

Verification Test Results for Solar Hydrogen Station in Japan

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ABSTRACT

A high differential pressure water electrolysis-type solar hydrogen station was installed on the grounds of the Saitama Prefectural Offices and a two-year verification test was carried out. This was the first time for Honda to hand over a high differential pressure water electrolysis-type solar hydrogen station to a public institution such as the Saitama Prefectural Offices for verification testing in this way. The verification test involved using hydrogen produced by a high-pressure water electrolysis system to supply as fuel for an FCX Clarity fuel cell electric vehicle used as an official vehicle by Saitama Prefecture, collecting data, and conducting analysis. During the two years of the verification test, the outdoor environmental suitability of the system and the changes in performance of the high differential pressure water electrolysis stack were confirmed. This also demonstrated the ability to maintain hydrogen quality and provide a constantly stable supply of hydrogen. All of the hydrogen supplied to the FCX Clarity automobile was provided entirely with the electric power from photovoltaic cells. Since the Saitama Prefectural Offices operated one FCX Clarity automobile, this had the reduction effect of approximately 16% on the CO₂ emitted by all the official Saitama Prefectural vehicles operated by the particular office that operated the FCX Clarity. There is a likelihood that a CO₂ reduction of approximately 41% can be further achieved by maximizing the use of electric power from photovoltaic cells.

1. Introduction

Honda has long been engaged with countermeasures under the three headings of atmospheric pollution, global warming, and the energy problem. The company has been developing fuel cell electric vehicles as a next-generation powerplant that is capable of simultaneously addressing those three headings.

At the same time, Honda has also been pursuing the parallel development of hydrogen generation technology. The company has been conducting verification tests of solar hydrogen stations that use high pressure water electrolysis technology with photovoltaic cells as the power source.

The first step was taken at Honda R&D Americas, Inc. Los Angeles Center in Torrance, California, where a solar hydrogen station that combined commercially available equipment was tested starting in July 2001. A normal pressure water electrolysis-type solar hydrogen station (SHS1)⁽¹⁾ with a water electrolyzer using unique Honda technology was added in October 2003. In January 2010, the SHS1 was replaced with a high differential pressure water electrolysis-type solar hydrogen station (SHS2)^{(2), (3)} and verification tests have been carried out.

This paper will introduce the results of verification tests conducted of the domestic SHS2, which has been operated since its installation on the grounds of the Saitama

Prefectural Offices in March 2012. The verification test period for this paper is the two years from March 2012 to March 2014.

The purpose of this verification test was mainly to confirm the matters under the following three headings.

- (1) Environmental suitability (waterproofing, low temperature)
- (2) Changes in high differential pressure water electrolysis stack performance
- (3) Hydrogen quality in the high pressure water electrolysis system

This system was installed by four parties: the Saitama Prefectural Offices; Iwatani Corporation; Honda Motor Co., Ltd.; and Honda R&D Co., Ltd. It was part of the CO₂ Emission Reduction System that Combined Small Scale Solar Hydrogen Station and Fuel Cell Electric Vehicles, which was one of the fiscal year 2011 Low Carbon Technology Research and Development Programs of the Ministry of the Environment.

2. System Overview

2.1. Principle of High Differential Pressure Water Electrolysis

Figure 1 shows a schematic view of the high differential pressure water electrolysis cell. When a water electrolysis

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cell using a solid polymer proton exchange membrane (PEM) is supplied with purified water and a voltage is continuously applied to the PEM, the cell continues to generate oxygen and hydrogen. When a high-pressure storage tank is installed at the hydrogen outlet, therefore, the pressure in the tank continues to rise gradually, ultimately yielding high-pressure hydrogen gas. The oxygen, on the other hand, is left at atmospheric pressure, so that interposing a PEM in the high differential pressure water electrolysis cell causes a pressure differential to form.

When a voltage is applied to both ends of a PEM in high differential pressure water electrolysis, purified water on the anode side becomes oxygen and protons (H^+). The protons migrate to the opposite electrode and form hydrogen. This phenomenon is ordinarily the same as normal pressure water electrolysis, but an electromotive force generated by the difference of partial pressure in the hydrogen has to be applied when the protons migrate to the opposite electrode.

Equation (1) is the equation for the electrolysis voltage E_{WE} that is required for high differential pressure water electrolysis. The electrolysis voltage E_{WE} is reached by applying the theoretical electrolysis voltage E_1 and the cell resistance Ir of normal pressure water electrolysis and, in addition, the potential difference in hydrogen concentration required by a gas concentration cell⁽⁴⁾. The second term of Eq. (1) yields the electromotive force from the difference of hydrogen concentration in the Nernst Equation.

$$E_{WE} = E_1 + \frac{RT}{2F} \ln \frac{P_1}{P_2} + Ir \quad (1)$$

R : Gas constant

T : Absolute temperature

F : Faraday constant

P_1 : Hydrogen partial pressure of high pressure side

P_2 : Hydrogen partial pressure of low pressure side

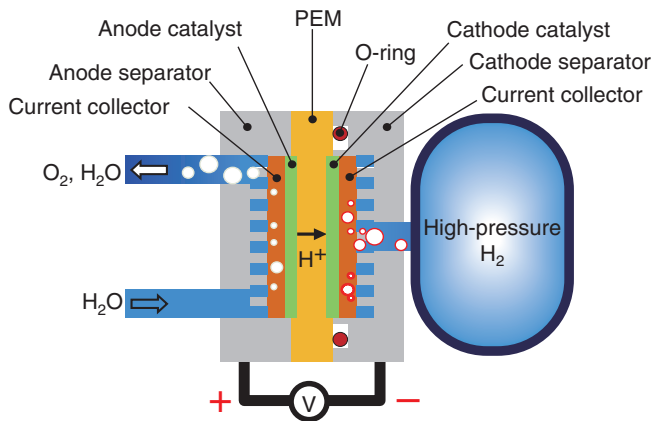


Fig. 1 Schematic of high-differential-pressure water electrolysis cell

2.2. System Configuration

Figure 2 shows a system configuration diagram of the domestic SHS2. This system is configured from a high-pressure water electrolysis system and photovoltaic cell in combination, and a distinctive feature is that it does not emit CO_2 in the course of producing hydrogen. The photovoltaic cell has a CIGS (copper, indium, gallium, and selenium compounds) thin-film solar cell⁽⁵⁾ with 10.5 kW output that is manufactured by Honda Soltec Co., Ltd. On the assumption that the FCX Clarity official vehicle would be driven an annual maximum distance of 20,000 km, the photovoltaic cell was designed with the capacity to produce the required amount of hydrogen using electric power obtained entirely from the photovoltaic cell.

The system also allows for use of the electrical grid so that hydrogen can be generated even in rainy weather and at night. Also, where the FCX Clarity hydrogen tank has a capacity of 4 kg, the system hydrogen tank has a storage capacity of approximately 20 kg (35 MPa, 828 L).

2.3. Exterior Appearance

The exterior appearance of the domestic SHS2 described in this paper is shown in Fig. 3.

The system with these specifications consists of an electrolysis unit that produces high pressure hydrogen gas by means of photovoltaic cell modules and a high differential pressure water electrolysis device, a dispenser

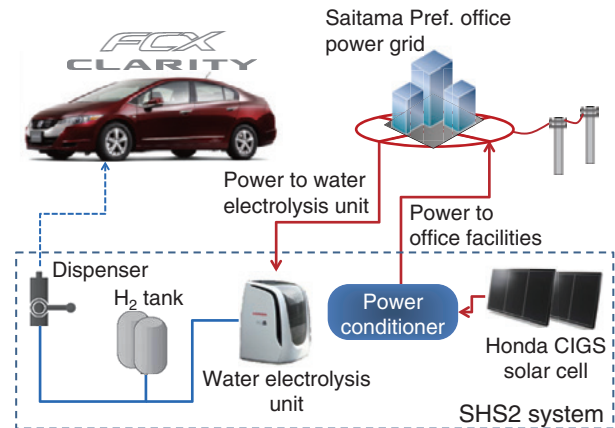


Fig. 2 System layout of SHS2



Fig. 3 External view of SHS2

Table 1 Specifications of SHS2

Hydrogen production	Flow rate	0.7 Nm ³ /h
	Filling pressure	35 MPa
	Purity	>99.99%
	Storage	20 kg
Component	Photovoltaic module	CIGS 10.5 kW
	Electrolysis unit	High-differential-pressure electrolyzer
Utility	Electricity	200 VAC /50 Hz
	Water	Tap water
Unit volume		Approx. 0.33 m ³

unit that fills the FCX Clarity with hydrogen, and a hydrogen storage tank.

The installation area was finished and system colors were selected so that the component units would merge harmoniously into the surrounding environment within the Saitama Prefectural Offices campus. The exterior was designed with simple curves to convey a sense of affinity, safety, and ease of use.

2.4. Specifications

Table 1 shows the specifications for the domestic SHS2.

Given a supply of tap water and electricity, the SHS2 can produce and store high-pressure hydrogen gas at a maximum pressure of 35 MPa, and when required can fill the FCX Clarity. The hydrogen generation volume is 0.7 Nm³ per hour, so if it is operated for 24 hours, it will produce enough hydrogen for the FCX Clarity to drive approximately 150 km.

The domestic SHS2 differs from the equipment installed at the Honda R&D Los Angeles Center. Projecting that operation at temperatures below freezing would take place, freeze-proofing measures were put in place within the electrolysis unit of the domestic SHS2.

Figure 4 shows an overview of the freeze-proofing measures. Parts that should be kept warm are not only inside the electrolysis unit, but also include the water supply pipe, the vent pipes for releasing generated oxygen, and other areas that are exterior to the electrolysis unit. Different heat retention methods that would be effective in the various parts were therefore adopted. The interior of the electrolysis unit was heated as a whole by coupling an

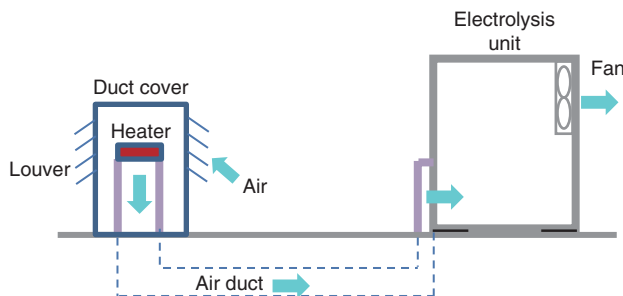


Fig. 4 Ventilation and heating system

air heater to the air intake duct that brings in outside air. For the water supply pipe and oxygen vent pipes, which are directly exposed to the outside air, an explosion-proof piping heater and insulation material were used as freeze-proofing measures.

3. Verification Test Results

3.1. Environmental Suitability

During the initial installation period, a sheet of sprayed rainwater could be sucked into the interior of the electrolysis unit from the ventilation fan during heavy rains, and especially during rainstorms, causing the interior water leakage sensor to mistakenly report leaks. This had not been experienced by the equipment installed at the Honda R&D Los Angeles Center. Weather conditions in Japan are rainier and more humid than in Los Angeles, and Japanese and US ventilation flow rate regulations are different⁽⁶⁾, so that the domestic equipment had been given a higher ventilation flow rate than the US equipment. These are thought likely to be the main causes of rainwater being sucked in. Measures to counter infiltration by rainwater were taken by adding a waterproof cover, as shown in Fig. 5, to the ventilator intake.

Figure 6 shows the changes in temperature in the



Fig. 5 Duct cover

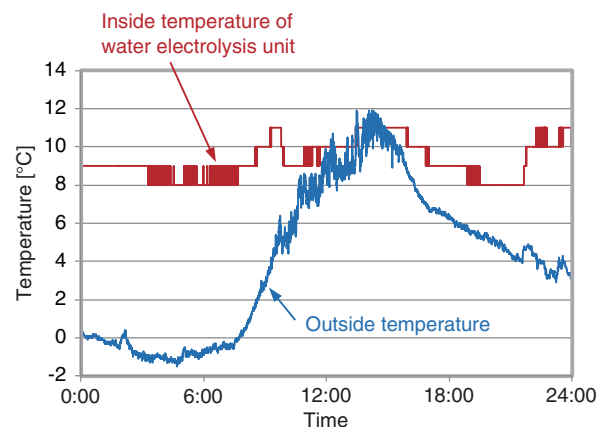


Fig. 6 Temperature change in a winter day (Jan. 16, 2014)

interior of the electrolysis unit and in the outside air in the course of one day during the winter. As anticipated in section 2.4, there actually were some times when the outside air temperature dropped below freezing. It was found, however, that the interior temperature of the electrolysis unit rose higher than the outside air temperature. This was found to be because part of the piping that drew outside air into the electrolysis unit was buried, and the heat retention effect of being underground warmed the piping. Therefore, the interior temperature of the electrolysis unit never actually fell below freezing. Piping exposed to the outside was also kept from freezing by the effects of piping heater and insulation material.

The equipment was operated at temperatures below freezing during the winter, but equipment trouble due to freezing was successfully avoided.

3.2. Changes in Performance of High Differential Pressure Water Electrolysis Stack

Figure 7 is a graph showing the rate of change in the efficiency of the high differential pressure water electrolysis stack with operation over time, where initial performance is taken as 100. Figure 8 similarly shows the rate of

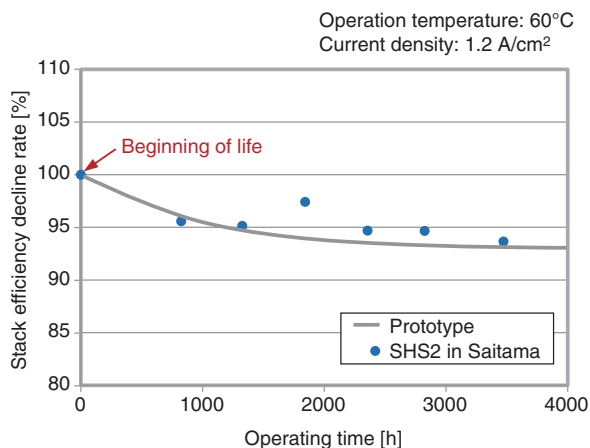


Fig. 7 Decline rate accompanied by operating time

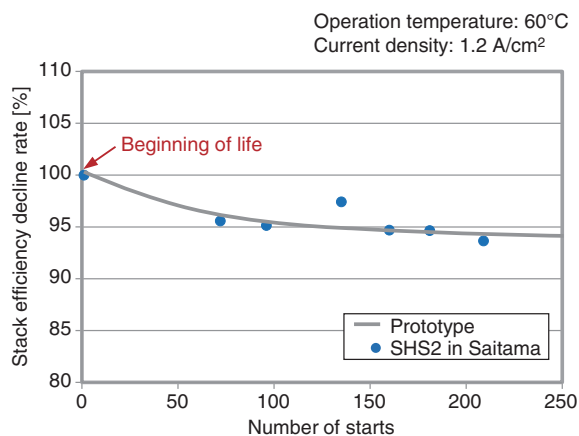


Fig. 8 Decline rate accompanied by number of starts

Table 2 Hydrogen quality of SHS2

	Sampling date		ISO 14687-2
	Feb. 16, 2012	Mar. 14, 2014	
H ₂ O (ppm)	< 5	< 5	< 5
O ₂ (ppm)	< 1	< 1	< 5
N ₂ (ppm)	4.7	< 1	< 100
CO (ppm)	< 0.1	< 0.1	< 0.2
CO ₂ (ppm)	< 0.1	< 0.1	< 2
HC (ppm)	< 0.1	< 0.1	< 2

change in efficiency with respect to the number of times the electrolysis unit is started. The electrolysis unit was subjected to confirmation of endurance by bench testing at Honda using the same system prior to the verification test at the Saitama Prefectural Offices. (The equipment evaluated internally at Honda is referred to as a prototype.) As shown in Figs. 7 and 8, changes in the performance of the high differential pressure water electrolysis stack operated at the Saitama Prefectural Offices and of the prototype stack are generally the same. The prototype was subjected to endurance operation of repeated starting and stopping under the constant condition of an ambient temperature of 25°C, and starting and stopping by a fixed schedule one time during each nine-hour period. In the verification test at the Saitama Prefectural Offices, however, the ambient temperature changed according to the season and the time of day. Furthermore, the operating times were changed randomly according to the FCX Clarity filling quantity, and the operating cycles were also irregular. As indicated in Figs. 7 and 8, there was no divergence in performance due to operating time or frequency. This demonstrated that there was no performance differential resulting from differences in the environment of installation, whether in-house with the prototype or in the real world at the Saitama Prefectural Offices. At the same time, therefore, this has also confirmed the validity of the operating mode used in endurance testing of the prototype performed in-house at Honda.

3.3. Hydrogen Quality

Table 2 shows the results from analysis of the main impurity elements found in the hydrogen produced by the electrolysis unit. There is no change in the hydrogen quality between the time of initial installation in February 2012 and two years later in March 2014. Furthermore, the values in either case meet the standard for Grade D⁽⁷⁾ purity specified in ISO 14687-2. This demonstrates that hydrogen of stable quality was successfully supplied over a two-year period. Consequently, the verification test at the Saitama Prefectural Offices was implemented without delays and without any malfunction due to fuel or other such issues occurring in the FCX Clarity. Since the electrolysis unit electrolyzes purified water to obtain

hydrogen, the only major impurities contained in that hydrogen gas are oxygen and moisture. Since an oxygen pressure differential of 35 MPa occurs between one side of the membrane and the other, only an extremely small amount of oxygen gas diffuses through the membrane to the cathode side. As to the moisture, it is removed by an adsorbent, which will be discussed later. Figure 9 shows the water concentration in the 35-MPa hydrogen manufactured by the electrolysis unit, converted into dew point temperature. The ISO reference value of 5 ppm when converted into dew point temperature at 35 MPa is approximately -16°C . As shown in Fig. 9, the water concentration was found to stay lower than the reference level, maintaining levels of 5 ppm or below throughout the entire two-year period of operation. The volume of adsorbent was set at a level to allow approximately three-month intervals between replacement when the electrolysis unit was operated continuously for 24 hours.

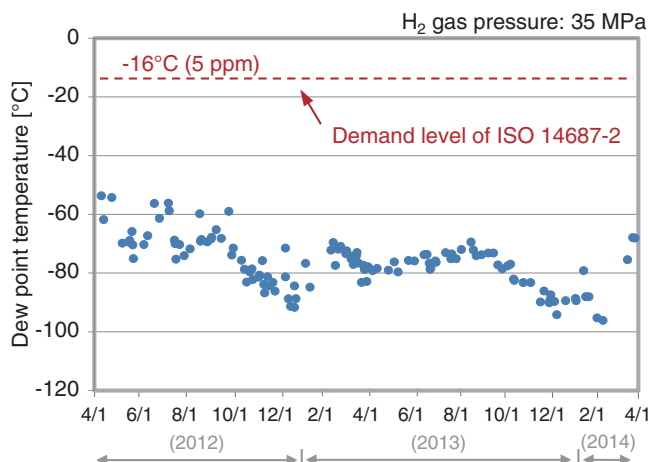


Fig. 9 Dew point temperature of hydrogen

4. Operational Results and CO₂ Reduction

4.1. Amount of Hydrogen Produced and Photovoltaic Power Generated

Figure 10 shows the amount of electric power generated by the photovoltaic cell during the two-year period of operation. The cumulative amount of electric power generated comes to approximately 28 MWh. The solid line in Fig. 11 likewise shows the cumulative amount of hydrogen produced by the electrolysis unit during the two-year period of operation. The hydrogen produced by the electrolysis unit was stored in the tank, and when the tank became full, the electrolysis unit would go into standby. When hydrogen from the tank was subsequently used to fill the FCX Clarity so that the pressure in the tank dropped, the electrolysis unit would resume operation. Since this operational cycle is repeated, the amount of hydrogen generated by the electrolysis

unit has a strong correlation with the amount of hydrogen consumed by the FCX Clarity. The cumulative amount of hydrogen shown by the solid line in Fig. 11, therefore, changes with the frequency of use of the FCX Clarity at the Saitama Prefectural Offices. The dotted line in Fig. 11, on the other hand, shows the amount of hydrogen production if it is assumed that the total amount of electric power generated by the photovoltaic cell is converted into hydrogen produced. This dotted line shows the amount of hydrogen production calculated from the amount of electric power generated by the photovoltaic cell, and this amount of hydrogen production is greater than the actual amount of hydrogen production by the electrolysis unit. This indicates that all of the hydrogen produced by the electrolysis unit was produced using electric power from the photovoltaic cell. Using only the electric power supplied from the photovoltaic cell, the amount of hydrogen that could be produced in the two-year period was 486 kg, whereas the actual hydrogen generation amount was 190 kg.

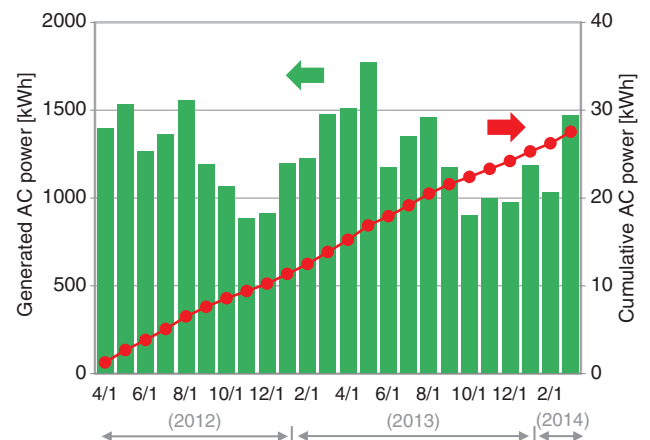


Fig. 10 Amount of AC power generated by photovoltaics

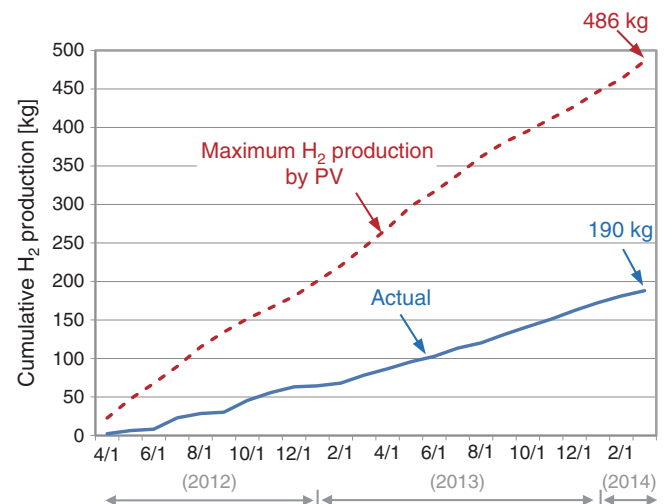


Fig. 11 Amount of H₂ production

4.2. FCX Clarity Filling Frequency

During operation over a two-year period, the SHS2 filled the FCX Clarity 165 times. Figure 12 is a histogram showing the amounts of hydrogen that were used to fill the FCX Clarity each time. When empty, the tank in the FCX Clarity can be filled with approximately 4.0 kg of hydrogen. As the figure indicates, the hydrogen filling quantities for one filling during this verification test centered on the average filling quantity of 1.0 kg, with 90% or more concentrated in a range of 2.0 kg or less. The fuel tank was therefore being filled when the amount remaining in the tank was 50% or more. Gasoline cars, by contrast, are generally said to be refilled on average when the amount remaining in the tank goes down to approximately 20%.

This is thought likely to be the result of psychological uneasiness about running out of fuel because there are no hydrogen stations at the destination or on the way to or from it when operating the FCX Clarity as an official vehicle of the Saitama Prefectural Government Office.

4.3. CO₂ Reduction Effect at the Saitama Prefectural Offices

One FCX Clarity was operated at the Saitama Prefectural Offices, resulting in the production of 190 kg of hydrogen over a two-year period. At the same time, the amount of electric power generated by the photovoltaic cell over the same two-year period was approximately 28 MWh. The amount of hydrogen that can be produced from those 28 MWh of electric power without emitting any CO₂, as shown in Fig. 11, is 486 kg. If the present utilization rate is taken as a reference, this amount of hydrogen production is sufficient to operate approximately three FCX Clarity automobiles. Figure 13 shows the CO₂ reduction effect from use of the FCX Clarity, based on the CO₂ emitted by all official vehicles used by the Saitama Prefectural Office that operated the FCX Clarity. As a result of using the 190 kg of hydrogen produced as fuel to operate the FCX Clarity, there was a reduction effect of approximately 16% on the CO₂ emitted by all the official vehicles operated by that

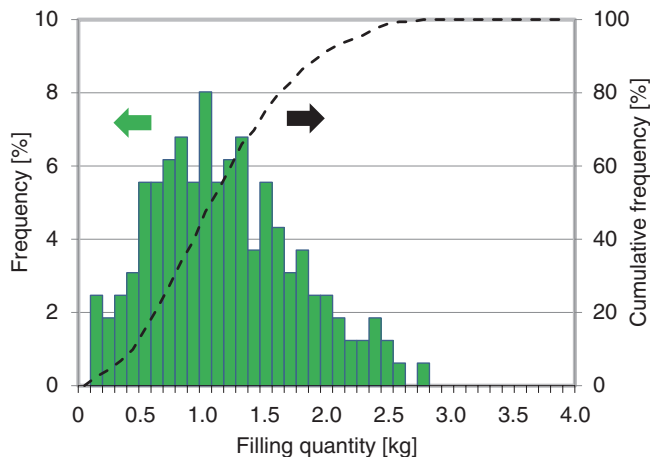


Fig. 12 Histogram of filling quantity

Saitama Prefectural Office. In addition, if it is supposed that all of the electric power from the photovoltaic cell is converted into hydrogen and used as fuel in the FCX Clarity, then it appears likely that CO₂ can be reduced approximately 41%. The above CO₂ reduction is the result of operating one FCX Clarity, and increasing the number of FCX Clarity automobiles operated could further increase the CO₂ reduction effect.

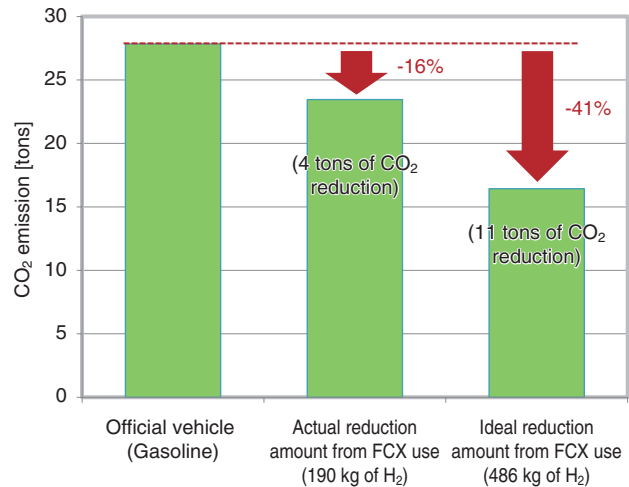


Fig. 13 CO₂ reduction effect by SHS2

5. Conclusion

Carrying out the verification test of the domestic SHS2 yielded the following results.

- (1) Findings regarding domestic specifications for environmental suitability (waterproofing, low temperature) were obtained.
- (2) The performance of the high differential pressure water electrolysis stack showed generally the same changes as the in-house Honda prototype, demonstrating that the difference between real world and test bench results is slight. At the same time, this also confirmed the validity of the operating modes used in endurance testing of the in-house Honda prototype.
- (3) The quality of the hydrogen produced by the electrolysis unit remained unchanged from when testing began, demonstrating the ability to supply hydrogen of consistently stable quality for the FCX Clarity. Consequently, the verification test at the Saitama Prefectural Offices was implemented without delays and without any malfunction due to fuel or other such issues occurring in the FCX Clarity.
- (4) Operation of one FCX Clarity automobile at the Saitama Prefectural Offices resulted in reduction of approximately 16% of the CO₂ emitted by all the official Saitama Prefectural vehicles operated by the particular office that operated the FCX Clarity. Furthermore, if it is assumed that all of the electric power from the

photovoltaic cell could be converted into hydrogen, it appears probable that CO₂ can be reduced approximately 41%.

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