dt \quad (P_{demand}(t) \leq P_{FC}(t)) \quad (7)$$

$$E_{neg} = \frac{1}{3600} \int_0^t \{P_{demand}(t) - P_{FC}(t)\} dt \quad (P_{demand}(t) > P_{FC}(t)) \quad (8)$$

Moreover, the relationship between the charge and discharge capacities is calculated using the energy efficiency of the battery (=0.83) [37], as follows:

$$E_{neg} = E_{pos} \times 0.83. \quad (9)$$

The peak power of the battery ($P_{bat_peak}(t)$) was calculated by subtracting the FC battery output ($P_{FC}(t)$) from the peak demand ($P_{demand_peak}(t)$).

$$P_{bat_peak}(t) = P_{demand_peak}(t) - P_{FC}(t). \quad (10)$$

Finally, the battery scale was set to satisfy the assisted power demand of the bicycle. The maximum output of the FC battery, i.e., the rated power, was decided based on the minimum demand, considering the FC specification and charge capacity of the battery. After the output from the FC was determined,

the amount of hydrogen required for the output and the heat generated as waste were calculated using the following Equations (11)–(13) [38,39]:

$$\eta = \frac{V_{out}}{1.25} \quad (11)$$

$$Q = P_{FC} \left(\frac{1.25}{V_{out}} - 1 \right) \quad (12)$$

$$m = 1.05 \times 10^{-8} \left(\frac{P_{FC}}{V_{out}} \right) / 0.95 \quad (13)$$

where η represents the efficiency of the FC battery cell, V_{out} [V] refers to the average voltage of one cell in stack, Q [W] is the heating rate, and m [kg/s] represents the hydrogen mass flow rate. In this study, we used 1.25 V as the maximum voltage value (LHV).

Next, the capacity of the Li-ion battery and the FC battery was compared. In this study, MH was used as hydrogen storage. The MH used was $\text{LmNi}_{4.73}\text{Mn}_{0.12}\text{Al}_{0.15}$, which is of the AB5 type. Note that the theoretical adsorption capacity of $\text{LmNi}_{4.73}\text{Mn}_{0.12}\text{Al}_{0.15}$ is approximately 1.47 wt%.

2.5. Discharge Experiment of MH

In our pre-experimental study, to ensure a stable and long duration, the experiments of discharging hydrogen from MH were conducted. In this research, based on the condition of running the e-bike, the periphery of the MH tanks is 25 °C. This study aims to understand the capacity of the cartridge required to maintain the designed flow rate. In general, when hydrogen is discharged, the inner temperature is decreased by the endothermic reaction, resulting in a flow degradation. However, the temperature drop can be compensated with heat generation owing to the recovery heat from the FC unit [40]. This indicates the significance of the cartridge size that is attributed to the expansion of duration of energy supply and/or the energy loss of weight gain. Accordingly, the hydrogen flow characteristic from the storage was also evaluated.

2.5.1. Design of Tank

Figure 5 shows the schematics of tanks. The tank shown in this figure was made of SUS 316 L (KUROIWA stainless steel industry inc.). The tank has inner and outer diameters of 43 mm and 48.6 mm, respectively, and a length of 90 mm. The components of MH are $\text{LmNi}_{4.73}\text{Mn}_{0.12}\text{Al}_{0.15}$. The weight of 557.35 g was filled in the tank and the net volume is $1.307 \times 10^{-4} \text{ m}^3$. Therefore, the bulk density is $4.264 \times 10^3 \text{ kg/m}^3$. The temperatures in the MH tank were monitored by eight thermocouple probes (T1, T2, T3, T4, T5, T6, T7, T8, and T9) (Figure 5).

Figure 5. Schematic of metal hydride reactor.

2.5.2. Experimental Apparatus and Procedures

Figure 6 shows the schematic of the experimental apparatus. Based on a previous study, MH activation was also conducted. Next, the periphery temperature of the tank was controlled to 6 °C and approximately 0.35 MPa hydrogen supply pressure was filled in the tank. The MH absorbed 85.464 L of pure hydrogen. Subsequently, the periphery temperature was controlled to 25 °C by a circulator (TR-3a, As One, Osaka, Japan). In the discharging hydrogen, the mass flow controller (SEC-N112MGM, SEC-N112MGRW, Horiba, Kyoto, Kyoto, Japan) controlled the hydrogen flow rate (1.0 NL/min) by LabVIEW, and hydrogen was released to the atmosphere. We showed the basic technical data of the measuring equipment (see Table 4).

Figure 6. Schematic of the experimental apparatus around the tank.

Table 4. Specification of measuring tools.

Mass Flow Meter	Temperature Logger
Sampling interval: 0.1 s Measurement range: 0.06–3.0 NL/min Accuracy: $\pm 1.0\%$ Setpoint.	Sampling interval: 0.1 s Measurement range: $-200\sim 1370$ °C Reliability: $\pm 0.05\%$ of display value

3. Results and Discussion

3.1. Electric Power Demand for e-Bikes

Figure 7a,b show the relationship between the power output of the Li-ion battery and the speed of the e-bike on flat and gradient roads, respectively. The bike speed was measured by a rotation speed sensor, electric demand was expressed by a voltmeter and ammeter, wind speed was measured by an anemometer, and distance traveled was measured by integrating the bike speed. The slope of the roads was derived from the distance traveled and elevation observed from Google Maps. After measuring the angular velocity from the rotational speed sensor, the bike speed was calculated using the radius of the wheel. Figure 7 could be obtained by operating each measuring instrument simultaneously. When a rider started to pedal, the power output reached approximately 300 W on the flat road. Upon attaining the steady condition, the average speed was 4.44 m/s for approximately 80 s, and the average power was 36.9 W (Figure 7a). The total travel distance was approximately 400 m for one trip. Note that the running test on a flat road was performed in the same trip.

The maximum power reached beyond 300 W on the gradient road (Figure 7b). The average speed for climbing up the gradient road was approximately 4.22 m/s for 49 s, and the total travel distance was

approximately 210 m. Accordingly, the rated power of the FC battery would be acceptable at 300 W for ordinary road conditions.

Figure 7. Relationship between the bike speed and power output: (a) flat road; (b) gradient road.

Figure 8 shows the change in power outputs under variable additional load conditions from 0 to 8 kg on the flat road. The output shown in Figure 8 shows the range of steady-state power demand during flat-road driving. We assumed that this range of output was caused by the difference in wind speed and vehicle speed on the same route at each loading weight. In this study, it is expected that h-bikes will be heavier than e-bikes, but the replacement of a Li-ion battery with an FC battery introduced a negligible performance drop.

Figure 8. Power output variation with loading.

3.2. Projection of the Assisted Demand

The power demand for the e-bike in the standardized running schedule was estimated using the proposed simulation model (Equations (1)–(3)). The simulation results were compared to the measurement results as shown in Figure 9; the coefficient of determination (R^2) was 0.823 and the slope of the approximating line was 1.04, which indicates that the measurement data can be reflected in the proposed simulation model represented by Equations (1)–(3) to a significant extent.

Figure 9. Comparison of the measurement data to the simulation results.

3.3. Performance Estimation of e-Bike

Figure 10 charts the power demand of the e-bike for a standardized running schedule against driving time based on the running test conducted in this study. Note that the driving durations on the flat and gradient roads were 247 and 369 s, respectively.

Figure 10. Power demand of the e-bike for standardized running schedule.

In Figure 10, the steady power demand on the flat road was approximately 54 W, and it took nearly 13 s to attain a constant speed. The maximum demand at the beginning of pedaling was approximately 220 W. In comparison, the steady power demand on the gradient road was approximately 215 W, and it took nearly 11 s to attain a constant speed. The maximum demand in this case was nearly 300 W.

3.4. Performance Estimation of h-Bike

Based on the proposed physical model (Equations (6)–(10)), the required power demand for the FC battery was simulated to be approximately 58 W and 215 W on the flat and gradient roads, respectively.

The capacity of the auxiliary battery, including the determination of the FC battery scale, was estimated based on the following conditions. The amounts of charge and discharge should be balanced during the bike operation, i.e., the FC battery is to be supplied with a certain amount of power to meet the assisted demand and charge of the battery. Note that the FC battery output corresponds with the sum of the assisted demand and battery charge. Conversely, if the assisted demand exceeds the rated power of the FC battery, the lack of power-excluding the FC battery supply—is compensated for by the auxiliary battery. In addition, the amount of charge was assumed to be equal to that of the discharge. Thus, the FC battery scale was balanced, and the battery capacity for the standardized demand (Figure 8) was estimated for both flat and gradient road conditions.

Consequently, the respective auxiliary battery capacity and compensated power output were 16.1 Wh and 162 W, respectively, for the flat road condition and 5.6 Wh and 90 W, respectively, for the gradient road condition. The specific power density and specific energy density of 567 W/kg and 62.5 Wh/kg, respectively, were determined from the Ragone plot (Figure 4). Therefore, the weight of the auxiliary battery was 0.285 kg. The suitability of the scale was realized considering the balance of relationship between the FC battery supply and the battery charge or discharge, in order to meet the assisted demand.

Based on these results, the scale of the FC used in this study was set to 200 W. Table 5 shows the hydrogen requirements and heat loss and efficiency values for FC operation calculated by Equations (11)–(13). Note that we used the I-V and I-P characteristics of a 300 W FC (Figure 11) and distributed the values to that of the FC rated at 200 W. The average efficiency of the FC in the running pattern from the characteristics demonstrated in Figure 10 is 0.741. Kheirandish et al. [30] stated that the minimum hydrogen flow rate required for a h-bike with MH at a high power output was 3.5 NL/min. However, the power demand had not been adequately investigated. In this study, the power demand was investigated. Consequently, 1.89 NL/min (see Table 5) was found to be sufficient. Therefore, it is suggested that the h-bike of this study can obtain longer travel distance than the h-bike of Kheirandish et al. [30].

Finally, the benefits of replacing the Li-ion battery with the FC battery for two scenarios of weight gain allowance, 4.0 kg and 8.0 kg, were estimated (Table 6). Note that the calculated weight of the FC battery unit including the stack and fan was 0.824 kg [40]. As a weight allowance, it was estimated from Figure 8 that the increase in the load weight up to 8 kg would have little effect on the power demand. Therefore, 4 kg was set as an intermediate point. In this load change, the amount of MH as hydrogen storage was also changed. In addition, it was considered that increasing the amount of MH increased the weight of the cartridge. The available energy storage was estimated and compared with that of a Li-ion battery. Note that the assisted demand remained constant in both scenarios (Figure 8).

Figure 11. Plot of the voltage-current and power-current curves of fuel cell stack.

Table 5. Operating condition of the fuel cell battery for an h-bike.

Road Condition	P_{FC} [W]	Hydrogen Flow Rate [NL/min]	Heat Generation [W]	Efficiency
Flat road	57.80	0.397	9.81	0.855
Gradient road	215	1.89	107	0.666

The AB₅-type LaNi₅ was introduced as the type of hydrogen storage alloy in this study because it has a pressure of 0.2 MPa at 300 K (Figure 12) and can release hydrogen in a normal temperature and pressure atmosphere. Thus, it is preferable for small-scale applications. In this research, LaNi_{4.73}Mn_{0.12}Al_{0.15}, having a storage capacity of 1.47 wt%, was used. This value was measured by the absorption experiment. Accordingly, the power capacities of the FC battery unit in both scenarios were 1162 Wh (Scenario 1) and 2083 Wh (Scenario 2). The battery capacity of the Li-ion battery was 306 Wh. This implied that the benefit of the FC battery system was an increase in the battery capacity by approximately 3.80 times (for 4 kg gain) or 6.81 times (for 8 kg gain) as compared with that of the Li-ion battery. Although this benefit depended on the road conditions, the significance of the FC battery with an MH cartridge can be realized from the simulated results of the proposed physical model. The power consumption under the driving conditions in Table 3 is approximately 30 Wh. Furthermore, 1 kg of MH corresponds to a mileage of 46 km, considering the efficiency of the FC. However, the e-bike can run 18 km on 1 kg of Li-ion battery. In the future, the design of an FC battery with an MH cartridge is being considered for small mobility applications.

Table 6. Scenarios of Li-ion battery and the fuel cell (FC) with a metal hydride cartridge. MH, metal hydride.

Scenario	Bike	Bicycle (w/o Battery) [kg]	Battery [kg]	Rider [kg]	Gain Allowance [kg]	Total Weight [kg]
1 (allowance: 4.0 kg)	e-bike	25.54	2.16 (li-ion) 0.824 (FC)	55	4.0	86.7
	h-bike	25.54	5.05 (MH/cartridge) 0.285 (aux. battery)	55	-	86.7
2 (allowance: 8.0 kg)	e-bike	25.54	2.16 (li-ion) 0.824 (FC)	55	8.0	90.7
	h-bike	25.54	9.05 (MH/cartridge) 0.285 (aux. battery)	55	-	90.7

Figure 12. Volumetric and gravimetric hydrogen density of some selected hydrides [27].

3.5. Experimental Result of Desorption

Figure 13 shows the temperature profile and the hydrogen discharge flow rate. The water bath temperature was 25 °C, the maximum hydrogen flow rate was 1.0 NL/min, and the discharged hydrogen was exhausted to an atmosphere. The temperature profile (Figure 13) shows that the temperature at the center was lowest, and that a larger radius resulted in a higher temperature. These temperature differences imply the desorption process would complete first in the metal regions near the vessel wall and hydrogen outlet side and then move toward the central and bottom regions of the vessel. The hydrogen discharge flow rate shows that the mass flow rate (1.0 NL/min) was maintained for about 7 min. Considering the running e-bike, this period will not satisfy the demand. From the above, it can be inferred that heat supply is essential for maintaining the hydrogen demand for an extended duration. In order to maintain the flow rate shown in Table 5, 8.87 W (on flat road) and 42.2 W (on gradient road) of heat must be supplied to the hydrogen storage alloy. However, this can be provided by using the waste heat from the FC shown in Table 5, suggesting that the hydrogen flow can be extended for a long time. Therefore, there is no need to introduce a new heat source into the system and no further weight increase needs to be considered. Kendall et al. [29] pointed out that the additional heat supply is absolutely required during the hydrogen discharge from the MH. On the other hand, if the exhaust heat from the FC stack is supplied to the MH, the advantage of continuous hydrogen discharge can be obtained thanks to the suitable scale of cartridge.

Figure 13. Temperature profiles of the metal hydride bed and flow rate during the dehydrogenating process.

4. Conclusions

In this study, the application of an FC battery with an MH cartridge to an electric-assisted bicycle was discussed, which can advance the implementation of hydrogen economy, as MH can store hydrogen in small spaces and can charge or discharge hydrogen at low pressures. For the experiment, an h-bike equipped with an FC battery was proposed and its performance was investigated to determine its benefit in comparison with the conventional Li-ion bike (e-bike).

A physical simulation model was developed based on measurements from actual running tests—conducted on flat and gradient roads—to determine the power demand required for assistance. The power demand was measured at 54 W for flat roads and 215 W for gradient roads, with no significant difference noted for variations in additional weight loading (0–8 kg).

As the FC battery cannot satisfy dynamic energy demands, a combination of an FC and auxiliary batteries was analyzed using the standardized demand data to estimate the benefits of replacing the Li-ion battery with the FC battery, considering weight gain allowances of 4 and 8 kg. Moreover, the weight of the FC unit, including the MH storage cartridge and the battery, was considered in the evaluation. The FC battery scale and auxiliary battery capacity were set at 220 W and 16.1 Wh, respectively, based on the measured data. Consequently, the benefits of the proposed model were assessed, and an increase in battery capacity was observed at 3.80 times (for 4 kg gain) and 6.81 times (for 8 kg gain) initial conditions before replacement. However, this benefit depends on the road conditions. At this stage, an MH cartridge was inserted into the frame part that connects the front brake and pedal part (Figure 1). In this study, the load weight limit that does not affect the power demand is set to 8 kg. From the hydrogen desorption experiments, it was observed that the time required for the loading of hydrogen was short (Figure 13).

5. Future Work

From a practical application perspective, we have still several issues that need to be investigated on the demand, the bike compositional unit, and the battery scale, among others. For instance, the close investigation of electric power demand including uncertainties is necessary, because we know that the demand depends upon the loading weight of a rider including baggage, the behavior, and the road condition.

From the hydrogen desorption experiments, it was observed that the time required for the loading of hydrogen was short (Figure 13). In future, designing an MH tank that can stably supply hydrogen from MH is planned to satisfy the output from FC during running. Chung et al. [41] used heat pipes to

enhance heat transfer in the tank by applying heat to the center of the tank. This resulted in a 44% increase in the desorption/desorption time for hydrogen discharge at 1 NL/min. In our prior study, we stated that the radius of the MH tank needs to be shortened to reduce the temperature gradient. Based on their research, we built a new MH tank (Figure 14). Ultimately, the tank must be designed to compensate for the amount of endothermy within the MH for the amount of hydrogen required during h-bike driving (Table 5). The amount of heat to be added will be investigated in more detail in the future.

Furthermore, a thorough design plan of an FC battery with an MH cartridge is intended for small mobility applications. H-bikes can potentially mitigate environmental burdens.

Figure 14. Metal hydride cartridge design plan for future work.

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