

Verification Test of Solar-powered Hydrogen Station (SHS) with Photovoltaic Modules

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ABSTRACT

A solar-powered hydrogen station (SHS) with photovoltaic modules has been established to produce hydrogen with zero CO₂ emissions. The SHS has been stably producing hydrogen for almost four years, and also, the hydrogen supply for the Honda FCX fuel cell vehicle has been demonstrated. This operational status has demonstrated that stable hydrogen production can be achieved using a renewable energy source. Using only the variable power generated by the photovoltaic modules, the SHS system operates at an efficiency of approximately 53%, and produces approximately 1500 Nm³ of hydrogen per year, equivalent to 8000 miles-run by the FCX. Using verification tests, feasibility studies of a household renewable hydrogen station, projected as a future mode of hydrogen supply, have been completed.

1. Introduction

Honda has developed fuel cells as the ultimate clean power plants for the next generation, from the viewpoints of developing a substitute for fossil fuels, reducing exhaust gases, and reducing the effect of automobiles on global warming. It is desirable that hydrogen, which is used in a fuel cell vehicle, be produced as far as possible employing a method that does not use fossil fuels in the production, storage, and refueling processes. In other words, it is desirable to use renewable energy (for example electric power generated by photovoltaic modules), which does not affect the global environment, to produce hydrogen in the future.

However, if the input uses renewable energy independently, power fluctuations will occur due to the characteristics of such energy. Consequently, in the case of a large scale station system, it is challenging to predict the operation mode in advance, thus high efficiency during actual running cannot be expected. Generally, currently available photovoltaic modules are connected to the power grid. However, it is conceivable that as these modules come into increasingly widespread use, variable power that cannot be connected to the power grid will increase. The production of hydrogen for fuel modules using such variable power alone is effective from the viewpoints of utilizing renewed energy and smoothening electric power. Consequently, a system that can cope with fluctuations of

input power and is capable of operating at higher efficiency is needed for equipment that uses renewable energy to supply hydrogen. Accordingly, the development of a small hydrogen station that could cope with variable power and supply power from photovoltaic modules directly to a hydrogen production system has been pursued. In July 2002, a second generation solar-powered hydrogen station (SHS) incorporating Honda's unique technology was installed in Los Angeles in the state of California⁽¹⁾. In addition, in 2003, the weak points extracted via a verification test on the SHS were modified, and technical evolution was carried out to realize a hydrogen station of even higher efficiency⁽²⁾. This SHS continues to be subjected to a proving test in which hydrogen is produced from electric power generated by photovoltaic modules alone.

This concept of attempting to efficiently obtain hydrogen from the variable power of photovoltaic modules alone is relevant to the form of a household hydrogen station as a hydrogen supply configuration in the future. The SHS was installed for the following two goals, as a means of thinking about the form of a compact, highly efficient water electrolysis station.

- (1) The stable production of hydrogen from renewable energy
- (2) The production of hydrogen that enables the FCX to travel 10000 miles per year

This paper sets out a report on the results obtained

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with respect to the above goals, from the verification test of the SHS which has been carried out over a period of approximately 4 years.

2. Solar-powered Hydrogen Station (SHS)

Figure 1 shows the configuration of the SHS subjected to the verification test. The SHS consists of the photovoltaic modules, which generate electricity, and three other additional units: the water electrolysis unit for producing hydrogen, the dispenser unit that compresses the produced hydrogen and charges it to the FCX, and the high pressure tank unit that stores the high-pressure hydrogen.

From the viewpoint of reducing CO₂ emissions, it is desirable that the photovoltaic modules be thin film photovoltaic modules consisting of a copper-indium-potassium-selenium compound (CIGS). Accordingly, in the autumn of 2003, the photovoltaic modules were changed from single-crystal silicon photovoltaic modules to CIGS thin film photovoltaic modules. Figure 2 shows the installation condition of the photovoltaic modules.

The water electrolysis stack shown in Fig. 3 is mounted on the water electrolysis unit, aiming at compactness and higher efficiency. A highly active, highly durable ruthenium-based (Ru) catalyst, which is a newly

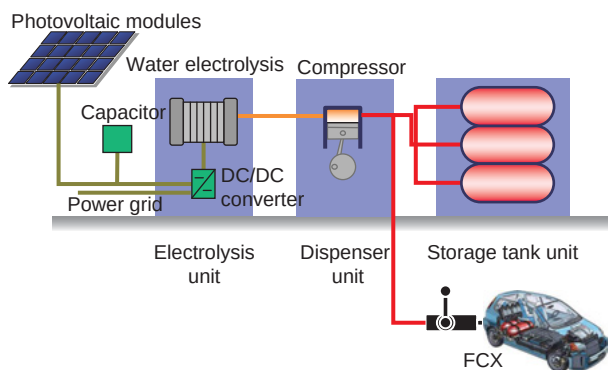


Fig. 1 Schematic diagram of SHS



Fig. 2 CIGS thin-film photovoltaic modules (prototype; manufactured by Honda Engineering Co.,Ltd.)

developed anode catalyst, is used for the stack.

All of the electric power generated by the photovoltaic modules is supplied to the system, and converted into hydrogen. Regarding the amount of hydrogen produced by the SHS, the amount that enables the FCX to travel 10000 miles per year is set to 2000 Nm³ from the fuel economy of the FCX⁽³⁾, and in order to achieve this, a sufficient number of photovoltaic modules to form a system of approximately 6 kW were mounted in the stack.

The SHS is actually a hydrogen supply station intended for performing a running test on the FCX, so it can also produce and store hydrogen by using the commercial power grid in order to cope with variations in weather and running distances.



Fig. 3 Water electrolysis stack using newly developed Ru-based catalyst

3. Verification Test of Hydrogen Production Using the SHS

3.1. Hydrogen Production Using Photovoltaic Modules

3.1.1. Production of hydrogen in one day using photovoltaic modules

Figure 4 shows the relationship between the amount of hydrogen produced in a typical day and the system efficiency. The system efficiency is the value of the produced hydrogen energy divided by the total amount of input power (energy). This value indicates the efficiency of the conversion of energy into hydrogen.

It was found that there was a tendency for the amount of hydrogen generated and the system efficiency to increase along with the increase in the generated power, which varies throughout the passage of the day. The total amount of hydrogen produced during this 1-day period is 5.4 Nm³, which enables the FCX to travel approximately 27 miles. This means that if this amount of hydrogen can be produced throughout the year, the target value will be achieved.

Along with the increase in the amount of electric power generated, the system efficiency reached an

instantaneous value of approximately 70% at the peak time of day. However, along with the intermittent startup of the compressor, the instantaneous efficiency during startup of the compressor fell by approximately 20%. Also, in the morning and evening and other time slots when the amount of power generated was low, the proportion of power generated by auxiliary devices increased, hence the amount of power used for hydrogen production decreased, thereby reducing the efficiency. As a result, the mean system efficiency calculated from the total amount of power generated and the total amount of hydrogen produced in one day was approximately 51.3%.

Figure 5 shows the relationship between the instantaneous amount of power (system input power) generated by the photovoltaic modules, and the system efficiency. The system efficiency showed a tendency to rise along with the increase in the input power, and indicated a possibility of the efficiency increasing if the input power was increased further. The reason for this is that for a rated output of 2 Nm³/hr (input power approximately 10 – 12 kW), the operation of the photovoltaic modules is a maximum of approximately 1.2

Nm³/hr (max power approximately 5.2 kW), enabling the input power to increase, and the power ratio of the auxiliary devices to be reduced. Also because of the power consumption due to startup of the compressor, a curve appeared even in the part where the instantaneous system efficiency fell by approximately 20%. Among the auxiliary devices, the power consumption ratio when the compressor started up was large.

3.1.2. Production of hydrogen for one month using photovoltaic modules

Figure 6 shows the amount of power generated, the amount of hydrogen produced, and the system efficiency for the whole month of August 2006. Apart from August 3, the weather was more or less fine, and it can be seen that a stable amount of electric power was generated. On almost all days, the generated output was at least 35 kWh/day. The amount of hydrogen produced was approximately 5.2 Nm³ per day and reached a maximum of 6.2 Nm³. The actual amount of hydrogen produced during this month was 160 Nm³, which enables the FCX to travel about 800 miles. If the production of hydrogen for this month remains stable throughout the entire year, it means that the FCX will achieve the target traveling distance of 10000 miles.

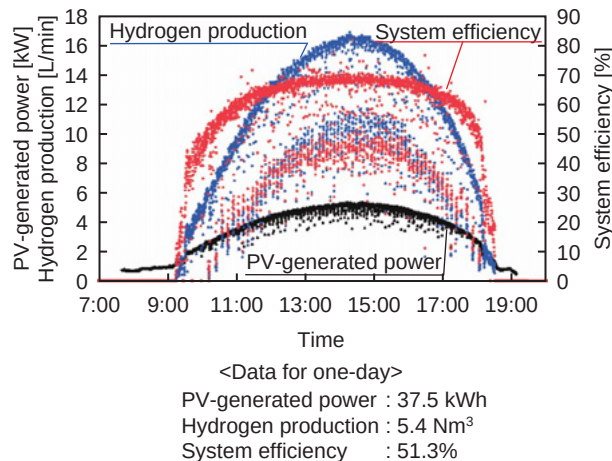


Fig. 4 Operating results for one-day in August 2006

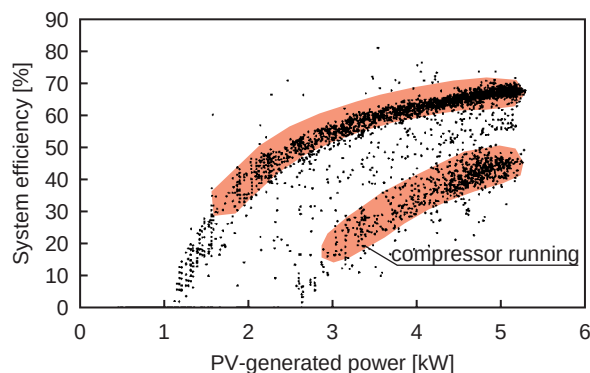


Fig. 5 Operating result for one-day in August 2006 (PV-generated power versus system efficiency)

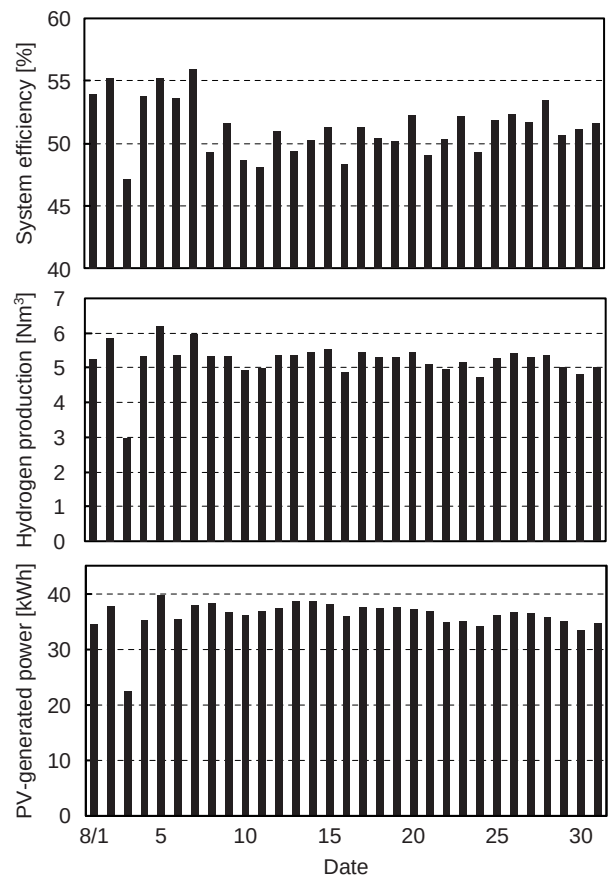


Fig. 6 Data for whole month of August 2006

However, the daily system efficiency varied between 48 and 56% even during the one month period in which stable hydrogen production was verified. One reason for this is that the power consumed by the compressor differs according to the difference in the storage tank pressure.

Figure 7 shows the power consumed by the compressor, for each storage tank pressure. The difference in the power consumption resulting from a change in the discharge pressure of the compressor between 7 MPa and 35 MPa is approximately 200 W/Nm³. This value is equivalent to 2-3% difference in conversion efficiency. Other reasons for the variation in efficiency are the fact that the necessary power for cooling the various parts (Peltier device, and the like) increases due to the rise in the atmospheric temperature, and also the fact that the auxiliary devices, such as the absorption tower recycling heater used in the production of hydrogen, start up.

From the above results, it can be said that the day-to-day fluctuations in the system efficiency were affected by the starting and stopping of the fluctuating auxiliary devices to a greater extent than the increase and decrease in the amount of power generated (input power) in one day. From this, it can be said that the reduction of the efficiency of the hydrogen production system which uses variable electric power can be minimized by using small devices that are relatively unaffected by the starting and stopping of the auxiliary devices.

3.1.3. Annual amount of hydrogen produced using photovoltaic modules

In order to evaluate the efficiency of an SHS that uses photovoltaic modules, it is recommended that a comparison of the efficiency be carried out by measuring the amount of hydrogen produced over a period of one year because the hydrogen production efficiency of the station varies according to the time, weather, season, and other factors.

Table 1 shows the amount of hydrogen produced over the past four years and also the corresponding system efficiency. The hydrogen production efficiency is 53%,

Table 1 Comparison of annual SHS performance

Year	2004	2005	2006	2007*
PV-generated power [kWh/day]	26.7	26.2	28.2	28.3
Hydrogen production [Nm ³ /day]	4.1	3.9	4.2	4.1
System efficiency [%]	54.1	52.2	53.2	52.3
Amount of produced hydrogen* [Nm ³]	1485	1400	1550	1520

*Data from January to July, 2007

and varies by $\pm 1\%$ over one year. This variation is smaller than the abovementioned day-to-day fluctuations, and indicates stable conditions. From this result, it was verified that in the case of the SHS, stable hydrogen production was maintained over a period of four years by using the variable power from the photovoltaic modules. Also, stable production of hydrogen using renewable energy, which is one of the goals of this research, has been achieved. When the amount of hydrogen produced in a year is estimated from the above efficiency value, a figure of approximately 1500 Nm³/year is obtained. This is equivalent to an FCX traveling distance of approximately 8000 miles.

Until now, hydrogen has been charged to the FCX one hundred and several tens of times using the SHS, and it is intended to continue performing this hydrogen refueling verification test.

3.2. Production of Hydrogen Using the Commercial Power Grid

In the production of hydrogen at the rated power using the commercial power grid, the electric power consumed by the auxiliary devices is the design value, so it is predicted that the SHS efficiency will be higher. In addition, it is considered that in the case of low power such as the power generated by photovoltaic modules, low current density electrolysis occurs, and the resistance loss is reduced, so reduction of efficiency does not occur. Accordingly, the efficiency obtained when the SHS was driven by constant electric power was compared with the necessary power consumption for producing 1 Nm³ of hydrogen. The results are shown in Fig. 8.

When the SHS was driven by a current of 50 A, which is equivalent to a current used in photovoltaic modules, the efficiency was 60.9%. In contrast, when the SHS was driven at the system rated current of 90 A, the efficiency was 66.3%. A detailed comparison of efficiency was performed, and it was found that when the system was driven at the rated system current of 90 A, the effectiveness of the power consumption ratio of the

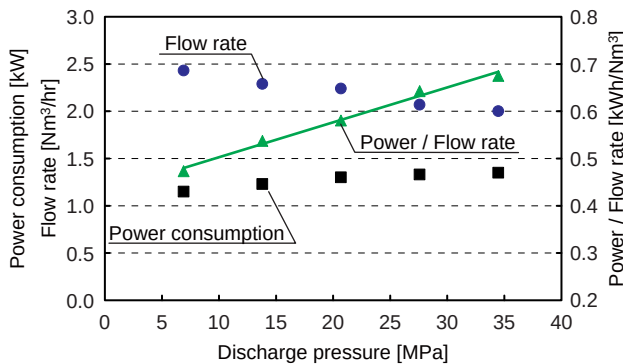


Fig. 7 Power consumption of compressor versus discharge pressure

auxiliary devices and the reduction of conversion loss due to operation at the high efficiency point of the DC/DC converter contributed to the increase in efficiency. In contrast, when the system was driven at 50 A, despite the fact that a reduction of loss in the water electrolysis stack was predicted, the electrolysis loss power actually increased due to the reduction of the temperature of the electrolysis stack. This is due to the fact that the amount of waste water from the heated water increased because the amount of pure water generated remained constant regardless of the electric power, and this is also due to the fact that the loss energy at low output is small, and the water temperature does not rise adequately.

It was found from the test results that the deficiency of hydrogen with respect to the initially planned amount of hydrogen to be generated from the abovementioned photovoltaic modules in one year was due to the following two factors.

- (1) Nonconformity between the actual zone in which the power converter (DC/DC converter) was used and the higher efficiency point
- (2) Reduction of the water electrolysis rate due to an insufficient increase in temperature in the highest operation current density zone of the water electrolysis stack (Stack not maintained sufficiently warm)

The above results suggest that even during operation at low output when photovoltaic modules are used, the stack efficiency can be raised by maintaining the electrolysis water temperature. Also, the prospect for raising system efficiency has become apparent. Furthermore, it was anticipated that the system efficiency could be increased by carrying out these measures in the case where photovoltaic modules were used, so the prospect for achieving a hydrogen production of 2000 Nm³, which would enable the FCX to travel 10000 miles per year, has also become evident.

3.3. Comparison with Other Hydrogen Stations

Figure 9 shows the results of comparing the efficiency

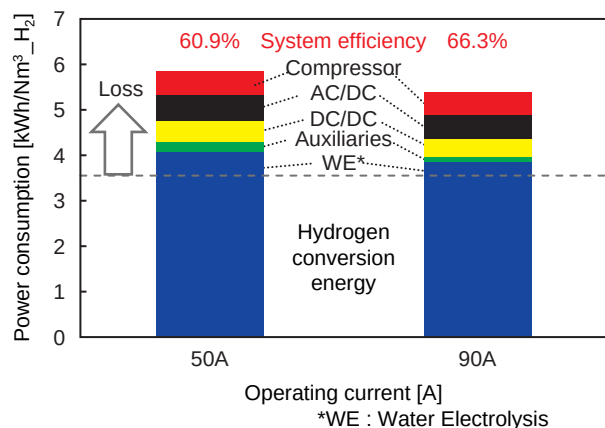


Fig. 8 Power consumption in power grid operation

of the SHS of this research with currently publicized electrolysis type hydrogen stations^{(4) - (6)}.

The efficiency of the SHS is equivalent to the efficiency of a medium scale station. Also, the SHS has higher efficiency than that of a small station that produces only a small amount of hydrogen. Generally, the efficiency of the compressor relies on the hydrogen production amount, and it is predicted that the efficiency of a small station will be low. In the case of the SHS, however, the reduction of efficiency is minimized, enabling high efficiency to be achieved.

Also, the efficiency of the compressor is affected by friction loss, so it varies depending upon the amount of hydrogen produced. It is thus conceivable that higher hydrogen production amount results in the higher efficiency of the station. In this respect, a large scale station is more advantageous.

Table 2 shows the breakdown of power consumed during the production of hydrogen at each station. All of the stations show an efficiency of slightly less than 70%, but there are differences in the contents of the efficiency. The electric power consumed per unit amount of hydrogen by the compressor of the SHS is larger than that of a medium scale compressor, and the power loss in the compressor is compensated for by highly efficient operation of the water electrolysis stack. The compressor of the SHS is a commercially available model, so its system conformity is inadequate. In order to raise the efficiency of the hydrogen station, it is necessary to enhance the method of controlling the pressure boosting section and also the system, and there is still room for

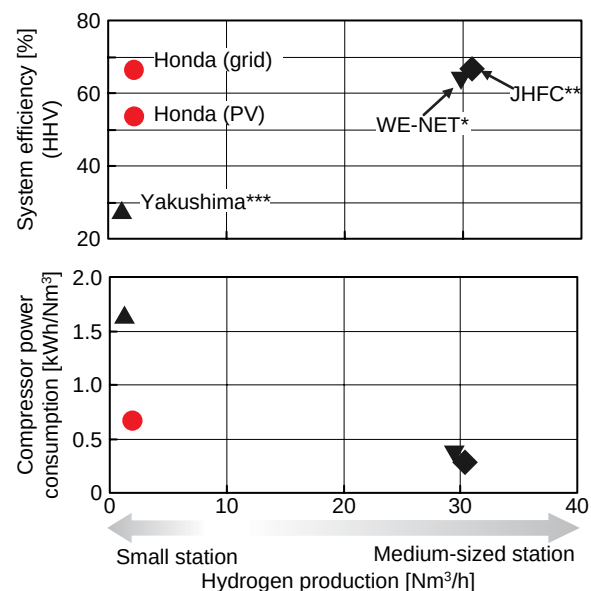


Fig. 9 Performance comparison of hydrogen refueling stations

Table 2 Comparison of hydrogen refueling stations

Manufacturer (Location)	WE* efficiency** (HHV)	Power consumption [kWh/Nm ³]	
		WE*	Compressor
Honda (Los Angeles)	95.1%	4.749	0.675
WE-NET (Takamatsu)	90.6%	5.165	0.308
JHFC (Sagamihara)	—	4.940	0.275
Yakushima project	—	5.769	1.638

* WE : Water Electrolysis

** Operating temperature : 80 °C
Current density : 1 A/cm²

developing the SHS as a household hydrogen refueling system. Also, it is evident that the efficiency of the water electrolysis stack of the SHS is higher than that of the stacks of other stations.

4. Water Electrolysis Stack with New Ru Catalyst Mounted on

It has already been mentioned that the efficiency of the water electrolysis stack of the SHS is high. This is because a stack construction which reduces the cell resistance and a new catalyst were adopted. In this subsection, the water electrolysis stack will be described in detail.

4.1. Features of the Stack Construction

Figure 10 shows an expanded view of the water electrolysis stack. The main feature of the developed water electrolysis stack is that the circulation line for supplying the necessary water for electrolysis and all of the auxiliary

devices are integral with the stack. As a result, miniaturization was achieved and stack temperature control made easy. Pure water, which is the feedwater, is supplied from the pure water production equipment to the oxygen gas-liquid separator, which is integrated with the anode end plate, and is taken to the cell by the water pump, which is integrated with the anode end plate, and electrolyzed. At the anode catalysis, oxygen is generated, and returns together with pure water to the oxygen gas-liquid separator, which integrated with the anode end plate. Because the circulation line and auxiliary devices are integral with the stack, the water passage shortens, enabling the power that is necessary to drive the water pump to be reduced, and thus achieving compactness and high efficiency.

Regarding the cell stack, current collectors consisting of sintered titanium fiber web plates are mounted on both electrodes of the membrane electrode assembly (MEA), and titanium separators are mounted on the outside of them. To help prevent the resistance at the point of contact between the feeder and the separator from increasing due to the formation of titanium oxide, the surfaces of the separator and current collectors were platinum-coated. The number of layers in the stack was set to 27 cells from the power supply voltage (48 V), and the catalyst area was made 100 cm² (100 × 100 mm) from the hydrogen production (1 Nm³/hr). Two of cell stacks were installed in order to generate the rated hydrogen production of 2 Nm³/hr. There is an optimum value of the loading between the current collectors and the MEA. In this stack, disc springs are inserted between the cathode end plate and the back-up plate so that the load between the MEA and the current collectors becomes the optimum value.

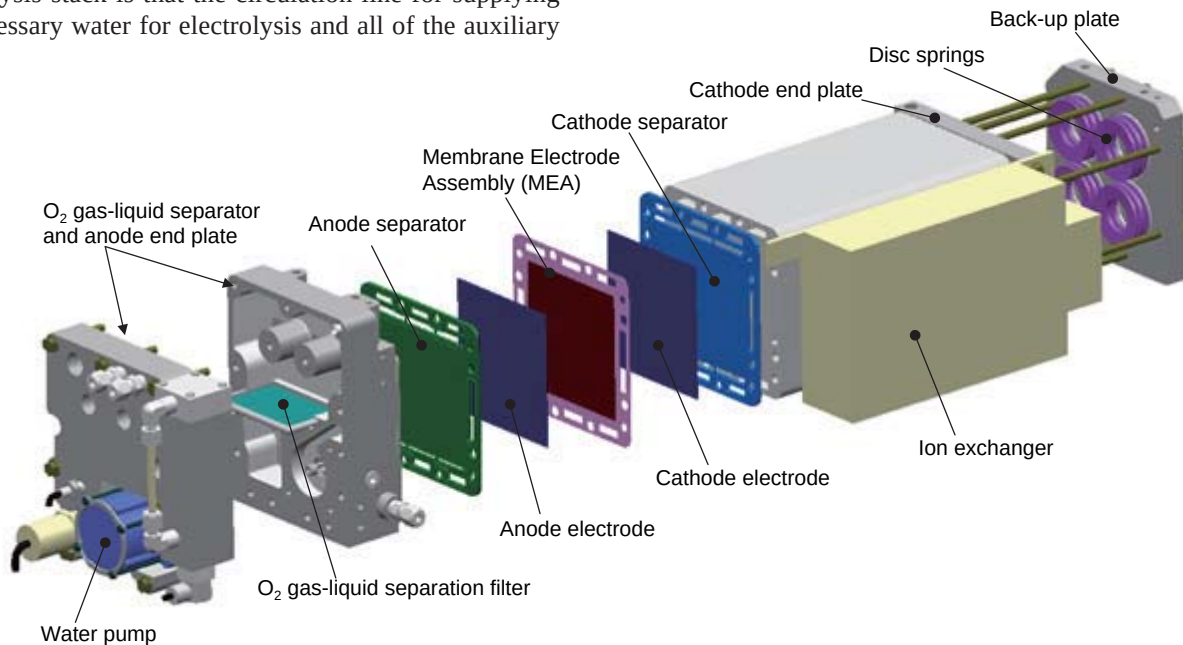


Fig. 10 Expanded view of water electrolysis stack

4.2. Features of the Newly Developed Anode Catalyst

Figure 11 shows a TEM photograph of the newly developed anode catalyst. The primary particle diameter of this catalyst is several nanometers, substantiating the fact that the catalyst is highly active. This catalyst is a compound oxide consisting of the three elements ruthenium, iridium, and iron (RuIrFeOx). Generally, it is known that RuO₂ exhibits high activity as the anode catalyst for water electrolysis, but has an issue with durability. However, because the highly active Ru of this catalyst is combined with Ir and Fe to form a compound oxide, the elution of Ru was suppressed.

It was confirmed as a result of a single cell test that this catalyst exhibits high activity and long life. Regarding the catalyst activation, the power efficiency found as a result of performing a single cell test was found to be 97% at a current density of 1 A/cm². Also, as the single cell durability performance, it was confirmed that the reduction of efficiency after 10000 hours was within 3%.

4.3. Stack Unit Performance Evaluation

Figure 12 shows the initial current-versus-voltage curves for the water electrolysis stack as a unit mounted

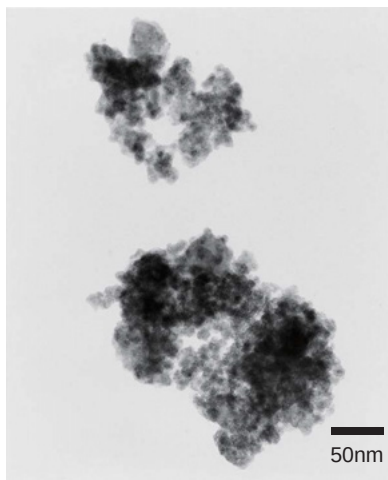


Fig. 11 TEM image of RuIrFeOx catalysts

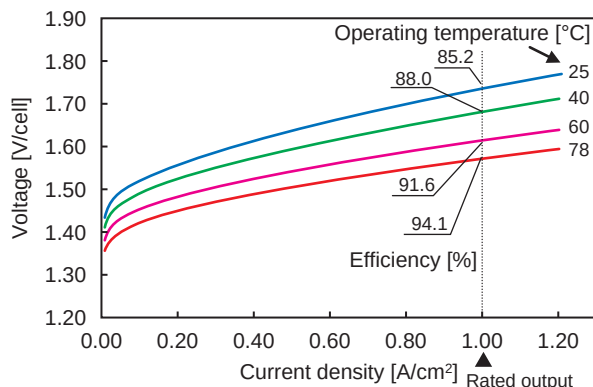


Fig. 12 I-V curve of water electrolysis stack

on the SHS. The efficiency shows a tendency to increase along with the rise of the operation temperature, and temperature control of the stack is effective for enhancing the water electrolysis efficiency. The initial efficiency of this stack is 94.1% at 78°C, and the single cell performance is maintained after the cell is mounted in the stack.

Also, as shown in Fig. 13, the performance of the cells varies between 93.8 and 94.4% for the 27 cells arranged in a straight line. This variation is within 1%, thus proving that the loading and the supply of water are uniform for the 27 cells comprising the stack.

Figure 14 shows the initial performance of the stack as a unit mounted on the SHS, and the change with time. The stack has been operated continuously for about four years without maintenance. The single cell durability test results are shown for comparison. The performance of the stack mounted on the SHS lies on an extension line of the single cell test, and the stack durability agreed with the prediction. No reduction of current efficiency due to

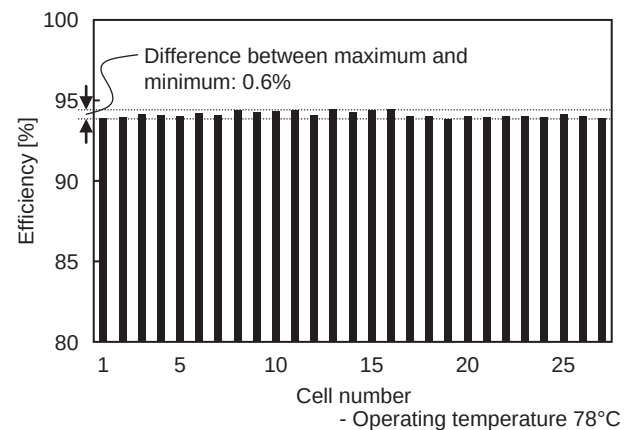


Fig. 13 Efficiency of water electrolysis cells

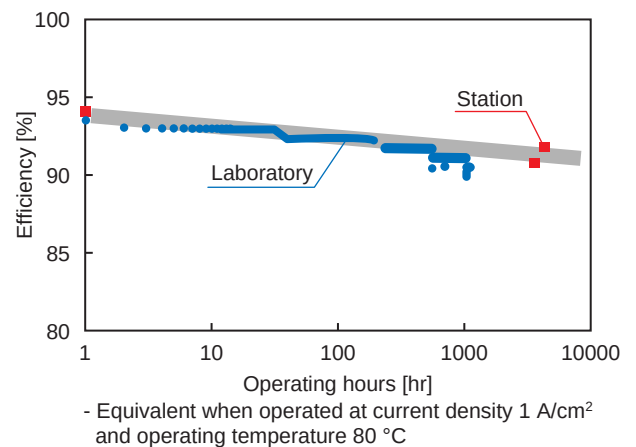


Fig. 14 Durability performance of water electrolysis stack (comparison of laboratory and station results)

deterioration of the membrane was found, thus verifying the durability of the stack. The stack mounted on the SHS showed no marked reduction of performance even when used outdoors or used under variable power. Also, the performance change was equivalent to the result obtained in the laboratory, thus proving that the stack can be used effectively as a water electrolysis stack for a household size hydrogen station.

5. Conclusion

A verification test of a hydrogen station that used photovoltaic modules for the purpose of reducing CO₂ emissions was carried out over a period of four years. The following results were obtained.

- (1) The system operated stably for about four years, and hydrogen continued to be generated without any emission of CO₂.
- (2) The efficiency of the annual hydrogen production over four years when only photovoltaic cells were used was $53 \pm 1\%$.
- (3) The hydrogen production for each 1-year period was approximately 1500 Nm³, which is equivalent to a traveling distance of 8000 miles for the FCX.
- (4) The hydrogen production efficiency at the rated power reached 66.3%, even for a small station. By raising the efficiency of the stack, the efficiency of production became the same level as that of medium and large scale stations.
- (5) The efficiency of the stack was higher than that of other stacks. The key technology used here was the RuIrFeOx catalyst. It was verified that this water electrolysis stack was effective as a water electrolysis stack for a hydrogen station.

A feasibility study of a household size renewable hydrogen station, which is one form of hydrogen refueling equipment that is expected to come into wide use in the future, was completed via a verification test.

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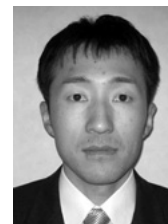
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