

# Verification Test of High Differential Pressure Water Electrolysis-type Solar Hydrogen Station (SHS2)

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## ABSTRACT

A high differential pressure water electrolysis-type solar hydrogen station (SHS2) was developed, envisioned for household use, and verification tests were conducted for approximately one year with production of hydrogen used by fuel cell electric vehicles. This SHS2 unit is equipped with a high differential pressure water electrolysis stack that raises the pressure of the hydrogen produced by water electrolysis to 35 MPa, enabling supply of the hydrogen to fuel cell electric vehicles. This technology has obviated the need for a mechanical compressor to compress the hydrogen, and has achieved low noise, high efficiency, and compactness.

As a result of the verification tests, it was found that the amount of hydrogen produced in one year was approximately 120 kg, and the amount of electric power needed for production was fully supplied by solar cells. The initial system efficiency was 55.5%, and 6.38 kWh of electric power was consumed per 1 Nm<sup>3</sup> of hydrogen. Increased efficiency and other such work on the stack and device is anticipated to allow system efficiency to be raised to as much as approximately 70%. Operation simulation using data obtained in verification tests showed that the convenience for most users could be increased by installing a storage tank together with the SHS2.

## 1. Introduction

Honda has engaged in the development of fuel cell electric vehicles based on its understanding that fuel cells utilizing hydrogen are the ultimate next-generation powerplant in terms of providing an alternative to fossil fuels, reducing emissions, and lowering the impact on global warming.

Compressed hydrogen is the main fuel for these fuel cell electric vehicles, but the adequate infrastructure to supply compressed hydrogen is not yet in place. At the same time it is developing the vehicles, Honda is also engaging in research on methods for producing hydrogen to supply to fuel cell electric vehicles.

A normal pressure water electrolysis-type Solar Hydrogen Station 1 (SHS1) was previously installed at the Honda R&D Los Angeles Center in California in the United States in 2001, and verification tests were conducted on the continuous production and filling of vehicles with the hydrogen required by fuel cell electric vehicles. After the efficiency of this system was upgraded in 2003, verification tests were conducted for over four years<sup>(1)</sup>. In January 2010,

the SHS1 was upgraded to the SHS2 using high differential pressure water electrolysis technology<sup>(2)-(4)</sup> and verification tests were conducted for a period of approximately one year. There was no precedent for long-term testing of a station using high differential pressure electrolysis technology, and the purpose of the verification tests was to confirm its acceptability in society.

This article will provide details of SHS2 system configuration and operation, after which it will present results of the one-year verification tests and initial system efficiency together with prospects for the future. The verification test results were also used in simulations that verified the convenience of the SHS2 and storage tank.

## 2. Detailed Explanation of the SHS2

### 2.1. System Concept

Figure 1 shows an overall view of the SHS2 system. This system is capable of producing compressed hydrogen that satisfies the hydrogen fuel standards for fuel cell electric vehicles without utilizing a mechanical compressor. The combination with solar cells enables hydrogen

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production without discharging any CO<sub>2</sub> during the production process.

The system specifications are shown in Table 1. The SHS2 specifications were created on the assumption that the system would be installed in ordinary households in the future. On the assumption of everyday use for commuting to work, the specifications are set according to the concept of a hydrogen flow rate and so on that allow for producing and filling a fuel cell electric vehicle with enough hydrogen during the night to enable 40 miles of travel per day. The discharge pressure of the high differential pressure water electrolysis stack is set to 35 MPa, the same as the maximum filling pressure of the onboard tank.

The unit is also installed with CIGS thin-film solar cells<sup>(5)</sup> with 6 kW output manufactured by Honda Soltec Co., Ltd. These are made to connect with the unit through the electrical grid. The electric power generated by the solar cells during the day is used by the electrical grid, and then at night, after the car returns, electric power from the electrical grid is used to produce hydrogen. This concept allows for reduction of CO<sub>2</sub> by the electrical grid as a whole.

Table 1 Specifications of SHS2

|                     |                      |                                                                    |
|---------------------|----------------------|--------------------------------------------------------------------|
| Hydrogen production | Flow rate            | 0.7 Nm <sup>3</sup> /hr (0.5 kg/8 hr)                              |
|                     | Filling pressure     | 35 MPa (max.) (approx. 5000 psi)                                   |
|                     | Purity               | > 99.99%                                                           |
| Component           | Photovoltaic modules | CIGS thin-film solar cell 6 kW system (approx. 53 m <sup>2</sup> ) |
|                     | Electrolysis unit    | High differential pressure electrolyzer                            |
| Utility             | Electricity          | 240 VAC                                                            |
|                     | Water                | Tap water                                                          |
| Unit volume         |                      | Approx. 0.33 m <sup>3</sup> (approx. 12 cf)                        |

In September 2010, a hydrogen storage tank was also installed, according to the initial plan. The purpose of this was to study the increased convenience for users and the higher utilization rate of the system.

## 2.2. System Configuration

### 2.2.1. Electrolysis Unit

The electrolysis unit is a device that uses the high differential pressure water electrolysis stack to generate hydrogen from water by electrolysis. At the same time, it also boosts the pressure of the hydrogen and dehumidifies it. Figure 2 shows the internal configuration of the electrolysis unit in schematic form with the connections to peripheral devices displayed around the high-pressure water electrolysis stack. The high-pressure water electrolysis stack continuously generates hydrogen within a closed space by breaking down water through electrolysis. It boosts the hydrogen to the configured pressure and supplies it outside the unit<sup>(6)</sup>.



Fig. 1 External view of Solar Hydrogen Station (SHS2)

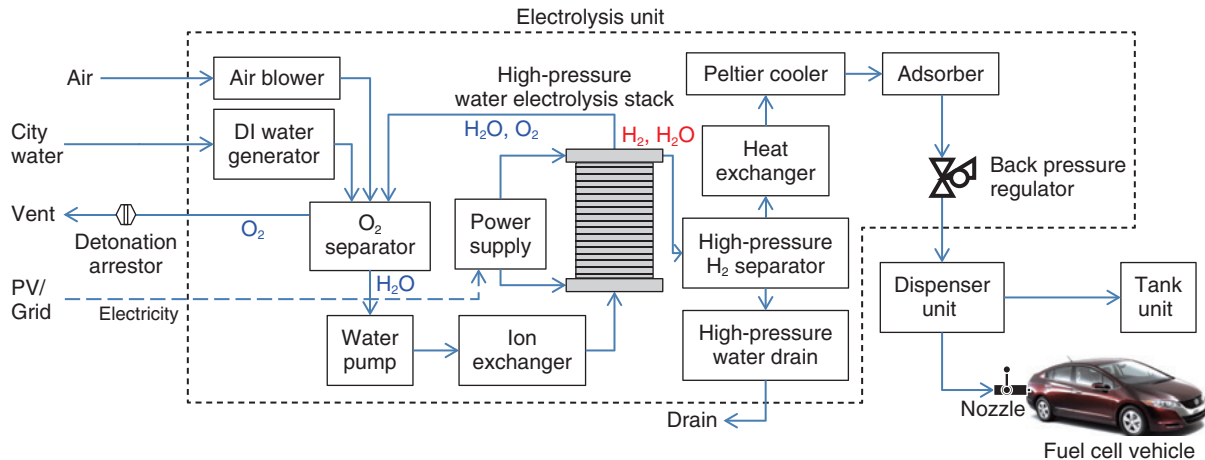


Fig. 2 Electrolysis unit configuration diagram

The deionized water required for electrolysis is produced from tap water by the deionized water generator and supplied to the deionized water circulation system. The deionized water supplied to the stack by the circulation pump passes through an ion exchanger to maintain its purity and is fed to the anode side of each cell in the stack. Inside the stack, the deionized water is electrolyzed, breaking it down into hydrogen and oxygen. The oxygen generated as a result of electrolysis is discharged from the stack together with the surplus deionized water and sent to an oxygen separator. The fluid mixture of deionized water and oxygen is separated by the oxygen separator, and the oxygen is diluted with air from the blower before being discharged through a detonation arrestor into the atmosphere. The deionized water passes through the circulation system and is again supplied to the stack.

Meanwhile, the pressure of the hydrogen that is generated by electrolysis at the cathode side of the stack continues to increase until it reaches the pressure set for a back pressure regulator (35 MPa) installed downstream. The hydrogen with boosted pressure is passed through a high-pressure hydrogen separator, a heat exchanger, a Peltier cooler, and an adsorbent that remove the water content to produce a purified dry hydrogen with a moisture concentration of 5 ppm or less. The liquid moisture in the hydrogen is eliminated by gravity in the high-pressure hydrogen separator, heat exchanger, and Peltier cooler, and that moisture is accumulated in the high-pressure separator. Consequently, when the amount of water reaches a determined level, it must be drained, and so the high-pressure drain line installed at the bottom of the high-pressure separator is opened as required to drain the water. The system operates in repeated alternation between draining water and injecting water, and this water drain cycle is shown in Fig. 3. It is apparent from Fig. 3 that variation occurs in the hydrogen flow rate of the product in linkage with the water drain cycle. While water is being

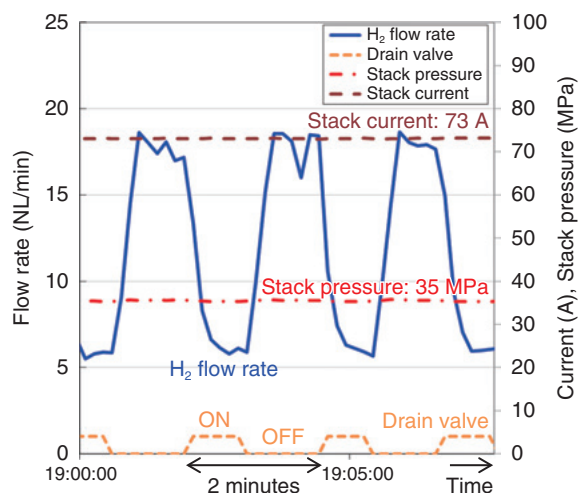


Fig. 3 High-pressure water drain cycle

Table 2 Hydrogen quality of SHS2

|                        | ISO14687-2 | SHS2        |
|------------------------|------------|-------------|
| H <sub>2</sub>         | >99.99%    | >99.99%     |
| H <sub>2</sub> O       | <5 ppm     | <1 ppm      |
| Hydrocarbon            | <2 ppm     | <0.1 ppm    |
| O <sub>2</sub>         | <5 ppm     | 1 ppm       |
| He, Ar, N <sub>2</sub> | <100 ppm   | <16 ppm     |
| CO <sub>2</sub>        | <1 ppm     | <0.1 ppm    |
| CO                     | <0.2 ppm   | <0.001 ppm  |
| Sulfur                 | <0.004 ppm | <0.0008 ppm |
| HCHO                   | <0.01 ppm  | <0.001 ppm  |
| HCOOH                  | <0.2 ppm   | <0.001 ppm  |
| NH <sub>3</sub>        | <0.1 ppm   | <0.02 ppm   |
| Halogenates            | <0.05 ppm  | <0.004 ppm  |

injected into the high-pressure separator, an amount of hydrogen corresponding to the volume of the water being accumulated is forced out, so that the apparent volume of the hydrogen product increases. On the other hand, when the water is being drained, the vapor phase hydrogen expands to a volume corresponding to that of the drained water. Therefore the pressure inside the separator diminishes, so that the hydrogen produced is used to replace the amount by which the pressure was diminished and the hydrogen product discharge volume drops or even disappears completely. This makes it appear that the production of hydrogen goes on and off in conjunction with the water drain cycle. When averaged, however, there is generation of a fixed volume of hydrogen that depends on the electric current flowing through the stack. The dehumidification performed by the adsorbent can occur using a small amount of adsorbent because the hydrogen passes through it at the high pressure of 35 MPa, where the dew point is low. The adsorbent is scheduled for replacement at approximately half-year intervals.

With normal-pressure water electrolysis, the oxygen generated at the anode side becomes mixed with the hydrogen at the cathode side as an impurity. With high differential pressure water electrolysis, however, it has been confirmed that the concentration of oxygen in the hydrogen can be held down to 5 ppm or lower when there is a pressure differential of 1 MPa or more between the anode and cathode. This can yield a hydrogen product with purity that satisfies the SAE J2719<sup>(7)</sup> and ISO 14687-2<sup>(8)</sup> hydrogen fuel standards for fuel cell electric vehicles. The fact that the hydrogen product satisfies the quality standards is also confirmed, as shown in Table 2, by impurity analysis.

The hydrogen produced in this way can either be supplied through a refueling nozzle to fill the tank on a fuel cell electric vehicle directly or, when there is a storage tank, the hydrogen can be placed in that tank to be stored.

### 2.2.2. Tank unit

The concept for this system when it was initially installed was to slowly fill vehicles at night with high-pressure hydrogen when they were not being used. This method makes a high-pressure storage tank unnecessary and allows for a simpler system that saves space. It also eliminates the need to satisfy standards and regulations related to hydrogen storage, easing installation in households.

Slow filling involves raising the pressure while filling. Although it can fill a vehicle tank completely, the long time taken for filling is a disadvantage. On the other hand, if a storage tank is present, then the pressure differential between tanks can be used for fast filling that takes a short time. This has the advantages of enhancing the user's convenience and enabling hydrogen production and storage while the vehicle is absent, which raises the utilization rate. Since this makes use of the pressure differential, there is the disadvantage that the vehicle tank cannot be filled completely full.

Installing a storage tank together with the system in this way to allow fast filling has advantages and disadvantages. In this case, an added storage tank was installed in September 2010 in order to conduct a study of user convenience and the system utilization rate. The tank has a capacity of 167 L and is capable of storing approximately 4 kg of hydrogen at 35 MPa.

### 2.2.3. Dispenser unit

The dispenser unit shown in Fig. 4 is equipped with a control panel by which users operate the system, an emergency stop button, a refueling nozzle, and a breakaway fitting for emergency separation of the nozzle.

When users fill a vehicle with hydrogen, they follow the display on the control panel and attach the nozzle to the vehicle, then press the start-filling button on the panel to begin filling. Figure 5 shows a schematic representation of

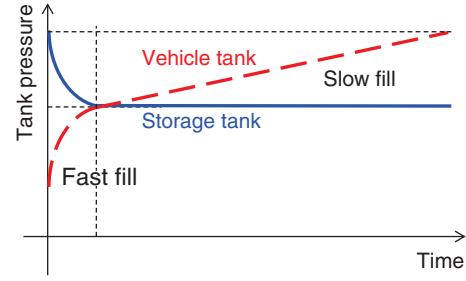


Fig. 5 Hydrogen charging sequence

the progress of the filling operation. When a storage tank is present, fast filling from the storage tank is implemented first, and after fast filling has ended, the system begins slow filling, which fills the vehicle tank directly with hydrogen produced by the electrolysis unit.

## 3. Initial Performance

### 3.1. Efficiency Analysis

In order to confirm initial system performance, the unit was operated with the temperature of the stack circulation water fixed at 60°C and the system efficiency was measured. The higher heating value of the hydrogen required to calculate efficiency was set at 3.54 kWh/Nm<sup>3</sup>. As explained in Section 2.2.1, the manufactured hydrogen flow rate varies with the water drain cycle of the high-pressure separator, so it is necessary to take an average over a sufficiently long time. In this case, the average value from 45 cycles (approximately 1 hour and 20 minutes) was sought (Fig. 6). The resulting hydrogen production in the calculation interval was 0.93 Nm<sup>3</sup> (= 3.31 kWh), and the electric power consumption was 5.96 kWh. Therefore, system efficiency in a steady state was 55.5%. This value places efficiency generally on a par with existing large-scale hydrogen stations<sup>(1)</sup>.



Fig. 4 Dispenser unit

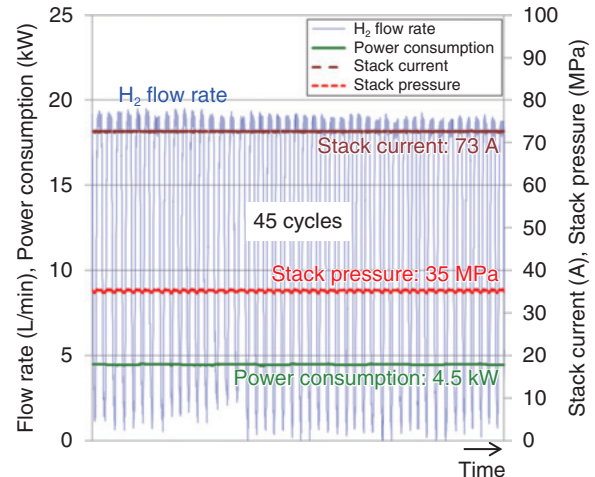


Fig. 6 Operation for efficiency analysis

Stack efficiency is of three types: the current efficiency, the voltage efficiency, and the stack efficiency (power efficiency). The current efficiency is the proportion of hydrogen obtained with respect to the theoretical hydrogen production. The voltage efficiency is the ratio of theoretical electrolysis voltage and the actual voltage. The power efficiency shows the efficiency of the stack in manufacturing hydrogen (current efficiency  $\times$  voltage efficiency). Measurement and calculation results showed a current efficiency of 96.1%, a voltage efficiency of 73.6%, and a power efficiency of 70.7%. These values were confirmed to be on a par with the initial measurement values for the stack as a unit.

In high differential pressure water electrolysis, one example is that cross-permeation across the membrane occurs with the hydrogen that has been generated, therefore reducing the amount of hydrogen obtained. In the SHS2, a proton exchange membrane two times thicker than necessary to assure the strength of the membrane was used in order to be certain of maintaining functionality. This resulted in a reduced amount of cross-permeation across the membrane, and reduced the loss of hydrogen. This yielded favorable current efficiency figures. On the other hand, the greater thickness of the proton exchange membrane increased the electrical resistance component, resulting in voltage efficiency that is on the low side.

### 3.2. Analysis of Electric Power Consumption

Electric power consumption at the time of rating was measured when calculating system efficiency, and Fig. 7 shows a breakdown of its components. Measurement results show that producing 1 Nm<sup>3</sup> of hydrogen at the high pressure of 35 MPa required 6.38 kWh of electric power. Breaking that down shows that, apart from 55.5% as the amount of energy converted into hydrogen, the energy required to boost the pressure is approximately 2.7%, electric power loss in the stack is 20.2%, loss from power conversion in the electrolysis power supply is approximately 9.3%, and

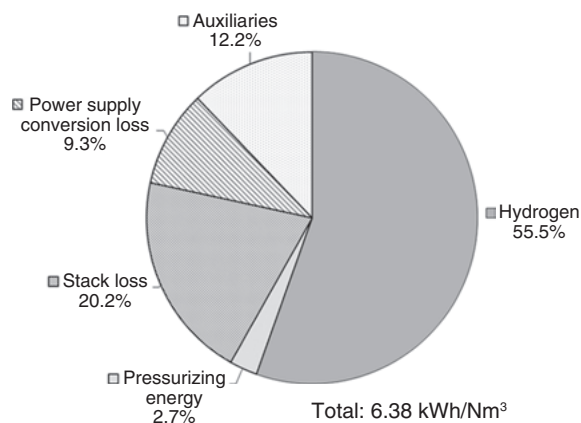


Fig. 7 Power consumption of SHS2

the total electric power consumed by auxiliary equipment is 12.2%. By item, the stack loss is considerable, followed by electrolysis power supply loss. This shows that enhancing stack efficiency and electrolysis power supply conversion efficiency would be effective in enhancing system efficiency.

### 3.3. Proposals for Enhancing Efficiency

The reason that stack losses are considerable, as explained in Section 3.1., can be considered to stem from increased resistance due to the use of a thicker proton exchange membrane. Basic study of efficiency enhancement relating to differences in thickness and type of proton exchange membrane has already been performed, and will be described briefly below.

Figure 8 shows the performance of a proton exchange membrane that is presently being compared with the proton exchange membrane that is currently in use. If only the thickness of the present proton exchange membrane is halved and the material is not changed, the electric resistance of the proton exchange membrane can be reduced and the voltage efficiency increased. However, reducing the thickness of the proton exchange membrane can lead to an increased amount of cross-permeation across the membrane so that the current efficiency is reduced. As a result, the apparent gain in power efficiency is slight. A proton exchange membrane made with a material that has low hydrogen penetrability to hydrogen and high strength is under study. When a proton exchange membrane with this different material is used, the amount of cross-permeation across the membrane is reduced and the current efficiency is enhanced. Since the material is stronger, the membrane can be made thinner, which enhances voltage efficiency. This has been found to yield an increase of approximately 10% in power efficiency. The proton exchange membrane with this different material has completed initial testing and results have been confirmed. At present, its durability is being confirmed.

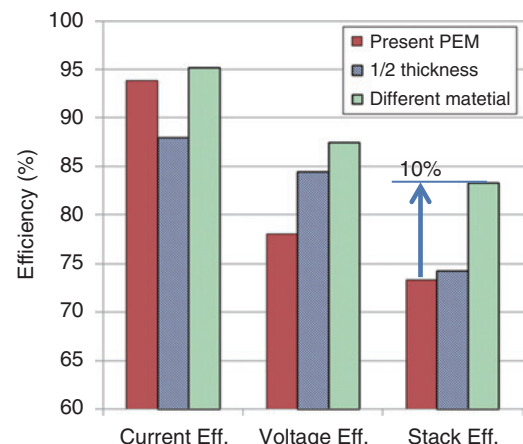


Fig. 8 Efficiency difference of alternative PEMs

Another component with considerable losses is the electrolysis power supply that performs high power conversion. It is thought that enhancement of system efficiency can be achieved most effectively by developing a power supply with greater conversion efficiency. Other measures that need to be taken include lowering the power consumption of auxiliary equipment and optimizing driving methods. These measures are anticipated to yield system efficiency of approximately 70%, as shown in Fig. 9. This figure places the unit at the highest level for compact hydrogen stations known to date<sup>(1)</sup>.

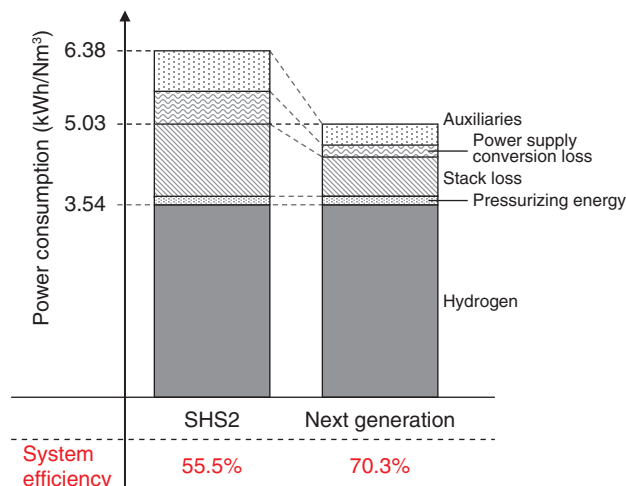


Fig. 9 Expected efficiency

## 4. Verification Tests

### 4.1. SHS2 Verification Test Results

The current verification tests used fuel cell electric vehicles operated to simulate commuting to work to test continuous manufacture of the required hydrogen and filling the vehicle with the SHS2. The testing was implemented employing local testers with fuel cell electric vehicles that they actually use to commute to work, go out, and so on.

Figure 10 shows the cumulative total of hydrogen generated by the SHS2 and electric power by the solar cells over the one-year period of operation starting in February 2010. The system is able to produce approximately 0.5 kg of hydrogen in eight hours of operation per day. An ideal line was therefore drawn in the graph for reference to represent the cumulative total of hydrogen generated if 0.5 kg of hydrogen were produced each day. In other words, if the SHS2 is operating normally, the slope of the total volume of hydrogen produced should match the slope of this line. In September 2010, a storage tank enabling 24-hour operation was installed. In other words, the unit became able to produce 1.5 kg of hydrogen per day, so the ideal line was drawn to show 1.5 kg/day from September on. It is apparent from this graph that the system operated without any major problems for a one-year period, excluding long vacations by

the operating location and periods of maintenance.

As a result of operation for a one-year period, the time spent in high-pressure water electrolysis at 35 MPa amounted to 1260 hours. The system was started and stopped 267 times, and the amount of hydrogen produced came to 120 kg. Fuel cell electric vehicles were filled 268 times, and after the storage tank was installed, fast filling was performed 107 times.

The total amount of energy generated by the solar cells over the one-year period was 8.82 MWh. On the hypothesis that the system produces hydrogen with energy consumption rate of 6.38 kWh/Nm³, the amount of electric energy required to produce the 120 kg (1344 Nm³) over the year would be 8.57 MWh. This means that the solar cells could supply the electric energy for the total amount of hydrogen produced, verifying the system concept.

### 4.2. Operation Simulation Using Test Results

Under the initial SHS2 system concept, the specifications were set on the basis of night-time slow filling at home. On the other hand, installing a storage tank with the SHS2 to enable fast filling would have some disadvantages, as explained in Section 2.3., but the unit's convenience may also increase, depending on the user's circumstances of use. SHS2 operation simulation was conducted using the verification test results as the means to verify this concept. The greatest advantage to the home fueling system is thought to be the convenience of being able to fill a car with fuel at home. The indicators of user convenience were therefore taken as the fuel level at the time of departure from home; or in other words, a measure of the amount of hydrogen supplied at home, together with the SHS2 utilization rate and the number of times the vehicle was filled at outside stations.

Operating patterns were defined for the simulation

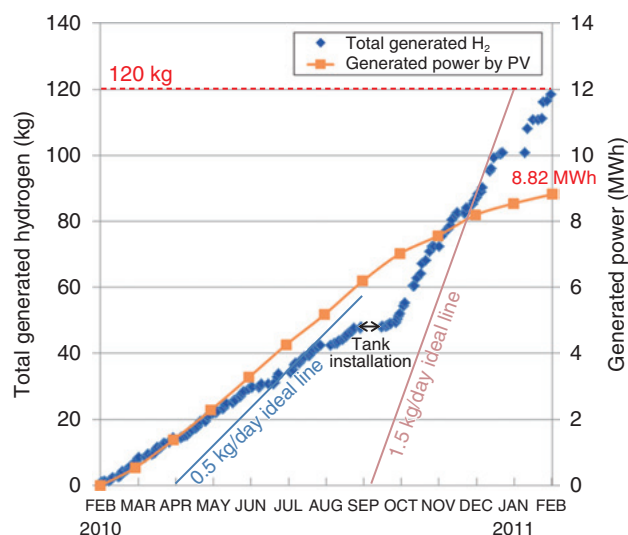


Fig. 10 Total generated hydrogen by SHS2 and power by PV

assuming low, middle, and high frequency of use of fuel cell electric vehicles. The simulation was then performed over a one-year period of operation of fuel cell electric vehicles and the SHS2 following the operating pattern for each user. The figures used for the simulation such as the fuel consumption of the vehicle, the hydrogen production efficiency of the SHS2, and so on were obtained in actual operation. Simulation was performed at first to show the impact of having the SHS2. Figure 11 and Table 3 show changes in the fuel level frequency distribution upon departure from home everyday with times filled at outside stations respectively. By having SHS2 low-frequency users (low: assuming use for commuting to work) able to maintain a high fuel level, the system was able to fully supply their required hydrogen. It is clear also from Table 3 that where the number of times the vehicle was filled outside was 61 times when there was no SHS2, this figure was reduced to 2 times when the SHS2 was present. High-frequency users were often away at night and more often travelled longer distances, so the system was not able to provide an adequate supply of hydrogen at home, and it is apparent that there was less advantage to having the SHS2.

The next simulation conducted was SHS2 with storage tanks to verify whether or not having a storage tank would have an impact on user convenience. Figure 12 shows the fuel levels obtained in the simulation, and Table 4 shows the system utilization rate, while Table 5 shows the changes in the number of times the vehicle was filled away from home. The storage tank was envisioned as having a capacity equal to the vehicle fuel tank. Table 4 shows that having a storage tank enhances the system utilization rate for all users, especially for high-frequency users. Figure 12 shows that low fuel levels could largely be eliminated. In Table 5, the number of times filled away from home could be reduced from 52 times to 15 times. This suggests that the addition of a storage tank enables adequate supply of hydrogen at home and shows that user convenience is enhanced.

Consequently, supplying the SHS2 with the storage tank as an option appears likely to meet the needs of users with various patterns of use.

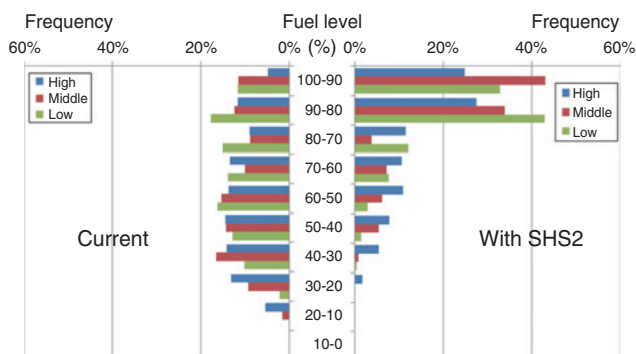


Fig. 11 SHS2 contribution for user

Table 3 Refueling frequency at public stations

|      | Current | With SHS2 |
|------|---------|-----------|
| High | 111     | 52        |
| Mid  | 101     | 31        |
| Low  | 61      | 2         |

Table 4 System utilization rate

|      | No tank | With tank |
|------|---------|-----------|
| High | 32%     | 79%       |
| Mid  | 44%     | 68%       |
| Low  | 32%     | 52%       |

Table 5 Refueling frequency at public stations

|      | No tank | With tank |
|------|---------|-----------|
| High | 52      | 15        |
| Mid  | 31      | 26        |
| Low  | 2       | 0         |

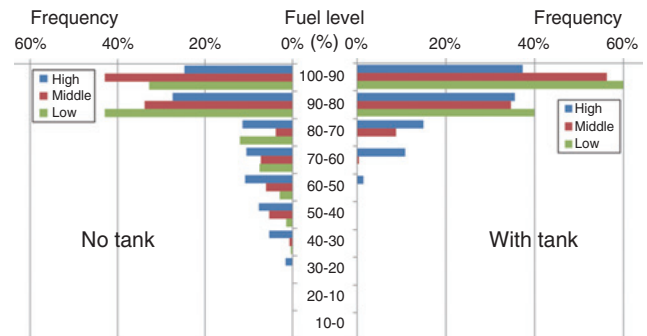


Fig. 12 Storage contribution for user

## 5. Conclusion

Development and installation of the SHS2 yielded the following conclusions:

- (1) Verification tests of the high differential pressure water electrolysis system were implemented for a period of approximately one year. The system was able to supply hydrogen continuously to fuel cell electric vehicles. This demonstrated the endurance reliability of the system as a whole.
- (2) The amount of hydrogen produced in the one-year period was 120 kg. It was found that solar cells were able to supply the entire amount of electric energy required for production. This proved the system concept.
- (3) The data obtained through operation was used to define

hypothetical operating modes and perform operation simulations. The results show that having a storage tank with capacity equal to the vehicle fuel tank enabled heightened convenience for many users.

- (4) The initial performance was measured when the system was first installed. The system efficiency was 55.5%, and 6.38 kWh of electric power were consumed per 1 Nm<sup>3</sup> of hydrogen. Future changes in the membrane material, increases in device efficiency, and other such measures are expected to yield an increase in system efficiency to approximately 70%.

Operation of the SHS2 will be continued, and plans call for accumulation of data on long-term performance and durability.

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