KSME

Springer

Journal of Mechanical Science and Technology 37 (7) 2023

Original Article
DOI 10.1007/s12206-023-0632-1

Keywords:
· Battery cell
· Environmental sensor
· Fuel cell
· Hybrid energy harvesting
· Solar cell

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Citation:
Cha, J. K., Kim, S. H. (2023). Solar, fuel, and battery cell-based small-scale hybrid power systems for long-term environmental monitoring using wireless sensors. Journal of Mechanical Science and Technology 37 (7) (2023) 3675~3681. http://doi.org/10.1007/s12206-023-0632-1

Received October 3rd, 2022
Revised January 28th, 2023
Accepted March 18th, 2023

† Recommended by Editor Chang-Soo Han

Solar, fuel, and battery cell-based small-scale hybrid power systems for long-term environmental monitoring using wireless sensors

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Abstract To provide stable energy for environmental sensors, we design a small-scale hybrid power system (SS-HPS) comprising a silicone-based solar cell (SC), polymer electrolyte membrane-based fuel cell (FC), and lithium-polymer-based battery cell (BC). An environmental sensor system (ESS), with a minimum power requirement of ~500 mW, is operated using the SS-HPS. The SC provides sufficient power to the ESS when the sunlight intensity is higher than 300-400 W/m^2. However, when the sunlight is insufficient under rainy weather or at night, the ESS malfunctions from a lack of energy. When supplied with hydrogen gas, the FC provides energy stably to the ESS. The long-term operation of the ESS is examined for 60 days in indoor and outdoor areas. The ESS successfully performs environmental monitoring with the support of the SS-HPS. An optimized design of the SS-HPS would be beneficial for the long-term stable operation of the ESS and wireless data acquisition.

1. Introduction

Recently, numerous studies on the development of renewable energy sources have been conducted to mitigate environmental issues, such as air pollution, water pollution, and climate change due to the burning of fossil fuels [1-21]. The critical difficulty in using renewable energy sources for load demand management is that electricity production is strongly dependent on changes in the local area, season, climate, and time [22, 23]. Therefore, hybrid energy generation systems, which comprise two or more renewable energy sources to compensate for their shortcomings, have been developed to supply electricity stably [24-35].

Among the various renewable energy sources, solar cells (SCs) are widely used as the primary electricity generation devices in hybrid energy generation systems because they can generate power sustainably from sunlight, provided it is sufficiently available. However, they cannot consistently generate electrical energy under cloudy or rainy weather conditions or at night. To produce sufficient energy, other auxiliary energy generation sources are required. Wind and geothermal energy applications can compensate for the drawbacks of SCs. However, they have disadvantages, such as relatively high initial costs, technology immaturity, and location restrictions in applicability [24, 36, 37]. Among other renewable energy sources, the hydrogen fuel cell (FC) can be used as a promising clean energy technology and as a source of versatile secondary energy generation for supporting SCs [29, 38, 39]. The hydrogen FC is an electrochemical device that generates electrical energy through a chemical reaction between hydrogen and oxygen. It can continuously generate sufficient electrical energy regardless of the environmental conditions under a constant supply of hydrogen and oxygen gases.

 DOI 10.1007/s12206-023-0632-1

With the assistance of wireless sensors and internet of things (IoT) networks distributed in a local area, various environmental conditions, such as temperature, pressure, and humidity, can be continuously monitored. Numerous papers on environmental sensors operating using a single renewable energy source have been reported [40-43]. However, for the long-term and stable operation of environmental sensors, a hybrid energy generation system incorporating an energy storage system — a battery cell (BC) — is required to generate sufficient electrical energy and store the surplus energy produced by various renewable energy sources for future use. Recently, large-scale hybrid power systems (HPSs) comprising SCs, FCs, and BCs have efficiently supplied electrical energy to residential and industrial facilities [44-47]. However, small-scale HPSs (SS-HPSs) for various types of sensors and IoT networks have rarely been developed. A low energy supply is a primary challenge when using sensors and IoT networks that monitor environmental conditions in an isolated area [48-51]. Using sensors and IoT networks together requires a sufficient energy supply for reliable and stable data generation, transfer, and storage. Therefore, optimization studies on the design of energy systems, control of energy generation, and energy management of SS-HPSs should be performed to realize self-powered smart environmental sensors and monitoring systems.

In this study, we manufactured an SS-HPS comprising SCs, FCs, and BCs to supply electrical energy stably for operating environmental sensors and IoT networks. We attempted to monitor various environmental conditions, such as temperature, humidity, and pressure, in both indoor and outdoor areas using environmental sensors and IoT networks. The sensors connected to the IoT networks using wireless communication had unique internet protocol (IP)s, and the data measured by the sensors were transmitted to the web server through Wi-Fi communication so that the computers and mobile phone could be used to visualize the transmitted data. The optimization process for the generation and control of energy for the stable and continuous operation of the environmental sensors and IoT networks was systematically performed.

2. Experimental

In this study, a small-scale SC/FC/BC-based HPS was designed and assembled to operate an environmental sensor system (ESS) with sensors and IoT networks to monitor temperature, humidity, and pressure in an area, as shown in Fig. 1(a). The maximum power generation outputs of the silicon SC i.e., the semi-flexible monocrystalline solar panel, DFRobot, and the hydrogen FC i.e., the polymer electrolyte hydrogen FC stack, horizon fuel cell, were ~5 (output voltage: 5 V, output current: 1 A) and ~12 W (output voltage: 7.4 V, output current: 1.6 A), respectively. The output voltage of the hydrogen FC stack was adjusted to 5 V using a DC/DC step-down converter. Hydrogen gas was supplied to the FC using a hydrogen storage tank. The power generated from either the SC or FC was supplied to operate a power management device (PMD) with

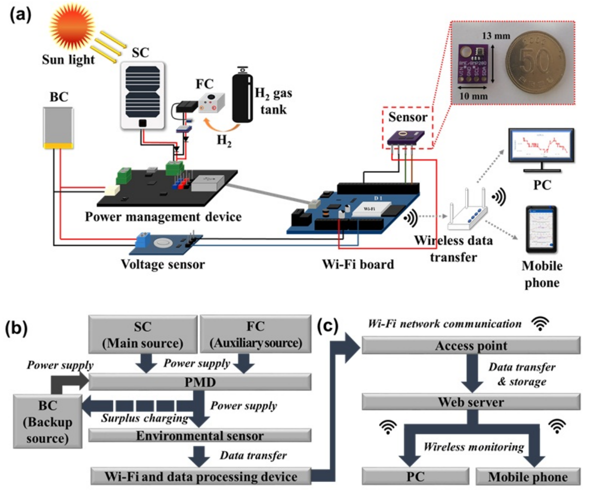

Fig. 1. (a) Schematic of an environmental sensor system (ESS) operated using a small-scale hybrid power system (SS-HPS) comprising a solar cell (SC), fuel cell (FC), and battery cell (BC); (b) electric power generation, control, and management of SS-HPS and ESS; (c) transfer, storage, and monitoring of sensor data.

an operating voltage of 5 V, current of 1 mA, and a solar power manager (DFRobot), a Wi-Fi board (WeMos D1 R1 board-ESP8266 Arduino) with an operating voltage of 5 V and current of 70 mA, an environmental sensor (BME280, Bosch Sensortec) with an operating voltage of 3.3 V and current of 1.4 mA, and a voltage sensor (ADM-425, ARDUINO) with an operating voltage of 5 V. The surplus power was stored in a lithium-polymer BC (DTP 634169, Taiwoo), which is a 3.7 V lithium-polymer battery. Figs. 1(b) and (c) show a schematic of the electric power generation, control, and management of the SS-HPS for continuously operating the ESS designed in this study. The electric power generated using the SC as the main power source was supplied to the PMD, which operated the sensor and IoT networks. The surplus power generated by the SC was stored in the BC. When the electric power generated by the SC was determined to be insufficient — based on the sunlight intensity measured using an isolation meter (TM-204, TENMARS) — the FC was selected as an auxiliary power source to supply electric power to the ESS. If the electric power generated using either the SC or FC was insufficient for operating the ESS, the PMD was used to extract the electric power from the BC so that the ESS would be continuously operated. The various temperature, humidity, and pressure data measured using the ESS were transferred and stored in the web server through Wi-Fi network communication, which enabled real-time monitoring using a PC and mobile phone. The ESS collected and transferred sensor data to the users through the network. Wireless environmental monitoring could be performed using the ESS to which specially programmed codes had been applied. The coding included the following three components: (i) network communication between the access point and Wi-Fi board; (ii) simultaneous connection and operation of temperature/humidity/pressure sensors and voltage sensors; (iii) wireless transmission of data to the web server using a Wi-Fi network. When the ESS was installed in the indoor and outdoor areas and operated every 30 min for 24 h, the sensor data on temperature/humidity/pressure were automatically displayed as graphs on either the PC or mobile phone.

3. Results and discussion

3.1 Characteristics of SS-HPS incorporated with SC and BC

The ESS, comprising a PMD, a Wi-Fi board, and integrated temperature/pressure/humidity sensors, was tested with the SS-HPS incorporated with silicone SC as the energy generator and Li-polymer BC as the energy storage device. The estimated power consumption of each part in the ESS was ~5 mW (operating voltage: 5 V; current: 1 mA) for the PMD; ~350 mW (operating voltage: 5 V; current: 70 mA) for the Wi-Fi board; ~4.6 mW (operating voltage: 3.3 V; current: 1.4 mA) for the sensors. When the PMD, Wi-Fi board, and sensors were used for environmental monitoring, electric power was supplied from the PMD to the Wi-Fi board and sensors, which required a minimum power consumption of more than 400-500 mW.

The light intensity at Miryang, Korea, which is the location where the study was conducted, was measured under various weather conditions on sunny, cloudy, and rainy days, as shown in Fig. 2(a). The light intensity increased from 6 a.m.-1 p.m. and then decreased from 1-6 p.m. on a sunny day. The light intensity on cloudy days was considerably lower than that on sunny days from 6 a.m.-6 p.m. As expected, the light intensity was approximately zero throughout rainy days. The electric power generated by the SC employed in this study was measured at various light intensities, as shown in Fig. 2(b). For several indoor areas, the intensity of the light irradiated by the lighting lamps was measured to be ~2 W/m^2 for a corridor in a building. However, the light intensity for some offices varied in the range of 2-600 W/m^2, depending on the partial or complete irradiation of sunlight at the location. For outdoor areas, the sunlight intensity was higher than ~900 W/m^2 for shaded areas on a sunny day. The power output from the SC in the SS-HPS increased linearly from 10 to 3300 mW with an increase in the light intensity from 2 to 1000 W/m^2. The SC in the SS-HPS was considered the main energy source when the light intensity was higher than at least 300-400 W/m^2, which enabled the generation of electric power higher than ~500 mW, meeting the minimum power consumption of the ESS. However, the electric power generated by the SC was much lower than ~500 mW at rainy days and night so that the ESS was malfunctioned (see Fig. 2(c)). This also suggested that an auxiliary energy source, such as an FC, would be required to stably provide electric power to the ESS when the electric power from the SC was insufficient.

3.2 Characteristics of SS-HPS incorporated with FC and BC

We investigated the characteristics of an SS-HPS comprising FC as an energy generator and BC as an energy storage for

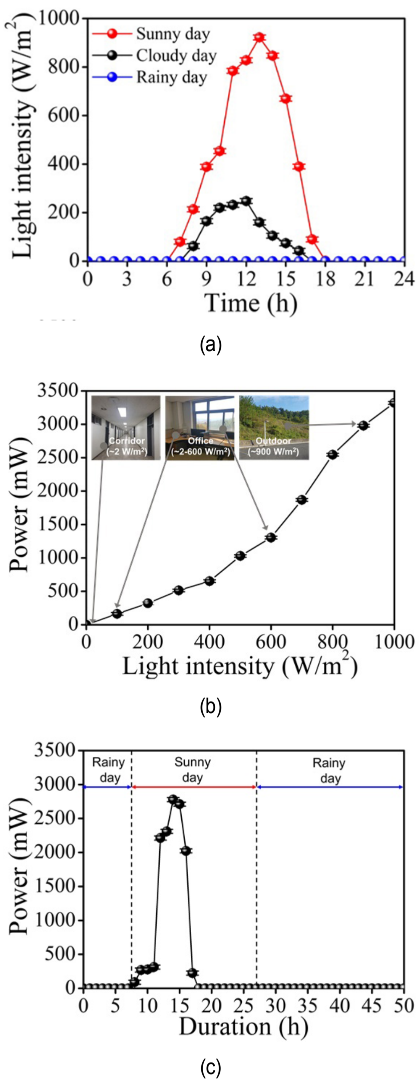

Fig. 2. (a) Evolution of sunlight intensity on sunny, cloudy, and rainy days during 24 h; (b) power output from the SC in the SS-HPS as a function of sunlight intensity. (Insets are the photographs of the indoor and outdoor areas under various light intensity conditions); (c) evolution of the power output of SC under various weather conditions.

operating the ESS, which consisted of a PMD, a Wi-Fi board, and integrated temperature/pressure/humidity sensors. The power output of the FC was recorded under a continuous supply of hydrogen gas, as shown in Fig. 3. The initial power output of the FC was ~2800 mW, which was significantly decreased and then maintained at ~500 mW. The FC was designed to automatically adjust the minimum power output of ~500 mW for operating the ESS and simultaneously protect the BC from overcharging after it was fully charged. The ESS incorporated with the FC and BC could be stably operated for a long time under a continuous supply of hydrogen gas.

3.3 Characteristics of SS-HPS incorporated with BC

If both the SC and FC failed to generate electric power, the

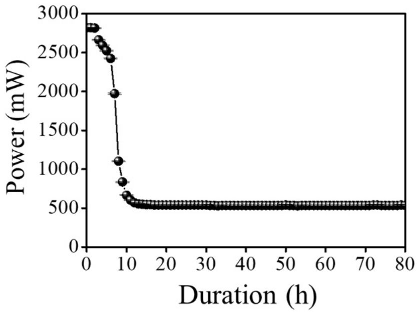

Fig. 3. Evolution of the power output of FC under the supply of hydrogen gas in the SS-HPS.

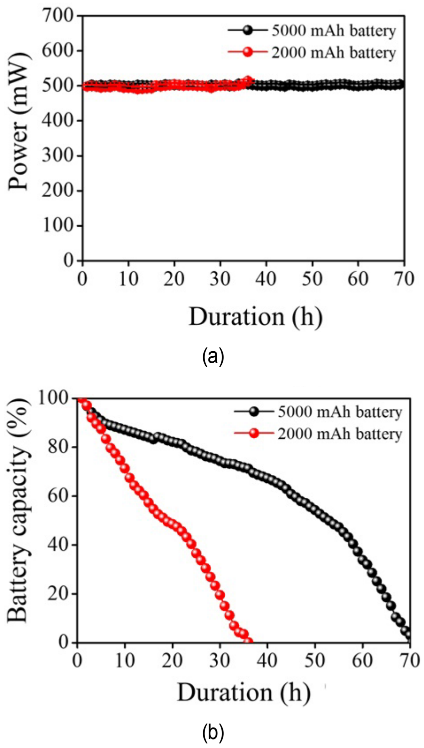

Fig. 4. Gradual evolution of (a) power; (b) battery capacity of the fully charged BC for operating the ESS.

BC would need to operate the ESS until the SC and FC were backed up. Therefore, a fully charged BC was tested to operate the ESS, as shown in Fig. 4(a). The minimum power output of ~500 mW of the BC for operating the ESS was maintained for ~34 h using a fully charged 2000 mAh BC and ~70 h using a 5000 mAh BC. The capacity of the BC gradually decreased (see Fig. 4(b)), and ultimately, the ESS malfunctioned when the voltage output of BC was less than ~3 V.

3.4 Characteristics of SS-HPS incorporated with SC, FC, and BC

The SS-HPS, comprising the SC, FC, and BC, was tested for its ability to operate the ESS for environmental monitoring. Fig. 5 shows the evolution of the power output of the SC and FC on a sunny day during the 24 h operation of the ESS. The ESS was operated between 10 a.m. and 4 p.m., during which the light intensity was sufficiently strong, and the power output was higher than ~500 mW. The surplus electric power was stored simultaneously in the BC unit. After 4 p.m., the SC could not generate electric power owing to the sunset. Therefore, the FC began to generate electric power between 4 p.m. and 10 a.m. for operating the ESS; the surplus electric power generated by the FC was stored in the BC unit. During the 24 h ESS operation, the minimum power output of the BC was maintained.

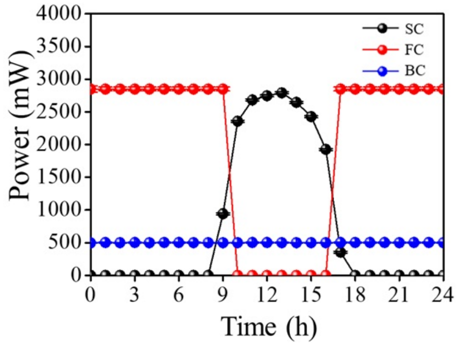

Fig. 5. Evolution of power outputs generated from SC and FC for operating the ESS during 24 h on a sunny day.

3.5 IoT-based wireless data transmittance and visualization

After connecting the integrated temperature/humidity/pressure sensors to each port terminal of the Wi-Fi board and the PMD incorporated with the SS-HPS, the operation of the ESS was started. The sensor data were then wirelessly transmitted through an access point in the data processing device and stored on a main web server, enabling the sensor data to be visualized on a PC monitor through graphs (see Fig. 6(a)). Additionally, the sensor data could be regularly transmitted to a mobile phone, allowing them to be easily visualized wherever wireless data communication was available, as shown in Fig. 6(b).

3.6 Operation of integrated temperature/humidity/pressure sensors powered by SS-HPS

The ESS was operated to measure the temperature/humidity/pressure in the indoor and outdoor areas every 30 min for 24 h, as shown in Fig. 7. For the indoor area on a sunny day, a temperature of ~20 °C and humidity of ~50 % were maintained owing to air conditioning. However, in the outdoor areas, the temperature and humidity were significantly changed owing to the weather conditions (see Figs. 7(a) and (b)). The pressure was maintained at approximately 1017 hPa under clear weather conditions. There was no appreciable change in the pressure in the indoor and outdoor areas, as shown in Fig. 7(c).

Additionally, the evolution of temperature/humidity/pressure in the indoor and outdoor areas was monitored for a relatively

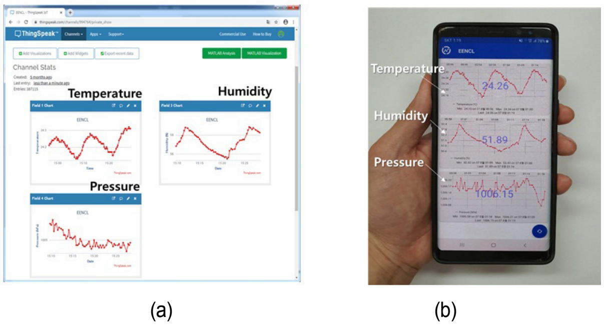

Fig. 6. Graphs of temperature/humidity/pressure sensor data transmitted through wireless communications and visualized in (a) PC monitor; (b) mobile phone.

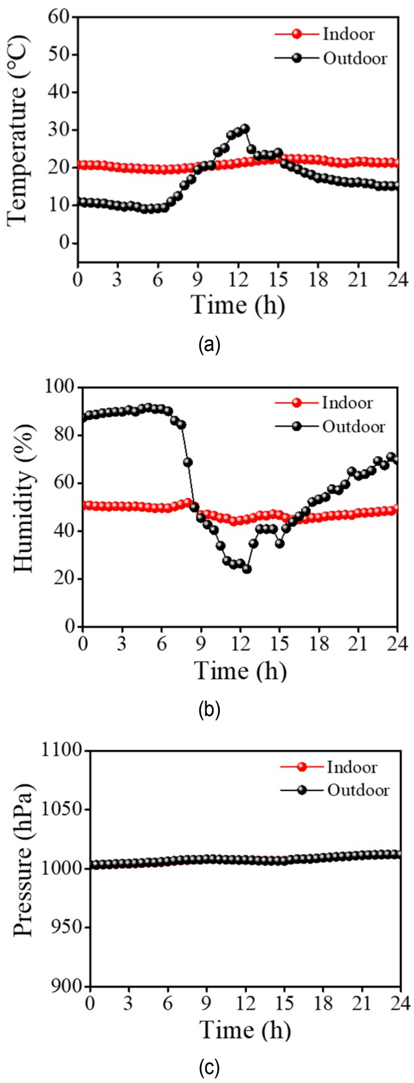

Fig. 7. Evolution of (a) temperature; (b) humidity; (c) pressure over time measured for 24 h using the ESS for environmental monitoring.

long period of 60 days from Oct. 10 to Dec. 10, 2021 using the ESS powered by the SS-HPS designed in this study, as shown in Fig. 8. The variation in the temperature and humidity was considerably smaller in the indoor area than that in the outdoor

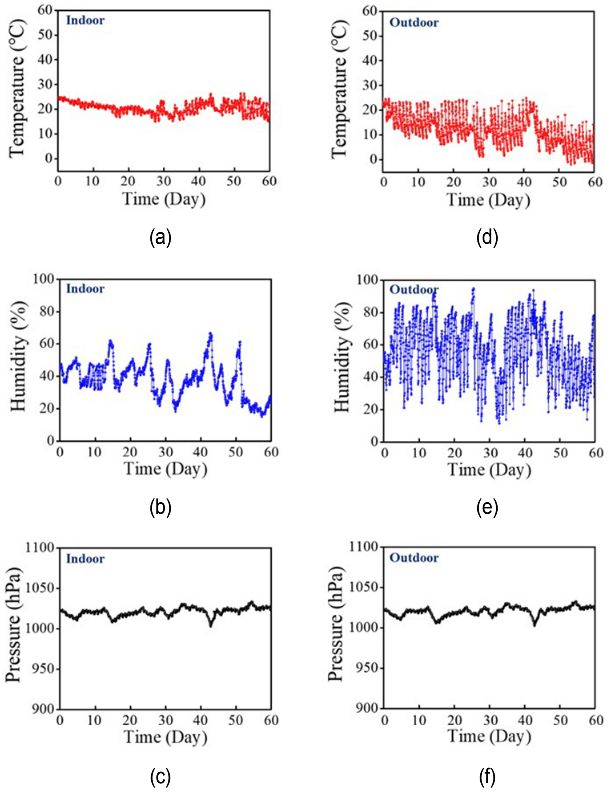

Fig. 8. Evolution of (a) temperature; (b) humidity; (c) pressure in the indoor area between October and December; evolution of (d) temperature; (e) humidity; (f) pressure in the outdoor area between October and December.

area owing to the cooling effect of the air conditioning system. The temperature and humidity frequently changed in the outdoor areas owing to the weather. However, the pressure did not appreciably change in either the indoor or outdoor areas. The SC/FC/BC-integrated SS-HPS designed in this study successfully provided sufficient electric power to stably operate the ESS for a long term, suggesting that the as-developed SS-HPS could play an important role as a reliable energy source to operate ESSs installed in both indoor and outdoor areas.

4. Conclusions

A single renewable energy source cannot stably generate electrical energy to operate the ESS because the electrical energy generated from a single energy source is strongly dependent on the environmental conditions. Therefore, an SS-HPS is required to supply stable electrical energy to an ESS. In this study, an SS-HPS, comprising an SC, FC, and BC, was designed to operate an ESS with a minimum power consumption of ~500 mW for the environmental monitoring of temperature, humidity, and pressure conditions in indoor and outdoor areas. The SC was employed as the main energy generation source, and surplus power was controlled to charge the BC. If the electric power generated from the SC was insufficient because of the relatively low light intensity (<~400 W/m^2), the ESS malfunctioned. Therefore, the FC was employed as an auxiliary energy generation source for continuously operating the ESS when the power from SC was insufficient. The sensor data on the temperature, humidity, and pressure conditions were wirelessly transferred using a Wi-Fi board and then visualized using graphs in real time on either a PC or mobile phone. The ESS could continuously perform the long-term environmental monitoring of the temperature, humidity, and pressure conditions in both the indoor and outdoor areas.

Acknowledgments

This study was supported by a 2-Year Research Grant from the Pusan National University, South Korea.

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