

Verification Test of Home Energy Station IV System Using Natural Gas Reforming

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ABSTRACT

A compact hydrogen supply system (Home Energy Station, HES) has been developed that reforms natural gas to supply hydrogen to fuel cell electric vehicles at households, while at the same time also enabling supply of electricity and heat. The Home Energy Station IV (HES IV) is the 4th-generation prototype model of this system, and was operated to verify both hydrogen supply to a Honda FCX and power generation that can be interconnected with the commercial power grid.

The results showed that introducing the HES IV together with a fuel cell electric vehicle to a typical household can reduce CO₂ emissions by 30% and energy costs by 54%. Verification tests demonstrated that this is a new energy supply system format that can simultaneously reduce the environmental load while providing merits to users.

1. Introduction

Honda has for some time considered hydrogen fuel cells as the ultimate next-generation clean power plants, and worked to develop fuel cell electric vehicles from the viewpoints of finding alternatives for fossil fuels, reducing exhaust emissions, and reducing the effect on global warming.

Achieving widespread acceptance of fuel cell electric vehicles requires the social approach of constructing an infrastructure for supplying hydrogen. Recently, research and development on these technologies has been led by the infrastructure industry and public agencies, and the advanced introduction of hydrogen stations is proceeding. However, regions where these facilities have been introduced are still limited, and the number of locations is insufficient considering widespread future use.

Honda therefore has promoted research on a compact hydrogen supply system that can be installed in households, with the aim of early widespread acceptance

of fuel cell electric vehicles. Experimental operation of a Home Energy Station (HES) that generates hydrogen from natural gas and supplies it to a fuel cell electric vehicle, and has a cogeneration function to supply electricity and heat to a household, commenced from 2003 at the Honda R&D Americas, INC. Los Angeles Center (California, U.S.A.)⁽¹⁾⁻⁽³⁾. Natural gas, selected as the raw material for hydrogen production, is considered to be the most appropriate fuel for promoting the early spread of fuel cell electric vehicles. This is because the infrastructure for supplying natural gas to households already exists, and less CO₂ is emitted when producing hydrogen compared to other fossil fuels.

Verification tests have been continuing since 2007 on a 4th-generation prototype model HES IV (Fig. 1) that has been downsized and made more efficient, based on the assumption of its more realistic use within households. This paper introduces the HES IV, and reports the energy cost merits and CO₂ reduction effects of practical application calculated based on the verification test results.

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Fig. 1 External view of Home Energy Station IV

2. Overview of HES IV

2.1. External View

Figure 1 shows an external view of the HES IV. The HES IV comprises a main unit that produces compressed hydrogen and generates electricity, a dispenser unit that fills the hydrogen tank of a fuel cell electric vehicle with hydrogen, and a hot water tank that accumulates the exhaust heat as hot water.

The system configuration was reviewed and the auxiliaries were downsized in consideration of its installation in households, and resulted in the main unit successfully being downsized by approximately 70% compared to the 1st-generation prototype model. The system is designed for outdoor installation, but it is more realistic to assume that filling work will be performed with the fuel cell electric vehicle parked inside a garage, so the configuration uses a separate dispenser unit that enables a flexible layout.

A touch panel control monitor that enables simple operation by users in an interactive format is installed in the dispenser unit (Fig. 2).

Figure 3 shows the main unit and dispenser unit sizes.

2.2. System Configuration and Specifications

Figure 4 shows the HES IV system configuration. The main system components are a fuel processor, dual mode

stack (DMS), pressure swing adsorption (PSA), hydrogen compressor, and interconnection inverter.

The fuel processor employs auto thermal reforming (AFR) using a reforming catalyst and an oxidation catalyst



Fig. 2 Dispenser unit with touch panel controller

as the natural gas reforming method to shorten the start-up time. A water gas shift (WGS) reactor and a CO preferential oxidation (PROX) reactor are located after that to reduce the carbon monoxide (CO) in the reformat.

The DMS device has both a hydrogen membrane pump function using a proton exchange membrane, and a power generation function as a fuel cell. Figure 5 shows a schematic drawing of these two functions. When functioning as a hydrogen membrane pump, the hydrogen in the reformat component is conveyed selectively to the cathode side using externally supplied electricity [Fig. 5(a)]. At the same time, the hydrogen pressure is boosted to the pressure required for PSA operation. The hydrogen transferred from the DMS contains moisture and minute levels of impure gas, so combination with the PSA secures a hydrogen purity that can be supplied to a fuel cell electric vehicle.

On the other hand, when the DMS generates electricity, air is supplied to the cathode and the DMS functions as a fuel cell [Fig. 5(b)]. The conventional system required a separate pressure booster device for hydrogen refining and fuel cell for electrical generation. However, the DMS enabled switching between both functions with a single device, which enabled a smaller system.

The hydrogen production capacity was set at 3 Nm³/h, which can fill enough hydrogen within 6 hours for the

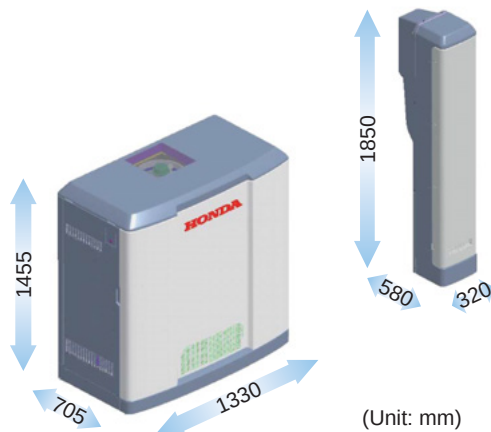


Fig. 3 Dimensions of HES IV

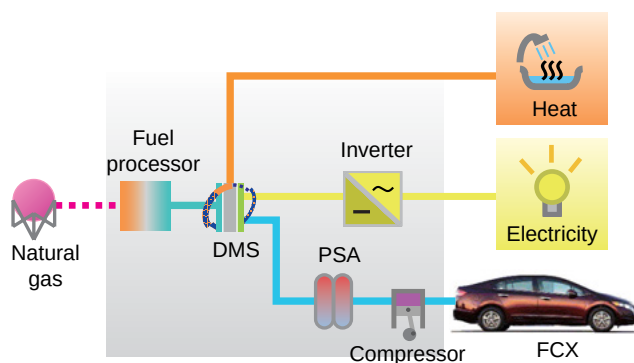


Fig. 4 System configuration of HES IV

Table 1 Specifications of HES IV

Hydrogen production	Flow rate	3 Nm ³ /h
	Filling pressure	35 MPa MAX
	Purity	> 99.99%
	Efficiency	40%
Power generation	Rated output	4 kW
	Voltage / Frequency	120/240 VAC / 60 Hz
	Efficiency	30%
Heat recovery		80°C hot water
Utility	Electricity	120/240 VAC
	Gas	Natural gas
	Water	City water
Fuel processor		ATR + WGS + PROX
Purifier		DMS + PSA
Compressor		4-stage piston compressor

FCX to run 100 miles. This assumes that the user connects the dispenser to the fuel cell electric vehicle after returning home in the evening, fills the vehicle's hydrogen tank with hydrogen through the night, and then drives the vehicle again the next morning. In this manner, the HES IV does not have a hydrogen storage tank, and instead employs the slow fill method that fills the vehicle's hydrogen tank directly from the compressor.

In addition, the power generation capacity was set at 4 kW, which is capable of supplying sufficient electricity to a typical household in the Los Angeles district. Table 1 lists the main specifications of the HES IV.

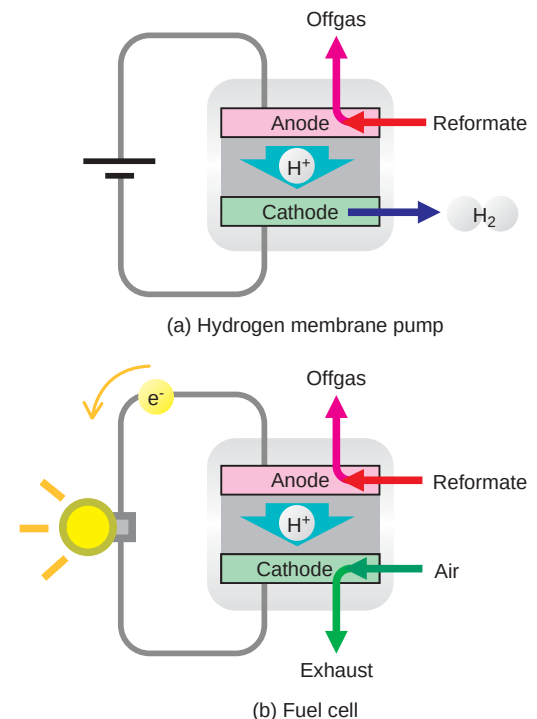


Fig. 5 Two functions of Dual Mode Stack

3. Operating Modes

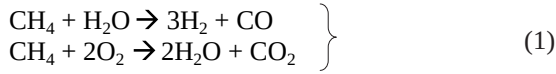
The HES IV operates while switching between two operating modes. In hydrogen production mode, compressed hydrogen, generated by the main unit, is filled directly to the hydrogen tank in a fuel cell electric vehicle via the dispenser unit. In power generation mode, electricity, generated by the DMS, is converted to AC by the inverter and used as electric power.

3.1. Hydrogen Production Mode

System operation in hydrogen production mode is as follows.

(1) Fuel processor

The natural gas that is supplied to the fuel processor undergoes the reaction shown in Eq. (1) on the surface of the ATR catalyst, together with the simultaneously supplied water and oxygen (air), and is reformed into hydrogen-rich reformat. After that, the hydrogen concentration of the reformat is increased by the CO shift reaction shown in Eq. (2) on the shift catalyst in the WGS. The CO concentration is then reduced to 10 ppm or less by the preferential oxidation action of the PROX catalyst as shown in Eq. (3), and ultimately reformat with a hydrogen content of approximately 40% to 50% is supplied to the DMS.



(2) DMS

Hydrogen is selectively separated by the proton exchange membrane by having the DMS function as a hydrogen membrane pump. In this stage the hydrogen concentration is increased to approximately 99%; at the same time the pressure is boosted to 0.8 MPa and the hydrogen is sent to the PSA.

(3) PSA

Non-hydrogen gases are eliminated by the PSA, and the hydrogen purity is increased to 99.99% or higher, which enables filling to a fuel cell electric vehicle.

(4) Compressor

The hydrogen is compressed by the hydrogen compressor and filled to the fuel cell electric vehicle.

Note that the auxiliary power needed when operating in hydrogen production mode is supplied from the commercial power grid.

The user can fill the vehicle with hydrogen at an optional time by operating the touch panel. The system stops automatically when the hydrogen filling pressure of the vehicle's hydrogen tank reaches 35 MPa, but the user can also designate that filling stop when an optional pressure is reached.

3.2. Power Generation Mode

System operation in power generation mode is as follows.

(1) Fuel processor

Like in hydrogen production mode, the natural gas supplied to the fuel processor is reformed into hydrogen-rich reformat and supplied to the DMS.

(2) DMS

The DMS generates power as a fuel cell using the reformat supplied to the anode side and the air supplied to the cathode side.

(3) Inverter

The electric power generated by the DMS is converted to AC by the inverter and used interconnected with the commercial power grid.

In power generation mode, the system operates automatically based on the power consumption of each household, but the system can also be started up and stopped as designated by the user.

4. HES IV Verification Tests

4.1. Hydrogen Production Mode

Figure 6 shows an example of the amount of produced hydrogen and the change in pressure inside the vehicle's hydrogen tank when the system is operated to fill the FCX with hydrogen.

Filling to the vehicle's hydrogen tank started in 10 minutes, and the rated hydrogen output (hydrogen production amount = 3 Nm³/h) was reached in 50 minutes after system start-up. In this example, filling by the slow fill method started from a hydrogen tank residual pressure of 15 MPa, and system operation stopped automatically when the tank was fully filled (tank pressure = 35 MPa) approximately 7 1/2 hours after start-up.

In addition, heat energy of 27.2 kWh was recovered as hot water during the approximately 8 hours of hydrogen production mode operation in this example. This shows that the heat recovery capacity of this system in hydrogen production mode is approximately 3.4 kW.

Figure 7 shows the system flow diagram during hydrogen production mode operation, and the rated hydrogen production efficiency and total efficiency. The hydrogen production efficiency (η_{H_2}) is the value obtained by dividing the generated hydrogen energy (E_{H_2}) by the sum of the input natural gas energy (E_{NG}) and the input electric power (E_{elec}). However, considering the power generation efficiency of the power station and the electric transmission loss up to the household, the input electric power was calculated with an energy efficiency of 38% when it reaches the household. Likewise, the total efficiency ($\eta_{H_2, total}$) is the value obtained by dividing the sum of E_{H_2} and the recovered heat (E_{heat}) by the sum of the input energy.

$$\eta_{H_2} = E_{H_2} / (E_{NG} + E_{elec} / 0.38) \quad (4)$$

$$\eta_{H_2 total} = (E_{H_2} + E_{heat}) / (E_{NG} + E_{elec} / 0.38) \quad (5)$$

4.2. Power Generation Mode

Figure 8 shows the electrical output when the system is operated for approximately 6 hours in power generation mode.

The DMS commenced power generation as a fuel cell in 10 minutes, and reached the rated power output of 4 kW

in 1 hour after system start-up. The DMS electrical output at this time was 5.5 kW (DC). The difference between the DMS electrical output and the system output is due to the electric power consumed by auxiliaries and the energy loss from DC/AC conversion inside the inverter.

Heat energy of 23.8 kWh was recovered as hot water during the approximately 6 hours of power generation mode operation in this example. This shows that the heat recovery capacity of this system in power generation mode is approximately 4 kW.

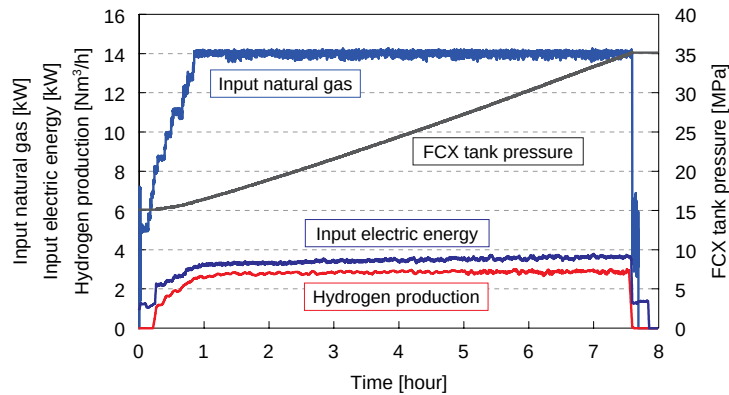


Fig. 6 Example of hydrogen production

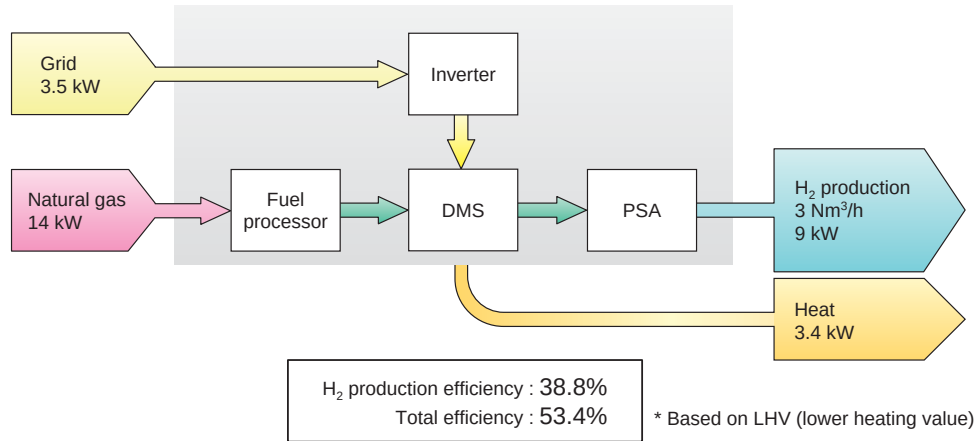


Fig. 7 System efficiency in hydrogen production mode

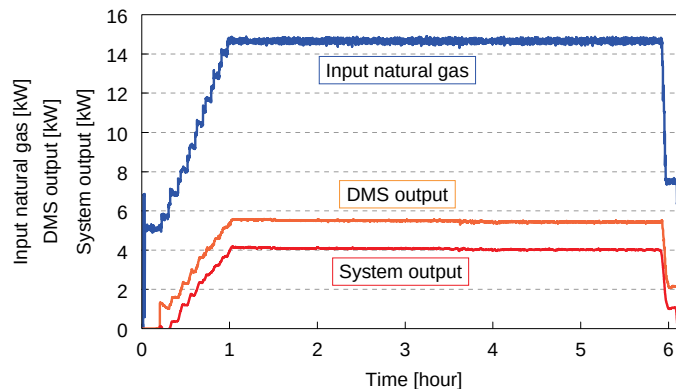


Fig. 8 Example of power generation

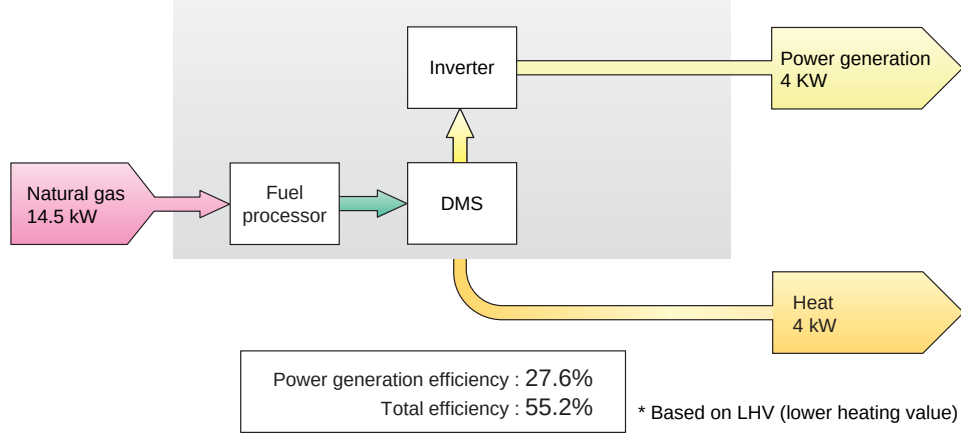


Fig. 9 System efficiency in power generation mode

Figure 9 shows the system flow diagram during power generation mode operation, and the rated power generation efficiency and total efficiency. The power generation efficiency (η_{AC}) is the value obtained by dividing the system electric output (E_{AC}) by the input natural gas energy (E_{NG}), and the total efficiency ($\eta_{ACtotal}$) is the value obtained by dividing the sum of E_{AC} and the recovered heat (E_{heat}) by the input natural gas energy (E_{NG}).

$$\eta_{AC} = E_{AC} / E_{NG} \quad (6)$$

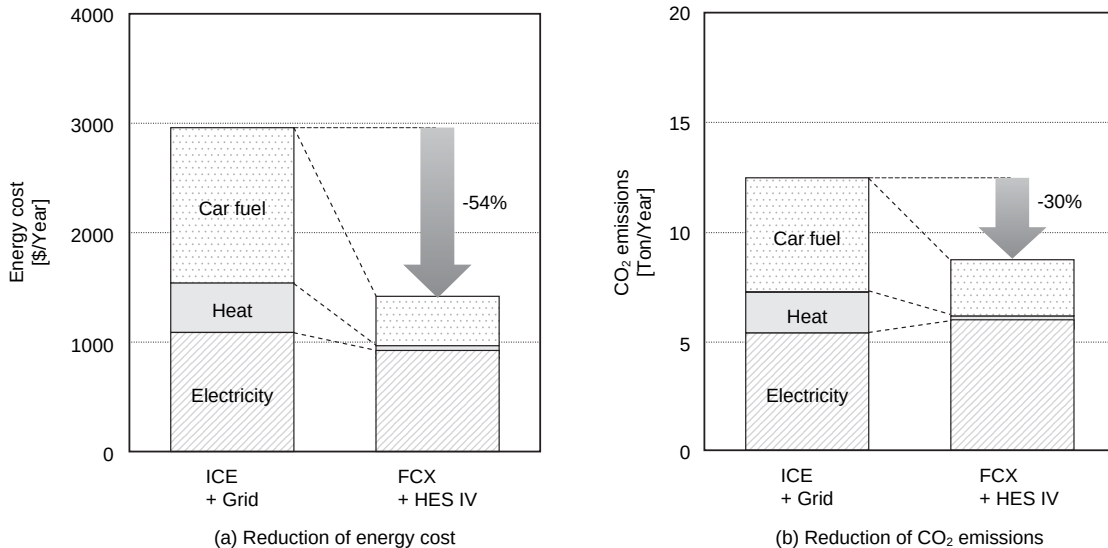
$$\eta_{ACtotal} = (E_{AC} + E_{heat}) / E_{NG} \quad (7)$$

5. Energy Cost and CO₂ Emissions Reduction Effects of Introduction

The energy cost and the effects to reduce household CO₂ emissions when the HES IV is introduced to a household were calculated based on the series of data obtained by the verification tests. The effects were

estimated by comparing the cases when using a conventional gasoline-fueled reciprocating engine vehicle and the commercial power grid (ICE + Grid), and when introducing the combination of the HES IV and the FCX. The amounts of electric power and heat energy consumed by the household used as the basis for the calculations were the average annual energy consumption amount and the energy cost for a typical household in the Los Angeles district (California, U.S.A.). In addition, the annual distance traveled by the vehicle was set at 10000 miles. Note that the CO₂ emissions from the vehicle were evaluated as the amount generated from extraction of the fuel to running (Well-to-Wheel).

Figure 10 compares the effects on annual energy cost and CO₂ emissions for a typical household. This shows that system introduction reduces the energy cost and CO₂ emissions due to heat use to almost zero. This means that almost the entire heat demand required by the household can be covered simply by the heat energy that can be


 Fig. 10 Reduction effects of energy cost and CO₂ emissions in typical household

recovered in hydrogen production mode and power generation mode. Focusing on the amount of CO₂ emitted by vehicle movement [Fig. 10(b) Car fuel], hydrogen is generated by reforming natural gas, so while CO₂ emissions cannot be completely eliminated, these results indicate that the emissions amount can be reduced by half, compared to the conventional method.

The calculation results showed that using the HES IV and the FCX together can reduce the energy cost by 54% and simultaneously reduce the amount of CO₂ emitted from the entire household by 30%. This provided prospects for establishing the HES IV as an energy supply system that provides cost merits to users while also reducing the environmental load.

6. Conclusion

Verification tests were performed for a Home Energy Station that aims to address energy issues and reduce the environmental load, and the following results were obtained.

- (1) A new energy supply system format was presented that can not only fill a fuel cell electric vehicle with hydrogen at the household, but also supply both the electric power and heat required by that household.
- (2) The system was downsized by approximately 70% compared to the 1st-generation prototype, which realized a size capable of installation in a typical household.
- (3) Introducing the combination of the HES IV and the FCX to a household can reduce the energy cost by 54% and simultaneously reduce CO₂ emissions by 30%.

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