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Experimental study on a laboratory scale Totalized Hydrogen Energy Utilization System for solar photovoltaic application

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HIGHLIGHTS

- Dynamic response of the Totalized Hydrogen Energy Utilization System was studied.
- Adaptability of the THEUS for the intermittent solar energy was investigated.
- Power, hydrogen, heat output from the THEUS were evaluated quantitatively.
- Efficiency of the THEUS was evaluated for a sunny day and a partly cloudy day test.
- A decline in WE efficiency was not observed for the fluctuating power input.

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ABSTRACT

Most of the countries have increased the production of renewable energy to reduce pollution and their dependency on oil and natural gas. In case of Japan, solar power is increased rapidly, especially after the Fukushima Nuclear Accident. The load leveling and fluctuation absorption are the main bottlenecks to the integration of solar PV power into the future electricity system. Hydrogen is considered as an energy carrier in a future energy system based on renewable resources. Totalized Hydrogen Energy Utilization System (THEUS) consists of a unitized reversible fuel cell and a hydrogen storage tank. The main objective of this paper is to evaluate the THEUS operation and performance at different variations in solar photovoltaic (PV) power during a sunny day and a partly cloudy day and to characterize its dynamic response. Energy efficiency of the THEUS was evaluated in water electrolyzer and fuel cell mode operation.

1. Introduction

The world population and energy demand for sustaining growth is increasing year by year. On the other hand, conventional fossil energy sources are dwindling and environmental concerns on climate change and air quality are growing every year. These problems urged on a need for clean and ecologically benign energy resources are crucial for the sustainable global economic growth. Over the last two decades, commendable efforts are being taken up by the researchers for promoting large scale use of renewable energy resources [1–17]. Renewable energy sources such as solar and wind energy are clean and abundant but both are intermittent power sources. Hydrogen based energy storage system can store energy for long periods and thus allowing load levelling in supply and demand from hourly to seasonal variations [18]. Hydrogen production from renewable energy sources such as solar and wind energy, its storage, distribution, and conversion back to electric power and heat, makes a hydrogen economy feasible. Water electrolyzer (WE) can produce hydrogen efficiently by taking electric power as an input and fuel cell (FC) converts hydrogen to electric power and heat by electrochemical reaction. Although most commonly used WE's are alkaline based, Proton Exchange Membrane (PEM) based WE's are being developed rapidly and are being commercialized due to their high efficiency, low operation temperatures, fast response and good integration with intermittent power sources [19–21]. Unitized reversible fuel cell (URFC) can operate alternately as a WE and as a FC. In the conventional systems, a WE is used for the hydrogen production, and a FC is used for the hydrogen conversion. Since, the fundamental structure of

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Nomenclature

Q	energy (J)
FC	fuel cell
WE	water electrolyzer
MH	metal hydride
HHV	higher heating value of the hydrogen (J/m^3)
C_p	specific heat of the circulation fluid at constant pressure (J/kg °C)
V	volume (m^3)
$\dot{V}$	volumetric flow rate (L/min)
ΔH	reaction heat per volume of the metal hydride (J/m^3)
ρ	density (kg/m^3)
η	efficiency (%)
ε	reaction heat recovery rate (%)

Subscripts

ABS	absorption
DES	desorption
cf	circulation fluid
FC_OUT	FC-power output
FC_HEAT	FC-heat output
FC_ACCS	FC-input power to accessories
FC_IN	FC-hydrogen energy input
FC_TO	FC-total energy output
FC_TI	FC-total energy input
FC+H	FC-including URFC heat output
FC+H+MH	FC-including URFC and MH heat output
H_2	hydrogen
MH_ABS	MH-ABS heat output
MH_DES	MH-DES heat output
TI	total energy input
TO	total energy output
WE_OUT	WE-hydrogen energy output
WE_HEAT	WE-heat output
WE_ACCS	WE-input power to accessories
WE_IN	WE-power input (DC power from DC power source)
WE_TO	WE-total energy output
WE_TI	WE-total energy input
WE+H	WE-including URFC heat output
WE+H+MH	WE-including URFC and MH heat output

the both systems are same, the URFC is designed in such way that, it can work in both modes of operation. URFC can bring down the capital cost without significant system performance reduction [22]. In the case of a URFC integrated with a photovoltaic (PV) system in commercial buildings, excess energy in day time can be used to produce hydrogen in WE mode operation, and then this hydrogen can be stored. During peak hours or at night time, the deficit can be supplied by the URFC in FC mode operation by using this stored hydrogen.

Energy storage with hydrogen, superior in gravimetric energy density when compared with the secondary battery, there is a great advantage that the energy loss due to long-term storage is small. On the other side, hydrogen has a low volumetric density, so it has to be drastically improved without reducing the gravimetric energy density. Hydrogen is stored in gaseous, liquid, and solid forms. The most common and simplest storage system is high-pressure gas cylinders with a maximum pressure of 200 bar. Storage of hydrogen in liquid form ensures higher energy density than the gaseous form. These two technologies are well understood but considerable energy is required for compression (15% of hydrogen heating value at 200 bar) or liquefaction (28% of hydrogen heating value), needs special maintenance and safety precautions [23,24]. Hydrogen molecules do not interact with the storage medium in both these cases. Hydrogen storage in physical–chemical methods involves physisorption–chemisorption processes of hydrogen molecules interaction with some materials. The physical–chemical methods of hydrogen storage are adsorption (ex. zeolites, activated carbon, and metal organic frameworks), bulk absorption in solids (ex. metal hydrides) and chemical interaction (ex. organic hydrides). Zeolites can adsorb hydrogen reversibly in the temperature range 20–200 °C and pressures 25–100 bar, however the maximum storage capacity is still low compared to the other methods. Hydrogen storage on activated carbon and metal organic frameworks require very low temperatures (usually −195 to −208 °C), which means additional energy is required to cool the storage medium. The hydrogenation/dehydrogenation process in organic hydrides takes at high temperatures (200–400 °C) and requires large amount of heat input [25,26]. Metal hydrides can store hydrogen at near ambient pressure and temperature over a long time. This method having various advantages compared to other storage methods, when system weight is not a major issue, but safety and compactness are essential. Hence, metal hydride based hydrogen storage system is highly suitable for small to medium scale stationary applications [27]. Gray et al. [28] compared the metal-hydride storage system and Li-ion batteries for grid-independent PV–hydrogen system and suitability of AB_5 alloys for use in PV–hydrogen systems was discussed. It was concluded that a significantly smaller package is possible with metal-hydride storage than Li-ion battery storage.

Most of the previous studies have used separate WE and FC systems for energy storage applications [1]. Some studies have been concentrated on stack performance of URFC [29–31]. However there is no previous study available in the literature about performance study of integrated system that includes URFC and metal hydride tank for renewable energy applications. Totalized Hydrogen Energy Utilization System (THEUS) consists of a URFC and a metal hydride based hydrogen storage tank (MHT). THEUS was designed for storing renewable energy such as solar energy, and bridge the gap between renewable energy supply and demand. It can supply electric power, thermal energy, and hydrogen to meet energy demand. The possibility of renewable energy storage and the flexibility in using hydrogen as a fuel for FC vehicles can make THEUS attractive as an energy storage solution for all types of energy systems. The system also utilizes the cold heat of reaction heat for air conditioning. National Institute of Advanced Industrial Science and Technology (AIST) and Savannah River National Laboratory (SRNL) had developed the MHT for THEUS under the Clean Energy Partnership Technology Program between METI and DOE [32–34]. The performance evaluation of the laboratory scale THEUS has been conducting with Takasago Thermal Engineering Co., Ltd under the R & D program of the hydrogen energy system of the New Energy and Industrial Technology Development Organization (NEDO). The fundamental performance evaluation of the THEUS was already reported [35]. In this study, the adaptability of the THEUS for the intermittent solar energy was investigated and the experimental results obtained from the THEUS operation at differ-