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A demonstration project of the hydrogen station located on Yakushima Island—Operation and analysis of the station

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Abstract

Since Yakushima Island is rich in rainfall, hydroelectric power produced on the island is sufficient to cover all the energy demands on this island. A hydrogen fueling station was constructed on this island and hydrogen was produced by water electrolysis. The hydrogen production rate is 1.25 Nm^3/h. The produced hydrogen was used for the driving tests of fuel cell vehicles, while the public acceptance of hydrogen energy was studied. This station is comprised of several systems, including hydrogen generation, hydrogen purification, compression and storage. During the operation of the station, the electricity consumption by each component and the production rate of hydrogen were measured. Since the facility is small, the energy efficiency is low. The total energy efficiency, which was calculated by dividing the potential energy of the compressed hydrogen by the total electrical energy input to the station, was 25% (LHV) and 30% (HHV).

Keywords: Hydrogen fueling station; Water electrolysis; Hydropower; Water potential; Yakushima

1. Introduction

The island called Yakushima is located in the ocean 60 km from the southernmost tip of Kyushu, Japan. A part of Yakushima Island has been inscribed onto the World Natural Heritage List in 1993. The island is circular and covers an area of 505 km^2. About 14,000 people live on this island, which is located in the subtropical zone and gets a lot of rain. The annual precipitation is about 10,000 mm in the mountainous area, while the average rainfall is about 4500 mm. In addition to this rainfall, one of its geographic features is that many areas of the island are considered mountainous. The altitude of the highest mountain on the island is 1935 m, while the average altitude is 600 m.

Many researchers have studied Yakushima as a model area to propose a method for a sustainable society based on the zero-emission concept [1] and [2]. Since the island is a steep alpine island on the sea with large amounts of water, the potential for hydroelectric power is sufficient to reduce the consumption of fossil fuels. Actually, almost all the electric power consumed on the island is supplied by hydroelectric power. Therefore, a unique energy strategy can be planned for this island. At the present time, however, about 70% of the energy consumption is supported by fossil fuels imported from the outside [1]. Some projects have been carried out to reduce the consumption of fossil fuels on this island. Yakushima has the highest potential in Japan to realize an energy system that is nearly independent of fossil fuels.

Fuel cell vehicles are now being intensively developed and are becoming an enabling technology as a transportation system. This system is based on the use of hydrogen as the fuel. In Japan, the hydrogen infrastructure and the use of hydrogen have been systematically examined [3], and now hydrogen-fueling stations based on various hydrogen sources have been demonstrated as the JHFC project [4]. In Germany, the first public fueling station for liquid hydrogen has gone into service at Munich Airport [5]. In this project, robot technologies have been developed.

A demonstration project has been carried out on Yakushima Island. A hydrogen fueling station was constructed and hydrogen is produced by the electrolysis of water, which is abundant on the island. The energy for the electrolysis is generated by a hydroelectric power station. Therefore, hydrogen is produced at this station without the direct use of any fossil fuels during the operation. The situation on this island is similar to that in Iceland, which is known as the country aiming to be the world's first hydrogen society. This unique environmental situation cannot be found in any other areas of Japan.

The outline of this paper is as follows. First, the potential energy of hydropower in Yakushima is presented. In Section 2, the demonstration project of the hydrogen station is introduced. Section 3 describes the hydrogen fueling station constructed on the island. Finally, we discuss the efficiency of the station based on the energy consumption data obtained during the operation of the station.

2. Potential energy of hydropower

As shown in Fig. 1, there are four hydroelectric power stations which convert the water potential to electric energy on the island. Three of them belong to a private company, Yakushima Denko Co., Ltd. This company uses hydroelectric power to manufacture silicon carbide and also supplies power to the residential sector. The amount of power generated by the three power plants is over 99% of the total power generation. Two of the main plants generate power using about a 300 m water head, and their capacities are 23.2 and 34 MW.

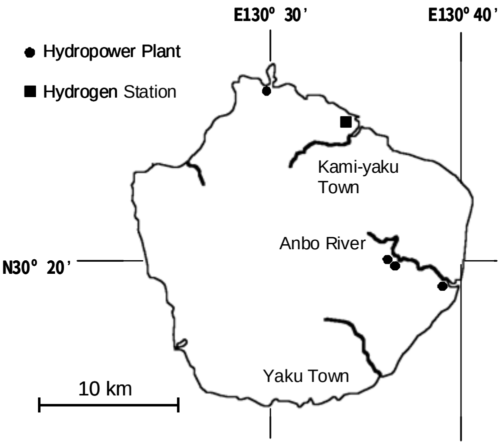

Fig. 1. Locations of the hydropower plants and the hydrogen station.

The Ministry of the Environment, a Japanese governmental agency, has researched the potential energy of hydropower on the island [6]. According to this report, there are 36 sites that are candidates for relatively large hydropower plants. Many mini- and micro-plants are also likely to be installed. The total potential of hydroelectric power was estimated to be 1127 GWh. Fig. 2 shows the potential hydropower and the generation by the existing hydroelectric power stations. The value of the power produced by the existing hydroelectric plants is about 342 GWh [7]. This potential power is about three times the present generation. However, the consumption of electric energy in the residential sector is 58 GWh [8], which is only 5% of the water potential on this island. As described above, a part of this island has been inscribed onto the World Natural Heritage List and the National Park Service. Even the unused hydropower outside of the National Park is 445 GWh and is still greater than the present generation.

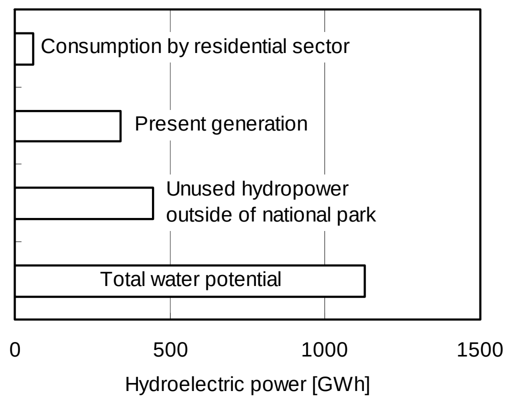

Fig. 2. Hydropower potential on Yakushima Island.

As described above, almost all of the electric power is produced from the renewable energy available on this island. Fossil fuels are used for other energy sources. The present annual consumption of fossil fuels in the residential sector is about 530,000 GJ (147 GWh) [7]. This value is about 40% of the present generation from hydroelectric power. If fossil fuels are displaced by the electric power, the consumption of fossil fuels in Yakushima would be significantly reduced. Devices, which can be operated on electricity, have already come onto the market for air conditioning and the hot-water supply. Since these devices utilize a heat-pump mechanism, the consumption of energy can be reduced. For cooking, induction heating cookers are becoming widespread and they are able to replace gas cooking stoves.

On the other hand, in the transportation sector, it is difficult to decrease the consumption of fossil fuels at the present time. Although electric vehicles are available, it is not realistic to expect the residents to purchase this type of car. Although fuel cell vehicles have been extensively developed, they are not commercially available at this time. In the transportation sector, about 60% of the total fossil fuel is consumed on Yakushima Island. Therefore, if the consumption of fossil fuels in the transportation sector is also reduced, the total fossil-fuel consumption on the island should be drastically decreased.

3. Hydrogen station project

The purpose of this project is not to let fuel cell vehicles immediately come into wide use on this island. Iceland is now trying to become the world's first hydrogen society. Judging from only the ratio of hydropower to the population on Yakushima, it may be possible to establish a hydrogen society on the island [1]. However, since the island is one component of the national economic system, it will be difficult for Yakushima to totally become a hydrogen society. The efficiency of the energy conversion should also be considered. The best way is to directly use the electric power, if possible. As already mentioned, many devices used during normal living can be powered by electricity. However, the transportation cannot become independent of fossil fuels using the present technology.

Although an electric automobile is one of the promising low emission vehicles on this island, at the present time, practical electric vehicles have not appeared on the market. This type of car has some disadvantages. Their batteries are expensive, have a short life cycle, and have a limited storage capacity [9]. However, since the circumference of this island is 100 km, the range of an electric vehicle is an insignificant weak point for most of the residents on this small island. If the recharging time and the cost of the batteries are reduced, electric vehicles will be the most efficient automobiles on Yakushima because electricity is directly generated from hydropower plants. Some Japanese automobile makers have started the development of electric vehicles based on new technology. If the car in the development stage goes on the market, it should be suitable for tourists who visit the mountainous areas on the island.

In consideration of the limited deposits of fossil fuels, some researchers have considered that, in the future, hydrogen sources should be shifted from fossil fuels to renewable energy sources [10], [11] and [12]. von Jouanne et al. [13] have carried out an infrastructure study to produce hydrogen from renewable energy sources. In their study, wind power and solar energy have been considered as the energy sources of water electrolysis. The quality of the wind power and solar energy is low and these systems induce some problems when they are connected to a grid. They propose a bi-directional grid connection. For the use of renewable energy sources, the design and analysis of a stand-alone hydrogen energy system have been carried out [14]. Battista et al. [15] have described that wind electrolysis is a favorite candidate to become the first economically viable renewable hydrogen production system. They proposed optimization of this system. When the existing electrical power grid is used, the water electrolyzer will be operated during the off-peak period of electricity demand [16].

Even on Yakushima, it is unclear that hydrogen from water electrolysis will be economically available in the future. Hammerschlag and Mazza [17] have concluded that hydrogen performs no better in mobile applications and questioned the quick transition to a hydrogen economy. In the case of this island, since almost all the electricity is produced by hydroelectric power, the electricity can be utilized by generating hydrogen when the electricity consumption is low at night. In addition, the price of hydrogen might be reduced by effective utilization of the oxygen by-produced [18]. If fuel cell vehicles become popular all over the world, they will also be used on Yakushima. In this case, the price of hydrogen produced on Yakushima and hydrogen imported to the island will be important factors for use even if hydrogen from outside the island is produced from fossil fuels.

In the present project, a transportation system to be totally independent of fossil fuels on Yakushima was demonstrated. A hydrogen fueling station was constructed on a 1000 m2 site in the town of Miyanoura, Yakushima Island, in April 2004. The location of the station is shown in Fig. 1. The site is in the residents' life space and is adjacent to a large market. Fig. 3 shows the layout of the station.

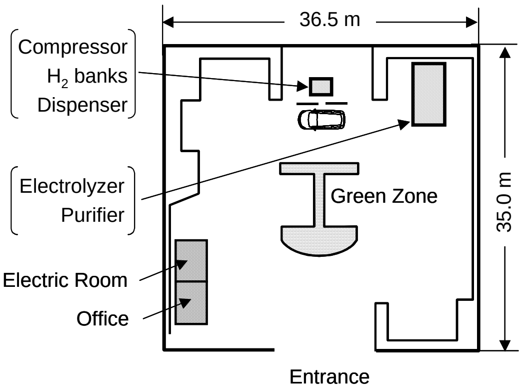

Fig. 3. Layout of the hydrogen fueling station.

The project was carried out by a collaboration of the following three participants: The University Joint-Research team (the U J-R team), Yakushima Denko Co., Ltd., and Honda R&D Co., Ltd. The U J-R team including Kagoshima University, United Nations University, Toyohashi University of Technology and Kanagawa University constructed the hydrogen station on the site owned by Yakushima Denko. The U J-R team researched the efficiency of the hydrogen production, the design of an energy supply network on the island, and the public acceptance of a hydrogen society. Yakushima Denko maintained and operated the station. Hydrogen was produced by on-site water electrolysis and stored as a compressed gas. Honda carried out the driving test runs using their fuel cell vehicle "FCX" [19]. The produced hydrogen was supplied to the fuel cell vehicles for their testing.

The project team has held some events for the residents. They visited the station, learned the operating principles of water electrolysis and fuel cells, and had the experience of a test ride in the fuel cell vehicles. It is important to establish the social acceptance when a new technology is introduced. Therefore, the methodology for the establishment of the social acceptance was studied using these activities and education [20]. Since hydrogen can be produced without exhausting carbon dioxide on Yakushima, the island is a suitable place for such a study. In this paper, the data obtained from the operation of this system are reported.

4. Hydrogen fueling station

Fig. 4 shows a schematic diagram of the hydrogen fueling station, which includes an electrolyzer, compression equipment and a vehicle fuelling dispenser unit. Since this station was a demonstration facility, each device was not necessarily a high-performance device. The main electrical consumption was by a water electrolyzer, an air compressor for the dehumidification unit and a hydrogen compressor.

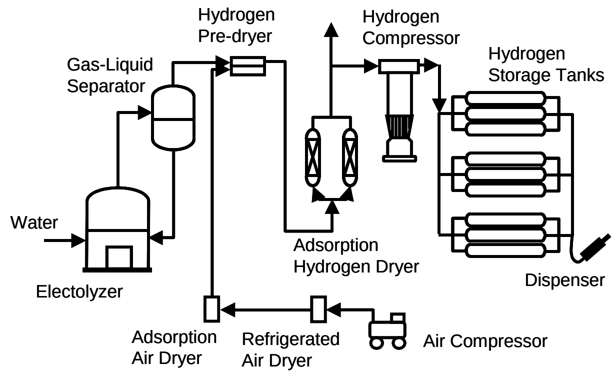

Fig. 4. Schematic diagram of the hydrogen fueling station.

The water electrolysis was carried out using proton exchange membranes as the electrolyte. The maximum stable rate of hydrogen production was about 1.25 Nm^3/h. The pressure of the generated hydrogen from the electrolyzer was 0.85 MPa (gauge pressure). Hydrogen was separated in a splitter and dried.

The water contained in the hydrogen flow was removed by a fluorine-containing polymer membrane using dried air as the sweep gas. In the next step, pressure swing adsorption technology was used for the dehumidification. The system had two adsorption columns. The adsorbent in one column was regenerated while the other column was used for the dehumidification. A part of the dehumidified hydrogen was used for the regeneration of the adsorbent and was released into the atmosphere. The purity of the generated hydrogen was above 99.9995% and its dew-point temperature was below −80°C. Oxygen was also produced by the electrolyzer. It was not used in this system and was released into the atmosphere.

The dried hydrogen was stored as a compressed gas in high-pressure cylinders. Three of them comprised one bank, i.e., high-, medium- and low-pressure storage banks. The volume of one cylinder was 0.041 m^3 and the maximum pressure was 35.1 MPa. Therefore, the hydrogen storage capacity was about 125 Nm^3 (11.25 kg). This system used a diaphragm compressor for the hydrogen compression. The maximum hydrogen storage rate was 1.2 Nm^3/h according to the specifications.

Hydrogen in the high-pressure cylinders is supplied to the hydrogen tank of a car by the pressure difference between the two tanks. First, hydrogen is transferred from the low-pressure storage bank. Next, the medium-pressure storage bank is used and finally the high-pressure storage bank (HPSB) is used. The tank pressure of a car can be enhanced in this way.

5. Analysis of hydrogen fueling station

Fig. 5 shows the change in pressure of the HPSB during operation. The other two banks were fully filled and only the HPSB was filled with hydrogen during this operation. The operation was started when the pressure of the HPSB was 23.0 MPa, and was stopped when the pressure reached 34.6 MPa. It took about 11 h for this operation. The capacity of the HPSB is 1/3 the total capacity of the banks, and it requires about 90 h to fill all the empty tanks. The slope of the curve was almost linear with the operation time in this region. This result does not mean that the hydrogen storage rate was constant with operation time, because the ideal gas state equation cannot be applied under such high-pressure region.

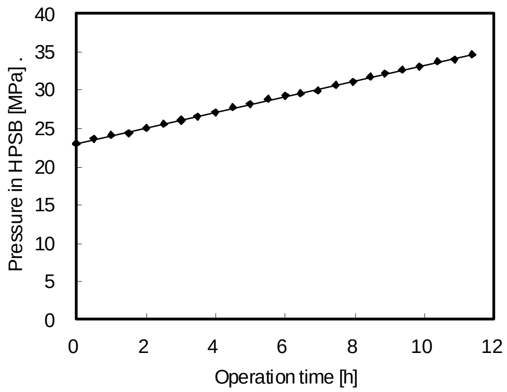

Fig. 5. Change in pressure in banks.

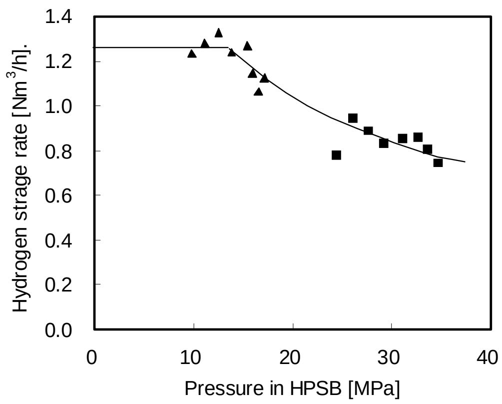

Fig. 6. Effect of pressure on hydrogen storage rate.

Fig. 6 shows the relationship between the pressure of the HPSB and the hydrogen storage rate. The hydrogen storage rate was constant when the pressure was less than about 17 MPa. This is because the hydrogen storage rate was dominated by the water electrolysis and was not influenced by the pressure of the banks. According to the specification of the electrolyzer, it can produce hydrogen at 1.25 Nm^3/h. On the other hand, when the pressure was higher than 17 MPa, the hydrogen storage rate decreased with the pressure. In this region, the compression rate controlled the overall storage rate. Fig. 7 shows the relation between bank pressure and the required energy to compress hydrogen gas from 0.95 kPa to that pressure. The compressibility factor of hydrogen was used in the calculation to compensate the deflection under high pressure. The required energy increases with the bank pressure. The consumption of electrical energy by the compressor was not affected by the pressure of the HPSB. Therefore, it resulted in a decreased storage rate with increasing pressure.

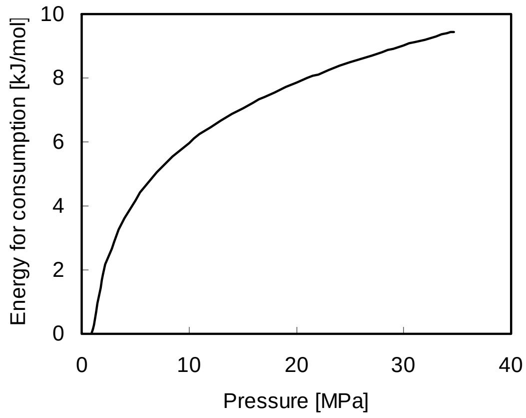

Fig. 7. Relationship between hydrogen pressure and compression energy.

The capacity of the storage banks is about three times the tank capacity of a fuel cell vehicle. Since hydrogen is transported by the pressure difference between the two tanks, the pressure of the storage banks will not decrease below half the maximum pressure when the fuelling starts after the storage banks are filled. During the daily operation of the station, the pressure of the banks varied in the high-pressure range as shown in Fig. 6. Therefore, the compression efficiency in the high-pressure range is important when the efficiency of the system is estimated.

Fig. 8 shows the relationship between the hydrogen generation and integrated electric power consumption. Hydrogen generation from the electrolyzer was obtained by adding the consumption at the regeneration process to the gas volume calculated from the pressure change in the banks. The straight solid line in this figure is the ideal relationship calculated on the basis of the assumption that water electrolysis can be carried out at the thermo-neutral voltage (1.482 V) and at a 100% current efficiency. This calculation also takes into account the energy consumption to elevate the pressure of the generated gases to 0.95 MPa. Based on these results, the energy efficiency of the present electrolyzer was calculated to be 63%. The efficiency of a commercially available electrolyzer was 74% according to the specifications [12], and the value of 78% has been used for the simulation by Kruger [21]. It is seen that this electrolyzer was not a high-performance device.

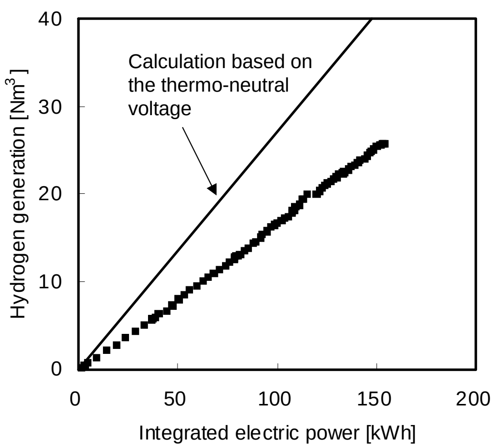

Fig. 8. Efficiency of hydrogen generation.

Fig. 9 summarizes the energy consumption of each operation when 1 kg of hydrogen was produced and compressed. The energy consumption was obtained from the operation shown in Fig. 6 and the pressure was between 23.0 and 34.6 MPa. The electric energy consumption was calculated from the measurements of the current, voltage and power factor. The electric energy was mainly consumed by the electrolyzer, rectifier, hydrogen compressor and air compressor for the pre-dryer. In addition, part of the dried hydrogen was used for the regeneration of the dehumidifier. Other devices that used electrical energy were the pumps, lights, controllers and the dehumidifier of the adsorption system. The energy consumption by the pressure swing adsorption was about 2.0 kWh/kgH_2 during this operation.

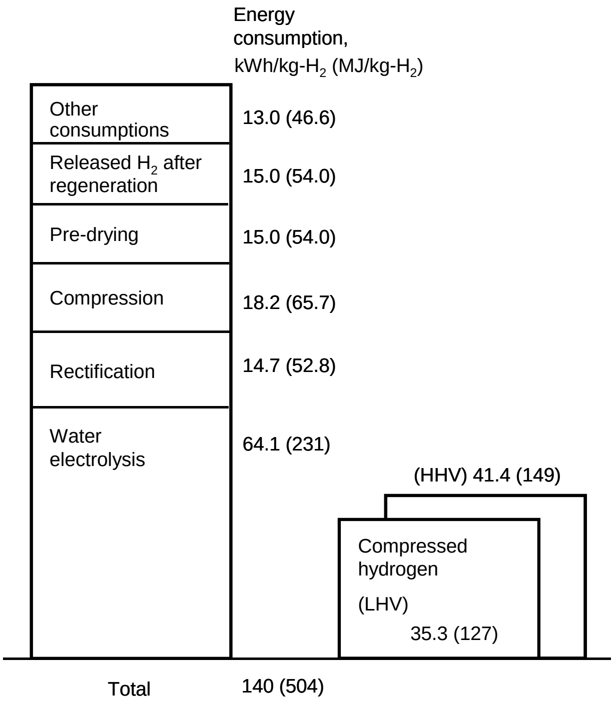

Fig. 9. Energy consumption during the operation.

As seen in this figure, a large amount of energy was consumed by the water electrolysis. The energy loss at the rectifier was also significant. The actual energy input to the rectifier was 78.8 kWh/kgH_2. As shown in Fig. 8, the efficiency of the water electrolysis was not influenced by the pressure of the HPSB and was 63% when the pressure was elevated from 23.0 to 34.6 MPa. The energy requirement from the DC power for the electrolysis was 64.1 kWh/kgH_2. Therefore, the efficiency of the rectifier was 81%.

Dehumidification of the hydrogen required significant energy. As described above, the water contained in the hydrogen flow was removed by a fluorine-containing polymer membrane in the first step. The dried air of 0.05 MPa (gauge pressure) was used as the sweep gas. To produce it, air was compressed and the moisture was removed by a refrigerated air dryer. Finally, an adsorption dryer was used for drying. The power consumption for the air compressor that included an air dryer in the package was 15.0 kWh/kgH_2. This energy consumption was significant for the small-scale station without the facility of instrument air.

The second step is the water removal by the pressure swing adsorption. In this step, part of the purified hydrogen was used for the regeneration of the adsorbent. According to the specification, the flow rate of hydrogen was 0.16 Nm^3/h. During the operation, 13.5% of the generated hydrogen was used for this purpose and released to the atmosphere. The energy consumption to produce the hydrogen used for the regeneration was 15.0 kWh/kgH_2. This operation significantly decreased the total efficiency in the present system. Since the energy consumption was small for dehumidification by the pressure swing adsorption than for the production of hydrogen by water electrolysis, the efficiency will be improved by the recirculation of the hydrogen used in the regeneration.

In the present system, the hydrogen compression was not efficient. The power consumption was 18.2 kWh/kgH_2, while it is theoretically 1.7 kWh/kgH_2. This consumption included the consumption by the controllers of the compressor unit, which was insignificant. The efficiency was only 9.4%, whereas it is generally about 40% for larger compressors.

The total energy efficiency, which was calculated by dividing the potential energy of the compressed hydrogen by the total electrical energy input to the station, was 25% (LHV) and 30% (HHV). This value depends on the range of the operating pressure. The obtained values are the average efficiencies when the pressure of the banks is increased from 23.0 to 34.6 MPa. If the empty banks are filled, the efficiencies will be increased.

The obtained efficiency was low as the efficiency of such a system. It is reported that the total efficiency is about 60% (LHV) for the Sagamihara hydrogen fuelling station [4]. The Sagamihara station produces hydrogen by water electrolysis using a hydroxide solution. The capacity of the station is 30 Nm^3/h (2.7 kg/h).

Since the total efficiency depends on the efficiency of each device used in the system, it can be easily enhanced by substituting with high-performance devices. In addition, some energy consumption is not affected by the scale of the system. Therefore, the efficiency is increased with the scale of the system. Since the data obtained from each separate stage have been reported in this paper, it will be convenient and useful for other researchers to discuss the economics of a hydrogen station using water electrolysis.

6. Conclusions

On Yakushima Island, hydro-electric power is sufficient to cover all the energy demands of the island. In the near future, there is the possibility that the island's inhabitants will be more independent of fossil fuels. In the transportation sector, fuel cell vehicles are one of the promising substitutions for gasoline-powered cars as well as electric vehicles. A hydrogen fueling station on this island was constructed, and hydrogen was produced by water electrolysis. The produced hydrogen was used for the driving tests of Honda's fuel cell vehicles, while the public acceptance of hydrogen energy was studied. During the operation of the station, the electricity consumption was measured. Based on these results, the efficiencies of the system were obtained. Beside the water electrolysis, losses occurred in the rectifier, hydrogen compressor and dehumidifier. These losses should be carefully considered for the cost evaluation of a hydrogen station based on water electrolysis.

Acknowledgments

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