

Introduction of Hydrogen Refueling Station with Photovoltaic Modules

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ABSTRACT

An experimental hydrogen refueling station has been built in order to propose a solution for energy and global environmental issues, using solar radiation as its energy source. An improvement in system total efficiency was achieved by using an electrolyzer with a newly composed catalyst. As a result, it is predicted that this system is capable of producing enough hydrogen to drive a fuel cell vehicle for 10 000 miles per year with electricity from only the photovoltaic modules. A drastic reduction of CO₂ emissions per unit of hydrogen produced is possible by employing a CIGS thin film compound photovoltaic module in place of a single-crystalline Si photovoltaic module. The hydrogen refueling station has demonstrated a form in which future hydrogen production may cleanly, efficiently, and renewably be achieved from solar energy, with a design that enables the everyday user to feel comfortable.

1. Introduction

To find a substitute for fossil fuels, reduce exhaust gas emissions, and help alleviate global warming, Honda has been developing fuel cell vehicles with the belief that hydrogen fuel cells will be the ultimate next-generation power plant.

As for the energy source for producing the hydrogen, it would be desirable to use sunlight that is readily available anywhere, as opposed to the case of petroleum, supplies of which are overly concentrated in a few areas. However, while there are sufficient quantities of sunlight on a global scale, the energy to be derived per unit area is still small and fluctuates depending on the time of day, the climate and the season. Because of this, it is essential to increase the energy density and to stabilize the energy supply.

As research and development into fuel cell vehicles has advanced in recent years, so has research and development into the large-scale production of hydrogen led by the

infrastructure industry and government agencies. This has included research into hydrogen production using sunlight⁽¹⁾. However, there has been no research into what capacity of photovoltaic modules would be required to produce the hydrogen needed to power a single fuel cell vehicle, or into how much CO₂ would be emitted by the manufacture of these systems. For these reasons, in 1998, Honda assembled commercially available equipment into a prototype hydrogen producing system using photovoltaic modules, and measured the energy inputs and outputs in tests of hydrogen production. The results indicated that because the auxiliaries consumed so much energy, the amount of hydrogen that could actually be derived was rather small and therefore it was necessary to research ways to make the system more efficient.

To conduct this efficiency research, Honda set up a first-generation hydrogen production and refueling station in Los Angeles, California, in 2001, and began testing. A Honda FCX, which was already being used in public road tests in

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Fig. 1 External view of Hydrogen Refueling Station

the area, was selected to serve as the fuel cell vehicle. This type of experiment was the first of its kind anywhere by an automobile manufacturer, and was announced in July 2001.

This paper discusses a second-generation refueling station (Fig. 1) that began operating in July 2002, using knowledge gained through the first-generation station and designing the new one to be more efficient and compact.

2. Outline of Hydrogen Refueling Station

2.1. Appearance

Figure 1 shows the appearance of the hydrogen refueling station discussed in this report. Thorough safety measures were taken, and the station was designed differently from existing plant equipment to impart a sense that the hydrogen society is coming closer, and not an image that such equipment is inaccessible to the average person.

As a symbol of the project, a design was chosen that features the image of a sailboat carrying society into the future with the help of natural energy. This image emphasizes the clean and advanced aspects of hydrogen produced from light and water (Fig. 2).

2.2. Specifications

The design goal for the amount of hydrogen production was calculated as the amount which would enable driving of 10 000 miles per year. This figure was based on historical solar radiation data⁽²⁾ and the average annual driving distance per household automobile throughout the US⁽³⁾. A goal was set to derive all the energy needed for this only from sunlight. To accommodate unpredictable climate conditions and variations in driving distances, it was decided to also allow production of hydrogen from grid power. Table 1 lists the major specifications.

2.3. Overall Configuration

The hydrogen refueling station consists of photovoltaic modules, an electrolysis unit for making hydrogen, a high pressure hydrogen storage tank unit and a dispenser unit for

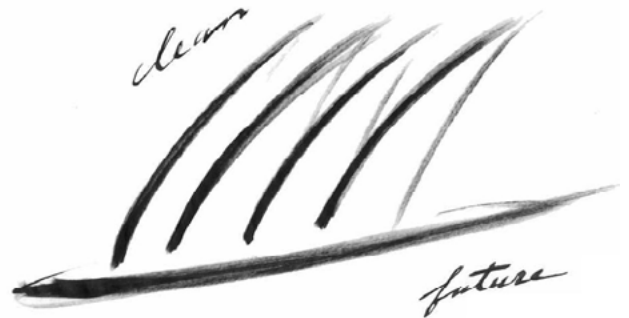


Fig. 2 Design image sketch

Table 1 Major specifications

Item	Specification
Hydrogen generation	2Nm ³ /h (Max.) over 2000Nm ³ /year
Unit size (L × W × H)	600 × 600 × 1200 (Electrolysis unit & Dispenser unit)
Storage volume	110 Nm ³
Charge pressure	35 MPa (Max.)
Charge system	Pressure gap
Energy source	Photovoltaic modules Grid power (aux.)
Type of electrolysis	Solid polymer electrolysis membrane
Input material	Tap water
Purity of hydrogen	99.9999% (without water)

filling the fuel cell vehicle with hydrogen (Fig. 3).

In order to keep each unit from being overwhelmingly large, even up close, the design standard called for each unit to be as wide across as a person's shoulder breadth and as high as breast height. The basic unit was a box measuring two feet on each side, and the station was constructed by combining multiple units (Fig. 4). The component

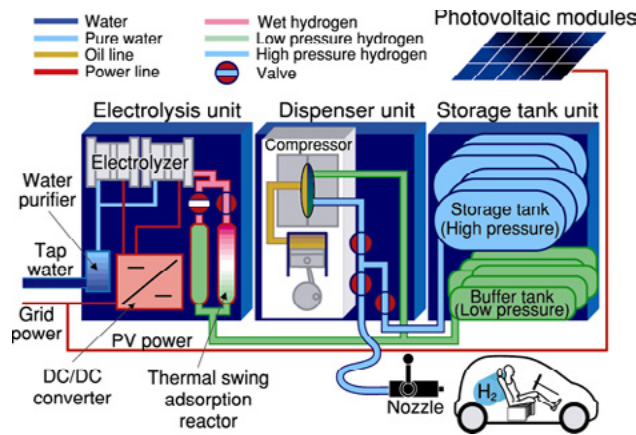


Fig. 3 Schematic illustration of Hydrogen Refueling Station

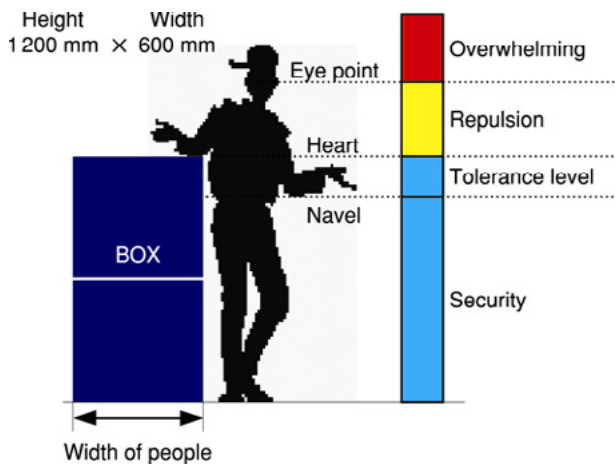


Fig. 4 Concept of unit size



Fig. 5 Scene of refueling for FCX

equipment was made compact and configured into individual units for each function. As a result, all of the equipment other than the photovoltaic modules could be placed under a canopy evoking the image of a sail, making the station resemble the project image.

The user interface has a touch panel screen and uses a dialogue system for easy operation (Fig. 5). Figure 6 illustrates the overall layout of equipment.

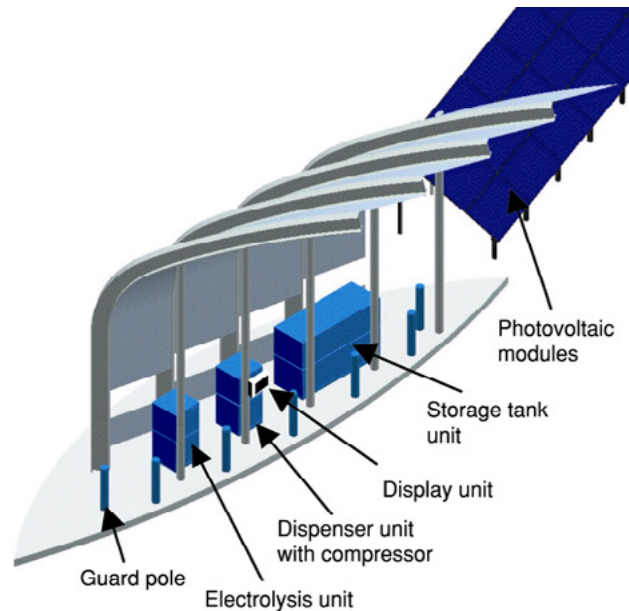


Fig. 6 Station layout

3. Photovoltaic Modules

The photovoltaic modules used are the single-crystalline Si type, which are the most efficient among those used in ordinary households; they are used in a quantity sufficient for about two households. To maximize annual power generation, it is desirable to place the photovoltaic modules at an angle to the planet surface that is about the same as the latitude. In this case, therefore, the modules were placed at about 35°, the approximate latitude of Los Angeles (Fig. 7).



Fig. 7 External view of photovoltaic modules

4. Hydrogen Production Unit

4.1. Configuration

The hydrogen production unit consists of a water purifier for turning tap water into pure water, an electrolyzer for producing hydrogen through the electrolysis of pure water, an H₂ gas-liquid separator for separating the water from the

oxidation catalysts and thermal swing adsorption reactors; O_2 gas is turned into water using the oxidation catalysts and the water is removed by adsorption using one of the molecular sieves. After a certain amount of water is adsorbed, the system switches to the other sieve. The sieve that has finished adsorbing water is heated and supplied with hydrogen so that the adsorption reactor is restored. The hydrogen used for restoration is reused after it is cooled and dehumidified.

4.2. Elektrolyzer

Figure 10 illustrates the basic principle of the electrolyzer. Pure water is supplied to the anode electrode, a voltage is applied between that and the cathode electrode, the pure water separates into hydrogen ions and O_2 gas, and the O_2 gas and unused pure water are released together. Hydrogen ions pass through a proton exchange membrane and at the cathode electrode are turned into gaseous hydrogen. As the hydrogen ions move, some of the pure water also moves to the cathode electrode side. When water is electrolyzed, there are two electrons transferred for every hydrogen molecule produced, and the theoretical amount of hydrogen that can be produced is determined by the amount of current. The electrolyzer's current-voltage (IV) properties indicate the relationship between current density and the voltage required to produce that current (Fig. 11).

Anode reaction

$$\text{H}_2\text{O} \rightarrow 2\text{H}^+ + \frac{1}{2}\text{O}_2 + 2\text{e}^-$$

Cathode reaction

$$2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$$

Proton exchange membrane

Anode catalyst

Cathode catalyst

O₂ / H₂O

Anode electrode

Cathode electrode

H₂O

H⁺

H₂

Anode metallic mesh

Cathode metallic mesh

A 3D cutaway diagram of a hydrogen production system. The diagram shows a blue frame containing several components. At the top is a yellow and red 'Electrolyzer'. Below it is a large, cylindrical 'Hydrogen purifier'. To the right of the hydrogen purifier is a 'Water purifier'. At the bottom right is an 'H₂ gas-liquid separator'. Arrows point from the labels to their respective components.

Figure 1 is a line graph showing the relationship between Voltage [V] (Y-axis) and Current density [A/cm²] (X-axis). The Y-axis ranges from 1.3 to 2.1 V, and the X-axis ranges from 0 to 2.5 A/cm². Two curves are plotted: a dashed line labeled 'conventional' and a solid line labeled 'Honda original'. The 'conventional' curve starts at approximately 1.5 V at 0 A/cm² and rises to about 1.95 V at 1.6 A/cm². The 'Honda original' curve starts at approximately 1.38 V at 0 A/cm² and rises to about 1.65 V at 2.2 A/cm². A large arrow labeled 'reduce electricity' points from the 'conventional' curve down to the 'Honda original' curve, indicating the goal of the improvement.

Current density [A/cm²]	Conventional Voltage [V]	Honda original Voltage [V]
0.0	1.50	1.38
0.5	1.68	1.48
1.0	1.82	1.55
1.5	1.95	1.62
2.0	-	1.65
2.2	-	1.65

The diagram illustrates a closed-loop water electrolysis system. The process begins with tap water entering an electric deionizer. The deionized water then flows into an electrolyzer, which is powered by a DC-DC converter. The electrolyzer produces hydrogen gas (H₂) and liquid. The H₂ gas is vented, while the liquid passes through an H₂ gas-liquid separator. The liquid then enters a heat exchanger, which is preheated by the H₂ gas. The preheated liquid then passes through a Peltier cooler, which is cooled by a catalyzer. The cooled liquid then enters a thermal swing adsorption reactor, which is cooled by a drain separator. The liquid then passes through a drain separator, which separates the liquid from the gas. The liquid then enters a product tank, which is cooled by a drain separator. The gas is vented, and the liquid is collected as the final product.

– 34 –

Achieving high efficiency, which is to say, producing hydrogen with minimal power consumption, requires minimizing the voltage needed for electrolysis. Three primary factors affect voltage: catalyst, membrane and ion supply. The voltage constituent determined by the catalyst is that required to break the water's state of equilibrium with the electrodes and promote the electrolysis reaction. This depends principally on the type of catalyst on the anode electrode side; in terms of IV properties, the voltage where the current density approaches zero in the graph corresponds to this. The voltage constituent determined by the membrane is affected by the resistance when the current is passing through the component materials and when the hydrogen is moving through the proton exchange membrane. It is expressed as the slope of the IV curve. The voltage constituent determined by the ion supply does not appear in Fig. 11, but it is what occurs as a result of insufficient ion supply. It occurs as a sudden increase in voltage in the region of the graph where current density is high. The grand total of these voltages determines the electrolysis voltage. For the purpose of lowering the electrolytic voltage, we have adopted a thinner proton-exchange membrane to reduce resistance, and developed a new Ru-Ir-Fe oxide catalyst to enable electrolytic reaction at a voltage lower than with a conventional platinum catalyst. Figure 11 shows the electrolysis voltage reduction effect of incorporating these improvements.

Figure 12 shows the layout of the electrolyzer. While the operating voltage is low in a single electrolysis cell, the high current makes it difficult to control the reaction to be stable and efficient. To deal with this characteristic, cells consisting of a combination of anode electrodes, proton exchange membranes and cathode electrodes are stacked. This is called an electrolysis stack. The endplate fastening each cell of the stack requires sufficient rigidity to assure uniform and appropriate surface pressure, so it becomes thick and heavy. To make the electrolyzer more compact and lighter, the endplate was not made solid, but rather the pure water circulation pumps and O₂ gas-liquid separators were all built integrated with the channels in the electrolysis stack's endplates so that there are no pipes on the exterior. Setting

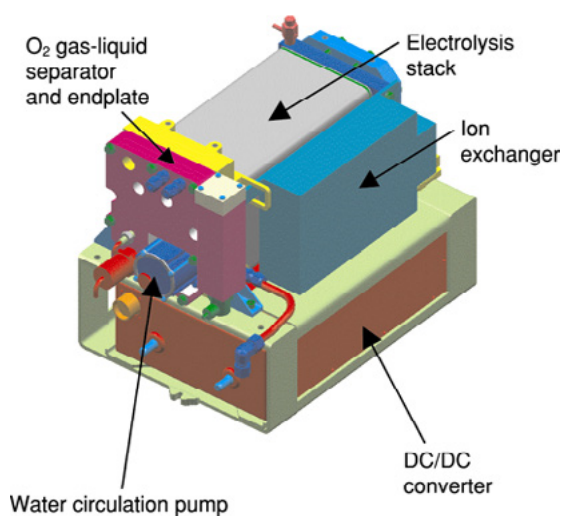


Fig. 12 Assembly of electrolyzer

the pure water channels within the electrolysis stack significantly shortened the pipes of the pieces of auxiliaries such as ion exchangers. Shorter pipes in turn reduced ion elution, so fewer ion exchangers were necessary. In addition, making the pipes shorter and the ion exchangers more compact resulted in reduced pressure loss in the pure water circulation system and reduced the work of the water circulation pump, thus achieving both compactness and efficiency.

4.3. Power Converter

Commonly marketed hydrogen production systems are designed to operate on a fixed amount of grid power. A feature of the system described in this report is that it does not depend on grid power but is able to produce and supply hydrogen efficiently even on the variable power supply from photovoltaic modules.

Because the refueling station was to be located outdoors, it had to be impenetrable by sand and rain and resist condensation caused by changes in humidity. The 5 kW-class power equipment used in this station is not commonly sold in a form suitable for outdoor use. To make it usable in this station, a sealed power system was developed using the electronic system technology of electric and hybrid vehicles to prevent the penetration of sand and rain and not allow condensation to occur. Heat dispersion is an issue with power devices used in sealed conditions, but the design assured reliability with a water cooling system using water emitted from the pure water production process; this also enabled the equipment itself to be more compact. As a result, it was possible to place the power source system directly beneath the electrolysis stack and greatly reduce the length of high-current (close to the 100 A) wiring peculiar to the electrolyzer, thus minimizing transmission loss.

As Fig. 13 shows, the photovoltaic modules can operate at any point on the voltage-current curve, but the power output will vary depending on the operating point. Moreover, the voltage at which peak power is produced (V_{Pmax}) will vary depending on fluctuations in amount of solar radiation and temperature of the photovoltaic modules, so a peak power tracker, or PPT, a system that keeps the photovoltaic modules constantly operating in their most efficient state, is typically used. This system, however, omits this device because it is possible to achieve the same function by controlling the load on the DC/DC converter used for electrolysis.

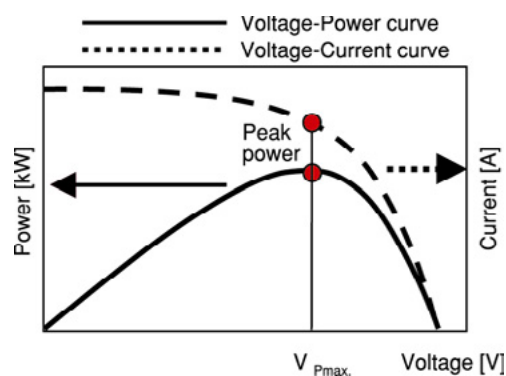


Fig. 13 Characteristic of photovoltaic modules

Moreover, this system was built to use a rectifier with an active filter when using grid power and to bypass the rectifier when the photovoltaic modules are used, thus supplying DC power to the respective power equipment. Using this system greatly simplifies the configuration of the power conversion equipment.

5. Tank Unit

The tank unit consists of six high pressure tanks for storing high pressure hydrogen and of six buffer tanks that temporarily store low pressure hydrogen prior to pressurization and protect the electrolysis unit from pressure fluctuations occurring during compressor operation. As Fig. 14 demonstrates, the high pressure tanks are set horizontally with the buffer tanks lying in the gaps, an arrangement that minimizes empty space and makes the tank unit smaller.

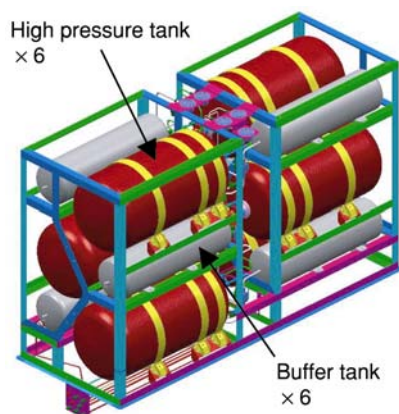


Fig. 14 Assembly of storage tank unit

6. Dispenser Unit

The dispenser unit has a diaphragm compressor capable of discharging 35 MPa hydrogen at a rate of 2 Nm³/h, a hose, a nozzle and a breakaway (Fig. 15). In case the vehicle starts moving before the nozzle is released from the vehicle, the breakaway has a mechanical device that causes the hose to break away if pulled and a valve to cut off the flow of hydrogen so that the hose will not break and let hydrogen gas escape.

The refueling station uses two different filling systems: fast fill, which uses the difference in pressure between the vehicle's tank and the station's high-pressure tank, and slow fill, which uses a compressor to fill the hydrogen directly without storing the hydrogen produced.

Fast fill employs a cascading, continuous supply system in which hydrogen is supplied in succession from those of the six high pressure tanks with relatively low pressure, and maximizes the supply of hydrogen to the automobile (Fig. 16). Fast filling takes under five minutes to complete, but it does not allow the on-board tank to fill completely as the temperature of the tank rises because of the sudden adiabatic compression. This phenomenon occurs not just with hydrogen but with any gaseous fuel under high pressure that is filled in a short length of time.

Slow filling takes more time so the heat can be sufficiently dissipated from the on-board tank. Therefore, the tank can be completely filled.

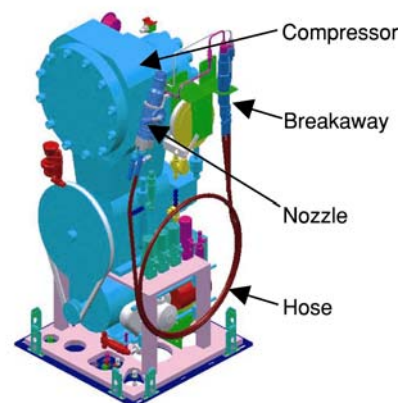


Fig. 15 Assembly of dispenser unit

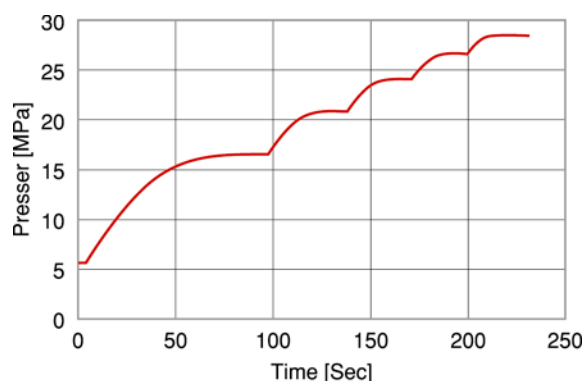


Fig. 16 Example of hydrogen refueling for on-board tank

7. Amount of Hydrogen Produced, Efficiency and Amount of CO₂ Emissions

Figure 17 gives an example of the measured amount of solar radiation, generated power and hydrogen production in one day during operation of the system, while Fig. 18 gives the energy flow. The efficiency of the station (the percentage of solar radiation energy hitting the photovoltaic modules that is ultimately supplied to the vehicle as hydrogen) was approximately three times better than that of the prototype.

Electrolysis loss, in particular, has been reduced to as small as 1.4% of the total power generated by the photovoltaic modules. This was made possible by the development of a new electrolytic catalyst, the optimization of the operating temperature and the electrolytic current density, the reuse of hydrogen for purifier regeneration, and other design improvements.

Because of the great improvements in the efficiency of various pieces of equipment as described above, the overall system efficiency has risen dramatically, to approximately three times the corresponding percentage of the prototype station assembled from commonly available equipment.

Based on these results and records of the amount of solar

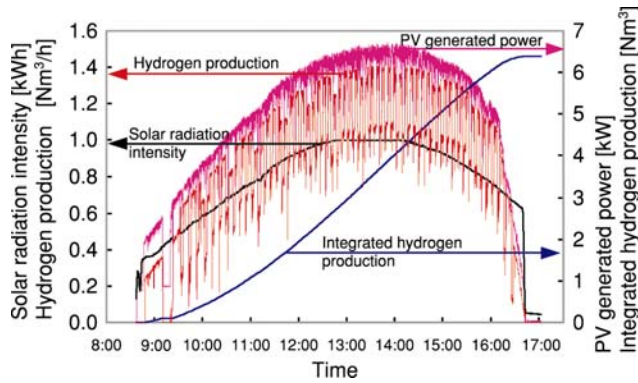


Fig. 17 Example of hydrogen generation

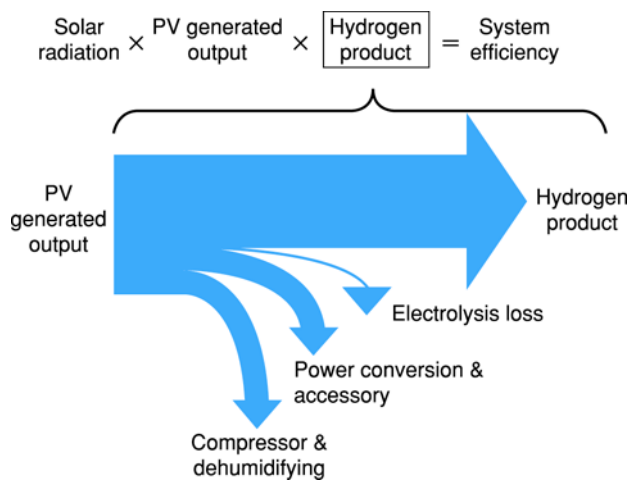


Fig. 18 Energy flow

radiation in Los Angeles from 1961 to 1990, it was estimated that this system could produce over 2 000 Nm³ of hydrogen annually. Performing calculations based on the fuel efficiency label values⁽⁴⁾ for city driving mode of the Honda FCX, sold since December 2002, as determined by the Environmental Protection Agency and the California Air Resources Board, this corresponds to about 10 000 miles (16 000 km), showing that the experimental station achieved its goal of providing enough hydrogen for driving 10 000 miles annually only with sunlight as the energy source.

The social significance of fuel cell vehicles includes the fact that not only do they provide an alternative to the use of fossil fuels and reduce exhaust gas emissions, but that they reduce CO₂ emissions. Therefore hydrogen production systems will not only have to be more efficient but also cause lower CO₂ emissions when the component equipment of the systems is manufactured.

In the case of fuel cell vehicles running on hydrogen, no CO₂ is emitted while driving, but CO₂ may be released from the energy source used, depending on the way in which the hydrogen is produced. This is because CO₂ is emitted as a result of burning fossil fuels in thermal power generation. Consequently when electrolysis depends on grid power, more CO₂ is emitted especially when thermal power is used to generate a greater proportion of the total energy used.

On the other hand, when photovoltaic modules are used to produce hydrogen, no CO₂ is emitted during hydrogen production itself, but it is still necessary to consider that CO₂ is released from the portion of thermal power generated electricity used to manufacture the photovoltaic modules. Because single-crystalline Si photovoltaic modules require a great deal of energy to produce⁽⁵⁾, the photovoltaic modules account for the majority of CO₂ emitted during the manufacture of the equipment used in the hydrogen refueling station. Improving system efficiency and reducing energy consumption during the manufacture of photovoltaic modules are crucial to reducing emissions of CO₂ per unit of hydrogen produced.

For the above reasons, this study tested the CO₂ emissions reduction effect of adopting CIGS (copper-indium-gallium-selenide) thin film photovoltaic modules developed by Honda, which consume considerably less energy during manufacture. This assessment used the Well to Wheels CO₂ emissions, that is, the amount of CO₂ emissions including all emissions from fuel production to fuel consumption while driving. Using the conditions listed below, CO₂ emissions to produce hydrogen of 1 Nm³ by electrolysis were compared for three scenarios: using grid power, using single-crystalline Si photovoltaic modules and using CIGS compound thin film photovoltaic modules.

- CO₂ emissions from grid power: 0.40 [kg-CO₂/kWh]
- Because there will be great differences according to time and region, this figure was set based on values from the US and Japan⁽⁶⁾
- Depreciation period for photovoltaic modules: 10 [years]
- Driving distance: 10 000 [miles/year]

The results show that, compared to the use of grid power, using single-crystalline Si photovoltaic modules will make no great difference in CO₂ emissions, but the use of CIGS thin film compound photovoltaic modules will reduce CO₂ emissions per unit of hydrogen significantly. This suggests that producing hydrogen with natural energy can be very effective for the objective of reducing CO₂ emissions.

8. Conclusion

The research described herein was conducted to improve the performance of hydrogen refueling stations using photovoltaic modules and to make the stations more compact with the ultimate objective of helping to solve energy and global environmental issues. Findings of the research were as follows.

- (1) Equipment efficiency was improved and total system efficiency approximately three times greater than that of the station assembled from commonly available equipment was achieved through such means as developing an electrolyzer with a newly composed catalyst.
- (2) It is predicted that the power generated from photovoltaic modules sized for approximately two households would supply enough hydrogen to fuel a Honda FCX for 10 000 miles or more in one year.
- (3) It is predicted that CO₂ emissions would be reduced significantly by employing CIGS compound thin film photovoltaic modules, as compared with single-crystalline Si photovoltaic modules.
- (4) By making the equipment smaller, it was possible to project an image of the future hydrogen society as clean and advanced.

Acknowledgements

Many individuals helped to make possible the unprecedented, personal-sized hydrogen refueling station described in this report. This was the first such station in Torrance, California, and city and fire department officials cooperated generously. The authors would like to take this opportunity to thank the many individuals at Honda and beyond who helped in this research.

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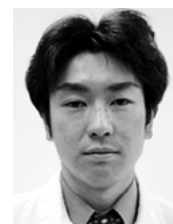
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