Journal of Scientific & Industrial Research
Vol. 84, July 2025, pp. 731-741
DOI: 10.56042/jsir.v84i7.14515

Internet of Things and Cloud based Monitoring of an Electrolysis and Fuel Cell System

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Received 21 October 2024; revised 01 May 2025; accepted 02 June 2025

This study presents a real-time Internet of Things (IoT)-based monitoring and control system for a hybrid green hydrogen setup powered by photovoltaic (PV) energy. The system integrates a Proton Exchange Membrane (PEM) electrolyzer, a fuel cell, and DC loads, with current and voltage data collected via IoT sensors and stored on a cloud platform. Data is sampled every 10 seconds and visualized through a user-friendly interface that supports hourly, daily, and weekly performance tracking via web and mobile devices. Experimental validation shows the PEM electrolyzer operates within 0.4–1.6 A and 1.6–3.2 V, achieving 58.25% energy efficiency at 1.2 A, while the fuel cell reaches 82.3% efficiency under the same condition. Hydrogen production rates, estimated through empirical equations, range from 0.38 to 8.36 mL/min. The system enables both real-time analysis and retrospective diagnostics, offering a practical tool for performance optimization and early fault detection in small-scale renewable energy applications. The uniqueness of this work lies in its fully integrated, cloud-based IoT approach for autonomous monitoring of a complete green hydrogen cycle.

Keywords: Clean energy technologies, Hydrogen, Internet of everything, Renewable energy, Renewable hydrogen production

Introduction

Currently, global energy production mostly relies on fossil fuels, significantly contributing to greenhouse gas emissions and global warming. Reducing greenhouse gas emissions associated with energy production is a key strategy in combating global warming.[1] It is projected that efficient energy utilization combined with the widespread adoption of renewable energy sources could account for approximately 80% of the anticipated emissions reduction by 2050.(2) Among renewable energy technologies, solar and wind are the fastest-growing renewable energy sources, with installed capacity increases of 45% between 2013 and 2020.(3) However, the intermittent and variable nature of renewable energy sources necessitates their integration with energy storage systems.[4] Battery technologies have emerged as promising solutions for short-term energy storage, while hydrogen-based technologies are considered more suitable for long-term storage due to their high energy density and environmental compatibility. Hydrogen technologies contribute to system stability, facilitate the integration of Renewable Energy Sources (RES), and offer a sustainable alternative to fossil fuel-based storage systems.[5] The International Energy Agency's projection for the years 2020–2030 indicates that by 2030, green hydrogen produced through electrolysis is expected to increase substantially. Hydrogen production is expected to make a positive contribution to climate change by reducing the 900 Mt of Carbon dioxide emission emissions per year from fossil fuels.[6]

Electrolysis, the process of converting electrical energy into chemical energy, plays a vital role in green hydrogen production.[5] Two primary electrolysis technologies are widely used: Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane (PEM) electrolysis. AWE is a mature and cost-effective technology. While AWE uses a corrosive liquid electrolyte, PEM employs a solid polymer membrane electrolyte. PEM is characterized by a compact design with high proton conductivity and the ability to operate under high pressure (15 to 30 bar at 50–90°C).[7] Its fast response time and the production of high-purity hydrogen (99.999%) offer advantages

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for PEM electrolyzers. Despite its performance benefits, the higher cost of PEM technology remains a significant challenge.[8,9] Fuel cells (FCs), on the other hand, enable the direct conversion of chemical energy into electrical energy through electrochemical reactions, producing only water as a by-product. This clean and efficient conversion process positions fuel cells as promising alternatives to conventional combustion-based power generation technologies.[10,11] Combined with these advantages, both hydrogen and fuel cell technology is a technology that will grow at a much faster trend in the future.[12–14]

In parallel with these technological developments, the transformation driven by Industry 4.0 has introduced significant innovations in the energy sector. The integration of Internet of Things (IoT) and cloud-based systems has provided critical solutions for reducing operational and maintenance costs, enabling predictive maintenance, remote monitoring and control, and performance optimization. Unlike traditional Supervisory Control and Data Acquisition (SCADA) systems that store limited data locally, modern IoT-based cloud platforms offer virtually unlimited storage capacity and advanced data analytics capabilities, thereby improving operational efficiency and reliability.[15] IoT-based cloud concept used today will play a very important role in shaping the future of the internet with unlimited storage opportunities together with the Industry 4.0 transformation.[16,17] Today, IoT and cloud-based systems are used together in different areas such as wired or wireless data networks, Radio Frequency Identification (RFID) structures, security structures, mobile applications, and different communication protocols in industrial structures or daily applications.[18,19] The combined use of these structures plays an important role especially in remote monitoring and control structures and provides important solutions for data transmission, acquisition, storage and data analytics.[20,21]

Hybrid energy systems that integrate various sources such as photovoltaic (PV) panels, fuel cells, and PEM electrolyzers require precise control and real-time monitoring due to their complex dynamic behavior. Recent studies have explored various hardware and software solutions for such systems, utilizing devices like PLCs, Raspberry Pi, BeagleBone Black, and ESP boards. However, existing research has primarily focused on individual components rather than integrated hybrid systems.

The Raspberry Pi hardware, which can be used in IoT applications, is a computer equipped with built-in wireless LAN and Bluetooth capabilities. Raspberry Pi can run various operating systems, including Raspbian Linux, Ubuntu Mate, and Windows 10 IoT Core.[22] Another hardware option, the BeagleBone Black, offers an Ethernet port along with numerous other connectivity options. It supports Debian, Android, and Ubuntu operating systems, and claims to boot Linux in under 10 seconds.[23] ESP boards, on the other hand, come with an integrated transmission control protocol/Internet protocol (TCP/IP) stack and a self-calibrating radio frequency antenna, supporting Wi-Fi Direct (P2P) and allowing operation under various conditions.[24]

Pramono *et al.*[25] and Srivastava *et al.*[26] have applied the ESP8266 for control and automation purposes. The author focuses on residential automation by evaluating the control of a hybrid system between wind energy and photovoltaic solar energy. The study is based on the ESP8266 microcontroller, which is responsible for monitoring whether residential loads and generators are in ON/OFF mode, and enabling remote activation of wind and/or solar energy generators through a simple command via a smartphone application.

Another study by Folgado *et al.*[27] used a PEM electrolyzer, Siemens PLC hardware and Node-Red software. The physical parameters of the PEM electrolyzer, such as current, voltage, pressure, and hydrogen flow, were monitored in real-time via web-based measurement results. In a study by Demircan and Akyüz, a PLC was used as a controller to monitor an industrial generator system. Measurement data were monitored in real-time via both local Human Machine Interface (HMI) interfaces and remotely through a web-based platform. The Minimum Message Queuing Telemetry Transport (MQTT) communication protocol and RS485 communication were utilized for displaying measurements to the user, as well as to the cloud system. The measurement data were recorded in the Microsoft Azure cloud for the performance evaluation of the generator.[28]

There are also studies in the renewable energy field that utilize widely used controllers that require inexpensive and compact. In the study conducted by Yang *et al.*[29] for a photovoltaic energy system, Arduino and ESP8266 hardware were used. The Think Speak cloud utilize for the real-time remote monitoring of critical data such as current, voltage, and energy measurements of the photovoltaic energy system.

The real time monitoring of performance for a small-scale wind turbine is used in another study and fundamental parameters such as wind speed, air temperature, battery voltage, and battery current were measured. The measurements were recorded via a data logger to assess the system's performance and prevent faults within the system. The data were analyzed in real-time and simultaneously stored on a cloud computing platform.[15]

Another study by Tran *et al.*[30] conducted a study on the monitoring and control of rooftop photovoltaic panel systems using IoT, supported by both Wi-Fi and GSM. They integrated the IoT control board they developed into the inverters of the photovoltaic panel systems to transmit data that would be shared online.

In a meteorological measurement station application, temperature, pressure, and relative humidity data obtained from sensors were recorded using a Raspberry Pi 4 and sensor components. Based on these measurements, air density and humidity correction coefficients were calculated. The study utilized a cost-effective board, such as the Raspberry Pi 4. Additionally, a web-based user interface was developed using HTML and CSS by the user.[31]

Watjanatepin *et al.*[32] achieved real-time monitoring and control of the greenhouse environment in their IoT-based study on agricultural greenhouse applications. A 900Wp PV system was utilized in the greenhouse, connected to the grid, and it was reported that energy consumption was reduced by 23.6%. An Arduino Mega board was used as the controller, and a LoRa module and GSM module were employed for wireless data transmission. Daily energy consumption, voltage, current, temperature, humidity, water temperature, and water flow rate data were used for remote monitoring.

A review of the literature reveals that a variety of controllers with different hardware setups, including PLCs, Raspberry Pi, microcontrollers, and data loggers, are employed in various applications. For data storage and analysis, both custom-built interfaces and those offered by cloud computing providers are utilized. Cloud computing solutions, in particular, are advantageous due to their user-friendly nature, which simplifies data visualization, and their compact structure. Nonetheless, these systems come with the drawback of added costs. Addressing this gap, the present study proposes an innovative, cost-effective, IoT-based real-time monitoring and control system for a hybrid setup combining a PEM fuel cell and a PEM electrolyzer. Utilizing the Arduino Uno R4 Wi-Fi board with integrated ESP8266 capabilities, this study offers a flexible, scalable, and low-cost solution for cloud-based data acquisition, control, and analysis. The developed system enables real-time performance monitoring, remote control via mobile devices, and historical data visualization through a cloud-based graphical user interface, providing a significant contribution to the advancement of intelligent energy management systems.

In this study, a system consisting of a small-scale PV, PEM fuel cell and electrolyzer, which has not been previously investigated in the literature, is examined. The system is designed to facilitate real-time monitoring, control, and cloud-based data storage. The Arduino Uno R4 Wi-Fi board was used due to several advantages compared to other control boards commonly employed in IoT systems. It offers a more cost-effective solution than PLCs, provides more flexibility with its built-in analog inputs (which are not available on Raspberry Pi boards), has a higher number of input/output pins compared to NodeMCU boards, and directly supports Cloud-IoT platforms. The control board utilized in this study offers significant cost advantages compared to those used in other applications, while also providing flexibility in platform support and scalability for application development. Equipped with an integrated ESP8266 module, this control board eliminates the need for additional hardware to establish an internet connection. Moreover, its analog input capability provides a compact and efficient hardware solution.

On the software side, the Arduino cloud infrastructure facilitates user interface development and simplifies remote programming of the control board, removing the necessity for a physical connection during software updates. Arduino Cloud web services have primarily been employed for big data storage, as well as for the remote monitoring and control of this data. A Graphical User Interface (GUI) was developed using Arduino Cloud services to allow users to monitor data in real-time and evaluate it over different time periods (day, month, week) through various dashboards. Additionally, mathematical expressions used for empirically calculating hydrogen flow rates were integrated into the cloud-based software. The program was also designed to enable the system's operation and shutdown via a virtual button on the cloud platform. Furthermore, the developed software provides monitoring and control functionalities through mobile devices.

Materials and Methods

In this study, an experimental system comprising an existing PV, a PEM electrolyzer, a fuel cell, and DC loads was implemented in the laboratory. The DC voltage generated by the PV is used by the PEM electrolyzer to separate water into hydrogen and oxygen, and the produced hydrogen and oxygen are subsequently utilized in the fuel cell to generate electricity. The experimental setup of the PEM electrolyzer used in the application is shown in Fig. 1. In addition, the energy required by the electrolyzer for hydrogen production is provided by the PV.[33]

PEM Electrolyzer

Electrolysis is an essential electrochemical process where electrical energy is transformed into chemical energy, enabling the decomposition of water into its elemental constituents, hydrogen and oxygen. In PEM electrolyzers, water is supplied to the anode catalyst layer. At this stage, water molecules dissociate into oxygen gas, hydrogen ions (H^+), and electrons according to the half-cell reactions. The anode and cathode reaction is presented in Eq. 1, and Eq. 2.(34)

$$H_2O \rightarrow \frac{1}{2} * (O_2) + 2H^+ + 2e^- \qquad \dots(1)$$

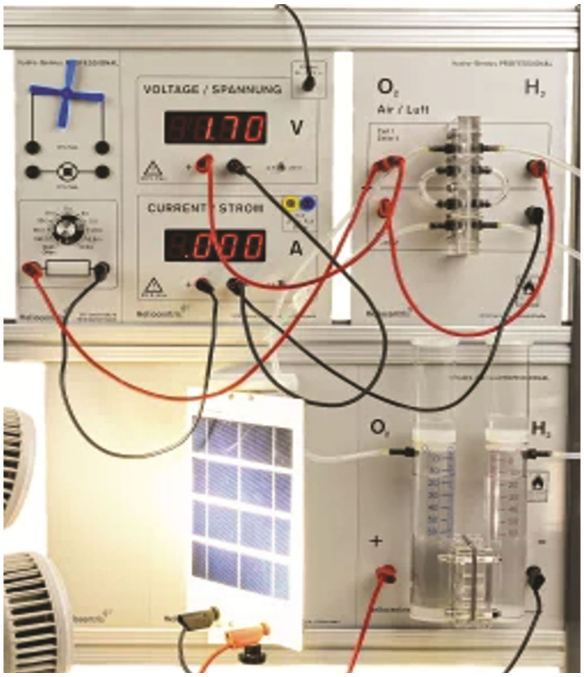


Fig. 1 — Hybrid energy system used in the study

$$2H^+ + 2e^- \rightarrow H_2 \qquad \dots(2)$$

During the electrolysis process, oxygen gas is released at the anode, while hydrogen ions (protons) migrate through the PEM toward the cathode. Simultaneously, electrons flow through the external circuit and recombine with hydrogen ions at the cathode to form hydrogen gas. Under standard thermodynamic conditions (25°C, 1 atm), the minimum theoretical cell voltage required to initiate water electrolysis is approximately 1.229 V, as determined by the change in Gibbs free energy. The thermodynamic relationship among enthalpy, entropy, and Gibbs free energy governing this process is defined by the Gibbs–Helmholtz equation, as presented in Eq. 3. (34)

$$\Delta G = \Delta H - T * \Delta S \qquad \dots(3)$$

In Eq. 3, ΔG represents the standard Gibbs free energy change (J/mol), ΔH is the reaction enthalpy (kJ/mol), ΔS is the entropy change (kJ/mol·K), T is the absolute temperature (K).

Under standard thermodynamic conditions, the minimum theoretical cell potential required for the electrolytic splitting of water is derived from the Gibbs free energy change and can be expressed by the following equation. The theoretical minimum potential difference (E_0) required for the dissociation reaction to occur during the electrolysis of water can be calculated using Eq. 4 for the reversible cell potential, which is ideally 1.229 V. In an electrolytic cell, the applied voltage must exceed the sum of the water's free energy and the activation and ohmic losses to effectively separate hydrogen and oxygen through electrolysis.[35]

$$E_0 = \frac{\Delta G}{nF} \qquad \dots(4)$$

In Eq. 4, the parameters are defined as follows: F is the Faraday constant (96485 C/mol), n is the number of electrons exchanged (2), and F is the Faraday constant (96485 C/mol).

The efficiency of the PEM electrolyzer is determined by comparing the chemical energy stored in the produced hydrogen to the electrical energy supplied during electrolysis. The efficiency is calculated from Eq. 5. (34)

$$\eta_{elc} = \frac{\dot{V}_{H_2} * HHV}{V_{cell} * I * t} \qquad \dots(5)$$

In Eq. 5, $\dot{V}_{H_2}$ represents the volumetric hydrogen production rate (Nm^3/s), V_{cell} is the cell voltage (V), I is the supplied current (A), t is the operating time (s), and HHV is the Higher Heating Value of hydrogen based on volume (11920 kJ/Nm^3).

Fuel Cells

A fuel cell directly converts chemical energy into electrical energy through electrochemical reactions. Hydrogen is continuously supplied to the anode, and oxygen is supplied to the cathode. In PEM fuel cells, protons generated at the anode migrate through the polymer electrolyte membrane to the cathode, while electrons flow through the external circuit, providing electrical power. The Gibbs free energy change (ΔG^0) associated with the electrochemical reaction within the fuel cell is calculated from Eq. 6 based on the number of electrons transferred per mole (n), the Faraday constant (F), and the reversible cell voltage (E_{rev}).[36]

$$\Delta G^{\circ} = -n * F * E_{rev} \qquad \dots(6)$$

In Eq. 6, E_{rev} denotes the reversible cell voltage (V). The thermodynamic performance of a fuel cell is calculated based on the relationship between the Gibbs free energy change and the reversible cell voltage, as given in Eq 7. (36)

$$E_{rev} = -\frac{(\Delta H - T * \Delta S)}{(n * F)} \qquad \dots(7)$$

In Eq. 7, ΔH represents the enthalpy change of the reaction (J/mol), T is the absolute temperature (K), and ΔS denotes the entropy change of the reaction (J/mol·K).

The efficiency of the fuel cell is calculated from Eq. 8 by comparing the electrical energy output to the chemical energy contained in the consumed hydrogen.[37]

$$\eta_{fc} = \frac{V_{cell} * I * t}{\dot{V}_{H_2} * HHV} \qquad \dots(8)$$

In Eq. 8, E_{rev} is the cell voltage (V), I is the output current (A), t is the operating time (s), $\dot{V}_{H_2}$ is the volumetric flow rate of consumed hydrogen (Nm^3/s).

Hardware Configuration of System

In this study, the Arduino Uno R4 Wi-Fi development board was used as the controller. The Arduino Uno R4 Wi-Fi and features onboard ESP8266, enabling direct connection to wireless networks. It runs at a clock frequency of 16MHz and includes 6 analog inputs and 14 configurable digital input/output pins. Additionally, the Arduino Uno R4 Wi-Fi is equipped with an onboard real-time clock (RTC) module.[38] The overall structure of the developed hardware is shown in Fig. 2.

In the PV, the MAX 471 module was used for voltage and current measurements. The currents drawn by the fuel cell and the battery being charged were monitored using the ACS712 sensor, which was connected to the analog ports of the control board. The Arduino board was programmed wirelessly with the support of the ESP8266 module and the software platform provided by Arduino. The overall structure of the developed main control system with IoT hardware is shown in Fig. 3.

IoT Architecture of System

The application structure is fundamentally realized by the IoT software, hardware architecture, and controller program. The overall application structure is illustrated in Fig. 4. The system consists of four different layers. In the first layer, measurements are taken and interpreted by sensors. In the second layer, the data acquired and interpreted by the controller board are transmitted over a Wi-Fi connection.

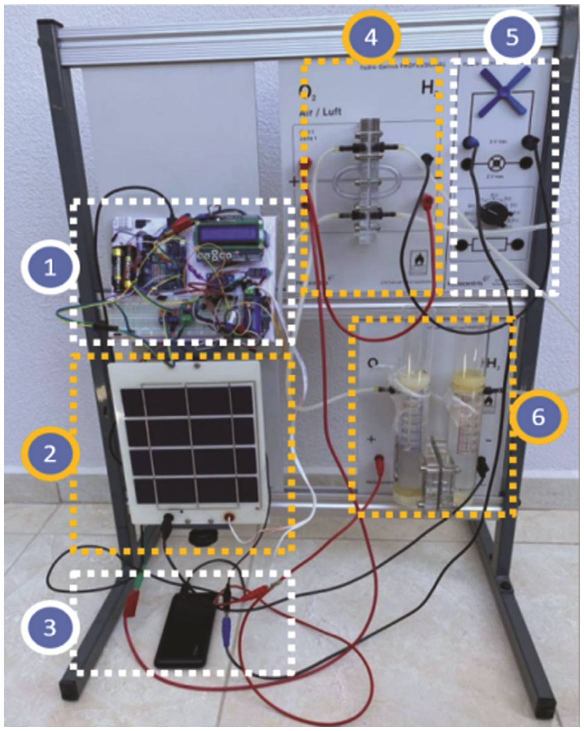


Fig. 2 — View of the system architecture (1-Main control system, 2-PV module, 3-Power supply, 4-Fuel cell, 5-Experimentel loads, 6-Electrolyzer)

The third layer involves processing the data sent to the cloud in a cloud-based environment, while in the final layer, applications are developed for the data available on the cloud computing platform, making it ready for presentation to the user.

The platform provided by Arduino for software developers, which allows for both paid and free development, was utilized for the cloud system. The structure used for obtaining measurements with the Arduino Uno R4 Wi-Fi board and for transmitting measurement data to the Arduino cloud framework is illustrated in Fig. 5.

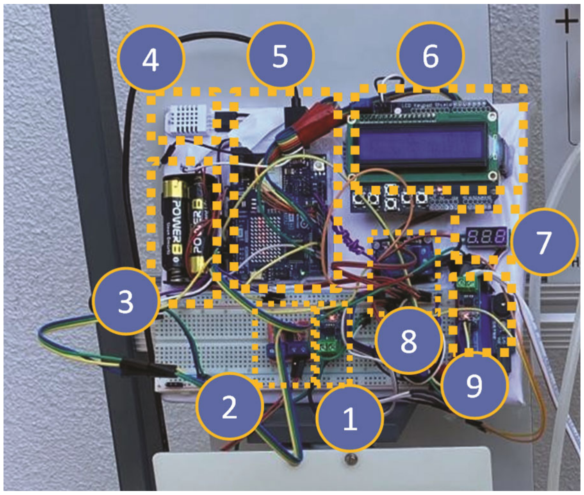


Fig. 3 — View of IoT hardware system (1-Current sensor, 2-Voltage sensor, 3-Battery for real time clock, 4-DHT22 sensor, 5-Arduino Uno Wifi-4, 6-LCD screen, 7-Voltage meter, 8-Relay output, 9-Current Sensor)

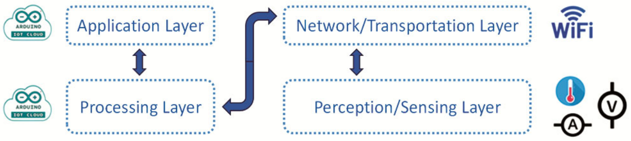


Fig. 4 — IoT system architecture

The detailed algorithm that used in study was showed in Fig. 6. In the program running on the control board, an internet connection is first established using Wi-Fi settings. Subsequently, measurements are taken from specific points of the system, which consists of PV, PEM fuel cell and electrolyzer components. After the measurement data is assigned to variables, it is transmitted to the Arduino Cloud. On the Arduino Cloud server, the data is visualized, logged, and broadcast to both mobile and computer platforms for remote users. The user can view and control the data through the cloud-based dashboard.

The activities used for internet connectivity of the Arduino Uno R4 Wi-Fi board to the Arduino cloud platform, including the last connection activities, device serial number, and IoT library version, are shown in Fig. 7.

The Arduino cloud platform provides support for both Arduino control boards and various hardware boards. It offers both paid and free support for machine learning applications. Additionally, applications can be developed for mobile devices on Android and iOS software platforms, as well as for web-based browsers.

Results and Discussion

In this study, Graphical user Interface (GUI) was developed on the cloud side is shown in Fig. 8. Software provides facile design possibilities in terms of visualizing and evaluating real-time data at the same time. The interface allows users to easily

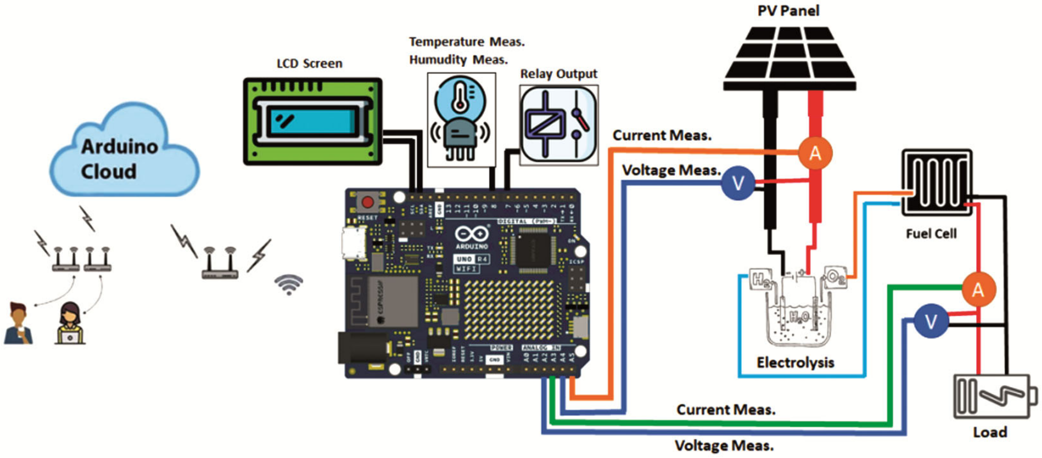


Fig. 5 — General structure of the architecture used in the study system

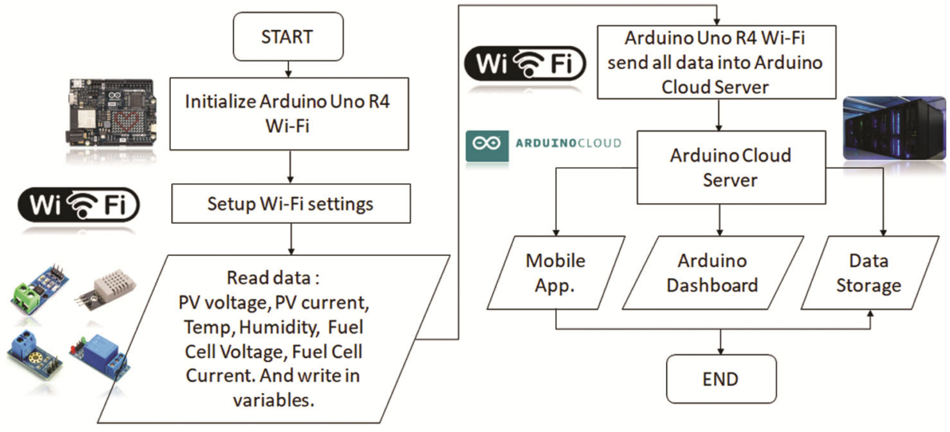
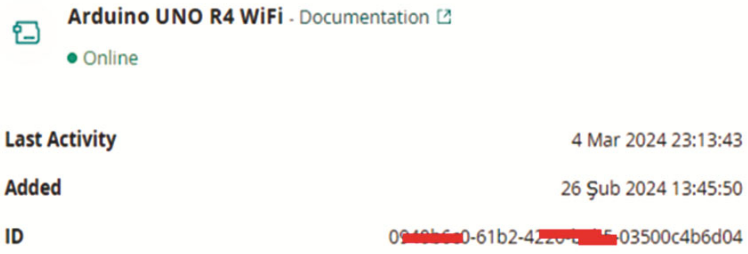


Fig. 6 — Flowchart of the operating of IOT cloud-based monitor system



Arduino UNO R4 WiFi - Documentation

● Online

Last Activity 4 Mar 2024 23:13:43

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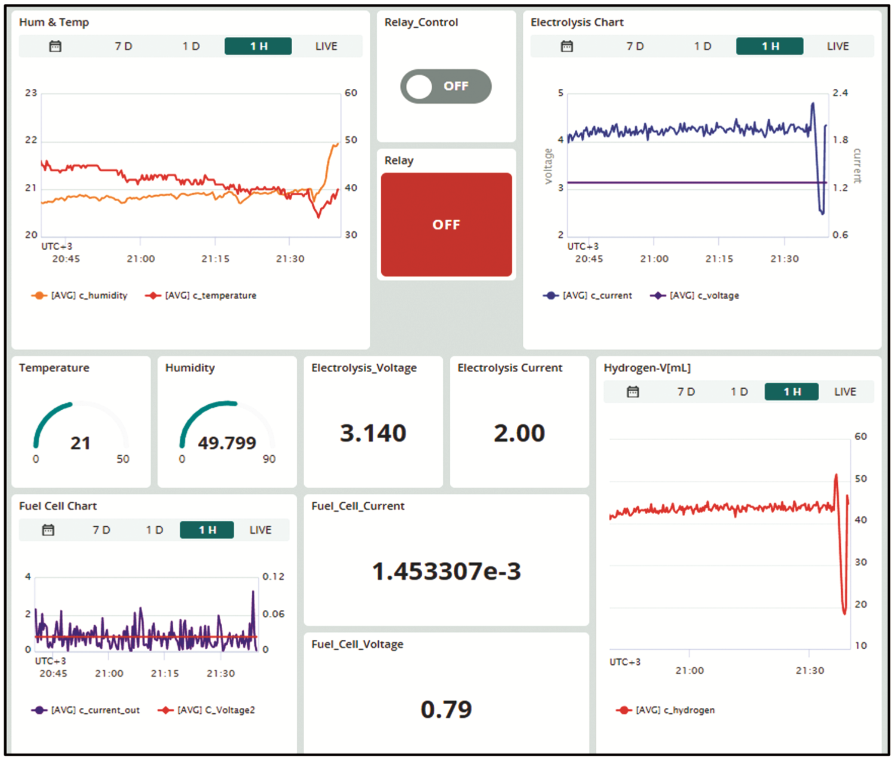
Fig. 7 — Arduino IoT platform and Arduino Uno R4 integration



Temperature: 21

Humidity: 49.799

Electrolysis_Voltage: 3.140

Electrolysis Current: 2.00

Fuel_Cell_Current: 1.453307e-3

Fuel_Cell_Voltage: 0.79

Relay_Control: OFF

Relay: OFF

Fig. 8 — Developed dashboard for user system (GUI)

monitor and assess critical measurement data such as current, voltage, temperature, and humidity. Each data set is measured at 10-second intervals and can be monitored hourly, daily, weekly, and retroactively. All data is accessible over the internet and can be monitored in real-time. The system enables remote control, especially under challenging operating conditions, and ensures the proper functioning of each system component. If necessary, the load can be remotely deactivated either when the user-defined critical temperature threshold is exceeded or by using the relay control button on the GUI. The data in the GUI is stored retrospectively for up to one year within the services provided by the Arduino Cloud subscription.

In addition to this, the monitoring data of the system can also be accessed by different users through mobile devices. The developed mobile interface, implemented via the Arduino Cloud platform, is shown in Fig. 9. This interface, accessible through the official Arduino IoT Cloud mobile application, enables users to monitor critical environmental and system parameters such as temperature, humidity, current, and voltage in real time. The interface provides various time range options including 1 hour, 1 day, and 7 days, as well as live tracking functionality. Each measurement is updated at fixed intervals (e.g., every 10 seconds), and the visualized data is synchronized seamlessly across both web and mobile platforms. Through this interface, users are able to remotely observe system performance, analyze fuel cell outputs, and respond to anomalies promptly without the need for physical access to the system.

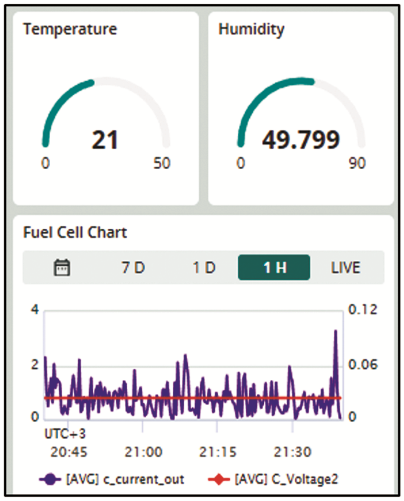


Fig. 9 — Mobile application dashboard of system

PV - Electrolyzer - Fuel Cell System

In this section, the performance of the system when operating with the PV is examined. The voltage measurements obtained from the PV at different times of the day are presented in Fig. 10. During the measurements conducted between April 9 and 18, 2024, the highest voltage value recorded was 3.448 V. Based on daily temperature measurements taken from the PV, the highest panel temperature was determined to be 38.81°C. Additionally, the highest panel voltage was measured at 3.45 V, while the lowest panel voltage output was recorded at 0.061 V. The maximum ambient temperature during the day was 36.5°C, the minimum ambient temperature was 20°C, and the highest humidity level recorded during the day was 64%. To enable real-time monitoring of the system from remote locations, the data were provided through an interface developed for different users.

Similarly, the measurement results containing the variations in ambient temperature and humidity are shown in Fig. 11. It is possible to analyze each data point in the interface over different time periods (hourly, daily, weekly, and in real-time).

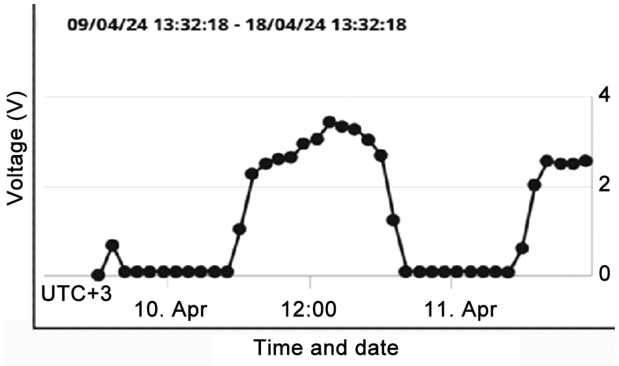


Fig. 10 — The amount of voltage generated by the photovoltaic panel

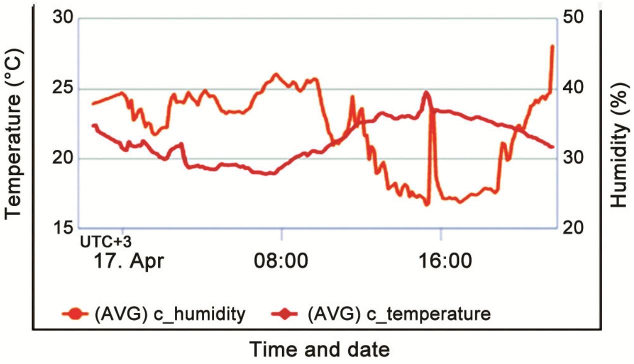


Fig. 11 — Daily measurement results of air temperature and humidity

In the implemented application, measurements of current, voltage, temperature, and H_2 production amount were recorded for the system. The variation of the H_2 amount obtained in the system with respect to current was first examined. For this purpose, the hydrogen production values of the electrolyzer at different current levels were measured by gradually increasing the current with the help of a power supply, and the data were recorded on the Arduino Cloud platform. The PEM electrolyzer begins hydrogen production at a threshold voltage of 1.48 V, and the maximum power of the electrolyzer was found to be 5.18 W, as shown in Fig. 12.

The variation of hydrogen production in relation to the electrolysis current is shown in Fig. 13. The change in the electrolysis current is linear; accordingly, the relationship between the hydrogen production amount m_{H2} (ml/min) and the electrolyzer current (A) is formulated in Eq. 9.

$$m_{H2} = 24.577 \times I - 4.07 \; (R^2 = 0.9981) \qquad \ldots (9)$$

Additionally, using the obtained measurement values in Table 1, H_2 production was analyzed based on the current flowing through the electrolyzer and time. Hydrogen measurement was performed using a measurement tube based on the current value. The hydrogen production values of the system in the current range of 0.4–1.6 A varied between 5.76 and 35.25 mL/min. The hydrogen variation has been formulated as a function of the current. This equation is utilized in the cloud-based software for calculating the amount of hydrogen production.

Electrolyzer Efficiency

The input and output power ratio of the PEM electrolyzer system provides the energy efficiency. To calculate the energy efficiency of the electrolyzer, the current-voltage characteristics and the amount of hydrogen produced must be determined. According to the set electrolyzer current of 1.2 A, the system produced hydrogen for 180 minutes. At this point, the measured voltage was 2.4 V. An exemplary efficiency calculation based on Eq. 5 is provided below, where the efficiency of the PEM electrolyzer is determined to be 58.25% by evaluating the ratio of the energy equivalent of the hydrogen produced to the electrical energy input to the system.

$$\eta_{elc} = \frac{\dot{V}_{H_2} * HHV}{V_{cell} * I * t} = \frac{0.02542 * 11920}{2.4 * 1.2 * 180} = 58.25\% \qquad \ldots (10)$$

Fuel Cell Efficiency

When examining the current-voltage curve shown in Fig. 14, it can be observed that the voltage decreases inversely with the increase in current. In the range of 0.4 to 1.2 A, the voltage varies between 0.68 and 0.4 V. Similarly, hydrogen production increases directly with current, varying between 3.2 and 8.36 mL/min.

The fuel cell reaches a voltage value of 0.38 V at a current of 1.2 A, as shown in Fig. 8. The amount of hydrogen produced at this current level is

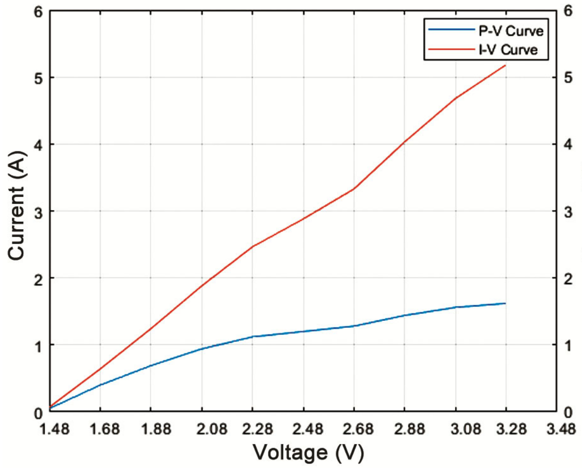


Fig. 12 — The Characteristics of the electrolyzer: P-V curve (blue) and I-V curve (red)

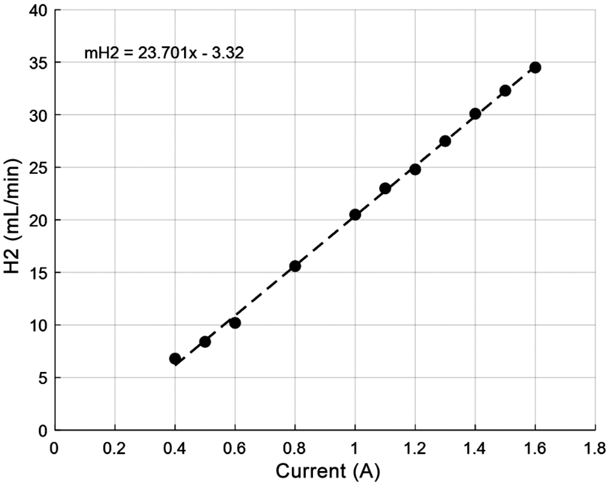


Fig. 13 — The change in current (A) and the amount of hydrogen produced from electrolysis (mL/min)

Table 1 — The amount of produced H_2 depending on the current [A]

I (A)	0.4	0.6	0.8	1.0	1.2	1.4	1.6
m_{H2} (ml/min)	5.76	10.67	15.59	20.50	25.42	30.33	35.25

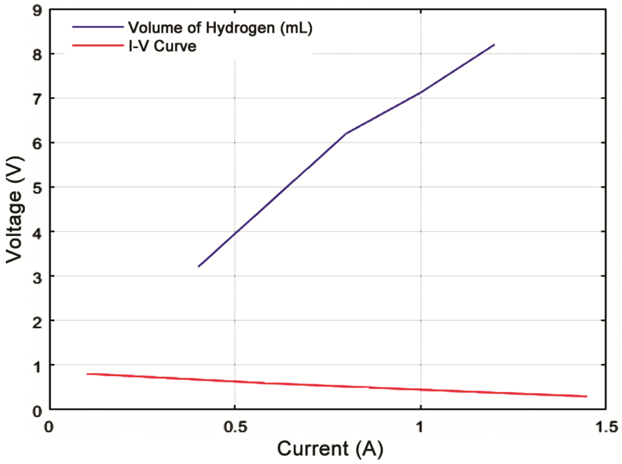


Fig. 14 — Fuel cell current-voltage-hydrogen quantity curve

8.36 mL/min, and the efficiency of the fuel cell, calculated according to Eq. 8, is 82.3%.

$$\eta_{fc} = \frac{V_{cell} * \mathrm{I} * \mathrm{t}}{\dot{V}_{H_2} * HHV} = \frac{0.38 * 1.2 * 180}{0.00836 * 11920} = 82.3\% \qquad \dots (8)$$

Conclusions

This study developed a cloud-integrated IoT-based monitoring and control system for a small-scale hybrid renewable energy setup comprising a PV source, PEM electrolyzer, and PEM fuel cell. The system enables real-time data acquisition, storage, and analysis of key parameters, offering remote access via web and mobile platforms. Its primary contribution lies in the low-cost integration of IoT hardware with cloud infrastructure to support live monitoring and control, unlike conventional offline approaches. Experimental validation confirms the system's applicability in educational, industrial, and research settings. However, limitations include sensor precision, Wi-Fi reliability, and hardware constraints. Future work may focus on incorporating high-accuracy sensors, implementing edge computing, and securing data communication through encryption. Expanding the system to support multi-node configurations could enhance scalability. Overall, the platform aligns with Industry 4.0 objectives, offering a flexible, practical solution for smart monitoring and performance evaluation in renewable hydrogen energy applications.

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