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Article

A Novel Design of a Low-Cost SCADA System for Monitoring Standalone Photovoltaic Systems

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Abstract: Standalone photovoltaic (PV) systems are pivotal in the global transition towards sustainable energy, offering reductions in fossil fuel dependence and helping homes and businesses lower electricity costs. Key to optimizing the performance and efficiency of standalone systems are supervisory control and data logging (SCADA) systems. They monitor and record operational data such as power output, facilitating early detection of potential issues. This paper introduced a novel design for both the Human-Machine Interface (HMI) and data storage in a SCADA system for standalone PV systems, addressing two crucial aspects: real-time monitoring and efficient data retrieval, both at very low cost. The proposed design utilized Bluetooth Low Energy technology to transmit voltage and current data from the PV panel to a mobile application, marking a departure from traditional HMI approaches. This method enabled historical data analysis for trend identification. Additionally, the system intermittently transferred collected data to a cost-effective cloud storage service via Wi-Fi, allowing for substantial data storage at no cost. Remote data storage, another key feature of this design, simplifies data retrieval, which is particularly beneficial for systems in rural areas. Emphasizing open-source development, this design ensured flexibility and customization options. To demonstrate its practical effectiveness of the design, a one-day power curve of the PV system and the battery voltage data are presented, showcasing the design's capability in handling extensive and remote data storage.

Keywords: human-machine interface (HMI), remote data storage, Bluetooth Low Energy, open-source SCADA, standalone photovoltaic systems

1. Introduction

Increased installation capacity of photovoltaic (PV) systems worldwide in the last two decades suggests that a higher green energy harvest from the Sun has been achieved. In 2000, cumulative installed solar PV capacity worldwide is 1,288 MW, while this number in 2022 was 1,177,000 MW [1]. The energy production performance of PV systems does degrade naturally with time; but any system faults should be detected and alarmed in time. Monitoring the performance of PV systems is thus crucial, since human intervention at an early stage can prevent serious damage from occurring.

Supervisory control and data acquisition (SCADA) is an industrial concept that helps to monitor and control industrial processes remotely, integrating hardware and software components to store and analyze real-time data [2]. Typically, SCADA system comprises of several components: one master terminal unit (MTU) to manage and monitor the other components in the SCADA network, remote terminal units (RTUs) to gather field information or control field devices, human-machine interface (HMI) to allow operators to view system

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parameters intuitively, sensors and actuators to collect information and execute physical actions, data historian to store historical data and display trends, and communication network to transfer data between MTU and RTUs.

Applications of SCADA system in PV system monitoring have been researched in many papers. Reference [3] investigated an IoT (Internet of Things) based SCADA system for PV system monitoring and control, featuring low cost and open source. Node-RED programming tool was used to present graphical interface that can be easily interacted. In [4] the authors developed a low-cost SCADA system to monitor a standalone PV system using Reliance SCADA software and MODBUS RTU protocol. These findings provide insightful contributions to SCADA system in PV system monitoring, however, none of them illustrate an HMI design that consumes low power and displays historical data; none of them proposed a remote data storage solution that supports large data storage without extra charge.

Predominantly, the research community developed different designs of SCADA systems for monitoring PV systems. Table 1 presents the comparison between related work.

Table 1. Comparison of HMI designs and data storage solutions in the literature review.

Reference	HMI Design				Data Storage	
	Customized Web Server	Website/ Software	LCD	Mobile App	SD Card	Website
[5]	√		√		√	
[6]		√	√		√	
[7]				√		√
[8]	√				√	
[9]		√			√	
[10]		√	√	√		√

For HMI designs, authors were using the customized web server [5,8], the third-party website [6] or software [8,10] and the LCD [5,6,10] to display the monitored parameters. A customized web server was built to display monitored electrical parameters from a PV panel rated at 15 W and environmental parameters [5]. The Arduino UNO Wi-Fi Rev2 built the web server via the embedded Wi-Fi chip. Every eight seconds, the HTML codes that corresponded to the web page were generated by a program running on the Arduino board. However, this method can only display a limited amount of data at a certain moment. The monitored parameters were also displayed on a Liquid Crystal Display (LCD) LM041L module, while lacking the ability to show the data trend. ThingSpeak is an open IoT platform that collects sensor data, shows the data in charts, and provides various plugins and mobile applications. This platform was used to store and display environmental and electrical parameters from a 30 W polycrystalline PV panel in [6]. While ThingSpeak platform integrates multiple services and functions for IoT applications, only eight channels of data were available for free to be transferred to the website. A 4×20 LCD with I2C interface was connected to the Arduino UNO board to be turned on with each iteration to display monitored results. Authors of [7] proposed that the PV panel current and power was first transferred from STM32 chip to Raspberry Pi 3 module via UART Tx/Rx interface. Then, the data was forwarded to a cloud server by Wi-Fi module on Raspberry Pi 3 and displayed on an Android app. For data visualization in an online monitoring system for PV panels, HTML containing real-time data was created by Raspberry Pi 3 [8]. Then, the HTML page was sent to a web server via Wi-Fi to display the monitored parameters. The HMI design by LabVIEW GUI software enabled users to retrieve the performance data of the PV system in (9). The interface could start data logging, check Bluetooth connection, and download logged data into the MTU. However, no data trend could be observed in this work. In [10], the monitored parameters were displayed on an Andriod app, ThingSpeak platform, and an LCD. Each Bluetooth message comprised of values of parameters and fixed prompt symbols, such as "I = ; V = ". No historical data could be seen from the mobile app and the LCD.

For data storage solutions, the SD card was massively adopted by the previous works [5,6,8,9]. ThingSpeak is another popular choice for remote data storage [7,10]. Nevertheless, data stored in the SD card are difficult to retrieve, especially when the standalone PV system locates in remote areas. Although ThingSpeak provides limited free service for messages under 3 million/year, only eight channels are available to upload the monitored variables.

In this paper, a novel design of HMI using a free Bluetooth Low Energy (BLE) mobile app to display monitored PV system parameters in live plot, and a new method of data storage using a website to massively and freely store the historical data are proposed. Section 2 introduces the materials and methods required to implement the experimental setup. Section 3 presents the experiment results, while Section 4 justifies the effectiveness of the proposed design. Section 5 concludes the paper.

2. Materials and Methods

For hardware components, an Arduino® UNO R4 Wi-Fi development board functioned as the RTU, an INA3221 module served as the voltage and current sensor. Software components comprised an Android application BlueTooth Terminal eDebugger as the HMI, a website PVOutput.org as the remote data historian. Section 2.1-2.4 introduces hardware and software components used in this paper, and Section 2.5 presents the experiment method.

2.1 *Arduino® UNO R4 Wi-Fi*

With UNO form factor, Arduino® UNO R4 Wi-Fi maintains the same pinout as the classic UNO Rev3. Projects can be transitioned from UNO Rev3 to UNO R4 Wi-Fi effortlessly. The faster clock than UNO Rev3 enhances its ability to handle complex project tasks. Furthermore, developers can add wireless connectivity to the projects due to the ESP32-S3 module, which supports Wi-Fi and Bluetooth. The larger flash and RAM capacity also guarantee the larger data storage and faster computational process. Table 2 lists the technical specifications of UNO Rev3 and UNO R4 Wi-Fi.

Table 2. Comparison of technical specifications between Arduino® UNO R4 Wi-Fi and Arduino® UNO Rev3.

	Arduino® UNO R4 Wi-Fi	Arduino® UNO Rev3
SKU	ABX00087	A000066
Microcontroller	Renesas RA4M1 (Arm® Cortex®-M4)	ATmega328P
Digital I/O Pins	14	14
Analog Input Pins	6	6
Operating Voltage (V)	5 (3.3, for ESP32-S3)	5
Input Voltage (V)	6-24	7-12
DC Current per I/O Pin (mA)	8	20
Clock Speed (MHz)	48 (up to 240, for ESP32-S3)	16
Memory	256 kB Flash, 32 kB RAM	32 kB Flash, 2 kB SRAM
Wi-Fi & Bluetooth connectivity	Yes	No
I^2C	Yes	Yes

2.2 *INA3221 Voltage Monitor*

Featuring three-channel and high-side, the INA3221 can monitor both voltage drops across the shunt resistor and the bus supply voltage with an I2C or SMBUS compatible interface. The range of sensed bus voltage varies from 0 V to 26 V, with a gain error of 0.25% at maximum. The INA3221 is powered at a voltage from 2.7 V to 5.5 V, consuming typically 350 µA. Figure 1 illustrates the schematic diagram of the INA3221 module.

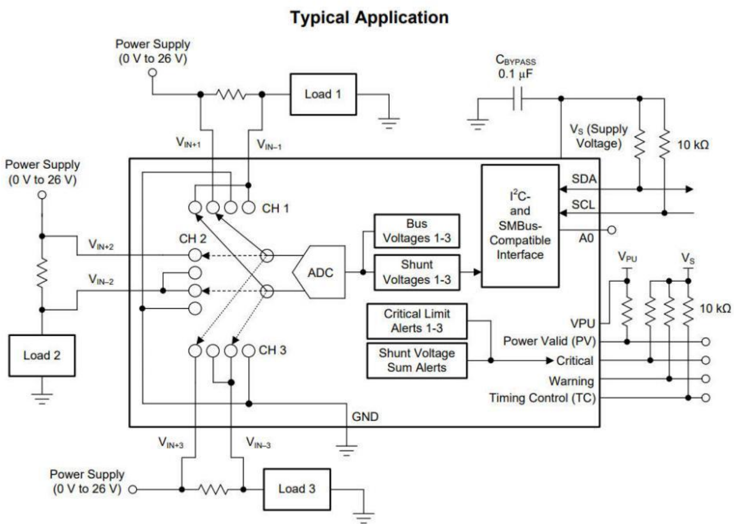


Figure 1. INA3221 schematic diagram.

2.3 *BlueTooth Terminal eDebugger*

Released in April 2023, BlueTooth Terminal eDebugger (BTeD) is a Bluetooth debugging assistant application running on Android OS. BTeD supports both Bluetooth Classic and BLE protocols, offering flexibility to Bluetooth developers. The technical specifications of Bluetooth Classic and BLE are presented in Figure 2. With considerably less power consumption down to 0.01-0.50 W, the BLE protocol has the edge over Bluetooth Classic in IoT projects where the power consumption is one of the most crucial aspects. A highlighted function of BTeD is to visually display the changes of data, by drawing the received data into a waveform diagram in real time. Since the maximum number of displayed data points is fixed, the higher the received data rate, the faster the plot scrolls.

Specifications	*Classic Bluetooth*	*Bluetooth Low Energy*
Range	100 m	Greater than 100 m
Data rate	1–3 Mbps	125 kbitps – 1 Mbps – 2 Mbps
Application throughput	0.7–2.1 Mbps	0.27 Mbps
Active slaves	7	Not defined
Frequency	2.4 GHz	2.4 GHz
Security	56/128-bit	128-bit AES with Counter Mode CBC-MAC
Robustness	Adaptive fast frequency hopping, FEC, fast ACK	24-bit CRC, 32-bit Message Integrity Check
Latency	100 ms	6 ms
Time Lag	100 ms	3 ms
Voice capable	Yes	No
Network topology	Star	Star
Power consumption	1 W	0.01 - 0.50 W
Peak current consumption	less than 30mA	less than 15mA

Figure 2. Comparison of technical specifications between Bluetooth Classic and BLE [11].

2.4 *PVOutput.org*

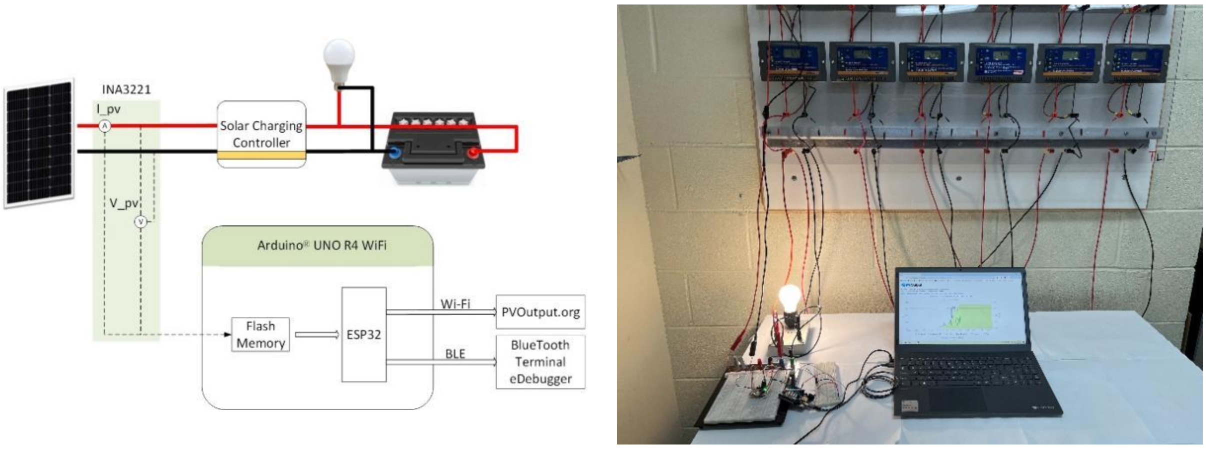
PVOutput.org is a free service for sharing and comparing PV output data. 2,515,654 solar panels are monitored, and 61,480,020 PV panel outputs are recorded [12]. Two forms of uploading data are supported by PVOutput.org: CSV loader and Live loader. The former records data daily, without historical limits. The latter allows intraday data upload at an interval of up to every five minutes. Only data from within the previous 14 days can be stored by Live loader. Data from an older date should thus be stored by CSV loader. Table 3 presents the differences between the two uploading modes.

Table 3. Characteristics of CSV loader and Live loader in for updating data in PVOutput.org.

	CSV loader	Live loader
Maximum Previous Days	No Limit	14 (90, in Donation Mode)
Data Interval	Up to one day	Up to five minutes
Maximum Number for per upload	200	288
Supported Parameters by both	Output Date, Energy Generation, Energy Consumption	Output Date, Energy Generation, Energy Consumption
Supported Parameters by CSV loader exclusively	Energy Exported, Peak Power, Peak Time, Conditions, Temperature Min, Temperature Max, Comments, Import Peak, Import Off Peak, Import Shoulder, Import High Shoulder, Export Peak, Export Off Peak, Export Shoulder, Export High Shoulder	/
Supported Parameters by Live loader exclusively	/	Output Time, Power Generation, Power Consumption, Temperature, Voltage

2.5 *Experimental Setup*

A PV test system in Memorial University comprised of two PV muls at 130 W rating each, an MPPT charging controller to regulate the PV output current, a backup battery as the energy storage, and a 12 V /50 W light bulb as the load. Sunforce 260W Crystalline Solar Kit contains two of the 130 W PV panels, where each has a maximum voltage of 12 V. Each panel has the dimensions of 63.5 x 34 x 13 inches. Figure 3a describes the SCADA system block diagram, and Figure 3b displays the experimental setup in the PV lab at Memorial University of Newfoundland. A PV panel with nominal output power of 130 W and current of 7.6 A was monitored, where the output voltage and output current were collected by an INA3221 module. Arduino® UNO R4 Wi-Fi saved the collected voltage and current in the flash memory, then transferred them via Wi-Fi and BLE. For data display in BTeD, collected data would scroll continuously on the interface when a mobile device running BTeD was available nearby. For data storage in PVOutput.org, data within 14 days were uploaded through Live loader every five minutes; while data before 14 days would be reshaped and uploaded according to the requirements of CSV loader. Figure 4 describes the flowchart for the data monitoring process.



(a) (b)

Figure 3. (a) The designed SCADA system block diagram. (b) Experimental setup.

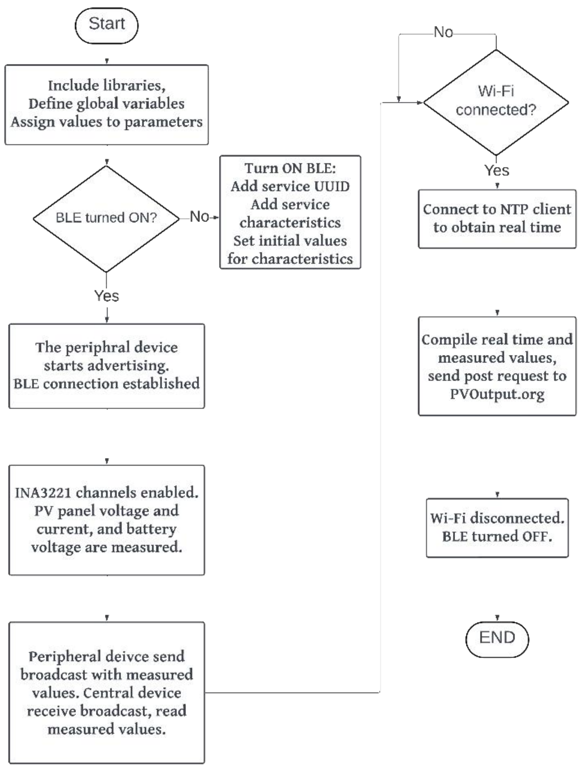


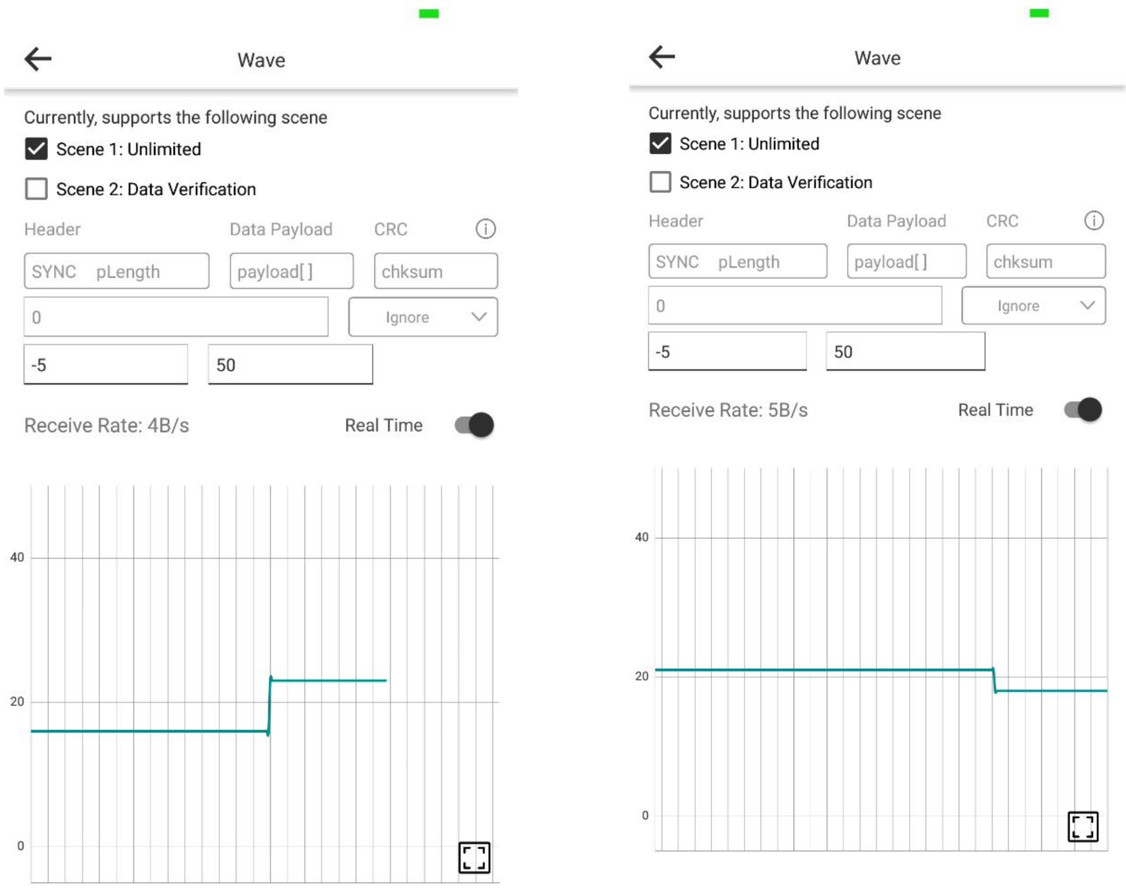
Figure 4. The SCADA system program flowchart.

3. Experimental Results

Table 4 lists the BLE service information. A Universally Unique Identifier (UUID) is a globally unique 16-byte number to identify profiles, services, and data types in a Generic Attribute (GATT) profile. The BLE specification supports for shortened 16-bit UUIDs for the purpose of efficiency. (0x)19 represents 19 W power produced by the PV panel. Figure 5 illustrates the output power of the PV panel in BTeD in a real-time manner. Data received within 55 seconds were displayed on the screen simultaneously. Power data received after 55 seconds scrolled to the right side of the screen, while the data received earliest disappeared from the left side. In Figure 5a, the PV panel power rose from 16.4 W to 23.1 W at 27 seconds. Conversely, the PV panel power decreased to 18.2 W from 21.0 W at 41 seconds as shown in Figure 5b. From the start to 55 seconds, the PV output power remained around 27 W, with a fluctuation of 3 W. During the data measurement, a digital multimeter was also added to verify the accuracy of the collected data. The results from the multimeter were observed to be the same as the power shown in BTeD. The received rate also fluctuated between 2 B/s to 5 B/s.

Table 4. BLE service information between BTeD and the RTU

PV System BLE Service	UUID	Result
Generic Access	00001800-0000-1000-8000-00805f9b34fb	\
Generic Attribute	00001801-0000-1000-8000-00805f9b34fb	\
PV power Service	0000180f-0000-1000-8000-00805f9b34fb	\
Power Characteristic	00002a19-0000-1000-8000-00805f9b34fb	\
Property	\	Read, Notify
Value	\	(0x)19



(a) (b)

Figure 5. BTeD live recording of the PV panel output power. (a) Increased power (b) Decreased power.

The output power of the PV panel on Dec. 10, 2023, was recorded on PVOutput.org website, as shown in Figure 6. The deep green line represented the power generated by the PV panel, while the light green area represented the energy generated by the PV panel. The red line indicated the battery voltage during the 24 hours. Before 8:15 am, there was no output power from the PV panel, nor was the energy output. After 8:15 am, starting from 1 W, the output power rapidly increased to 23 W at 10:15 am. The output power peaked at 12:15 pm, with a value of 40 W. After noon, the output power generally decreased with occasional upward fluctuations. After 3:40 pm, the PV panel did not generate any power.

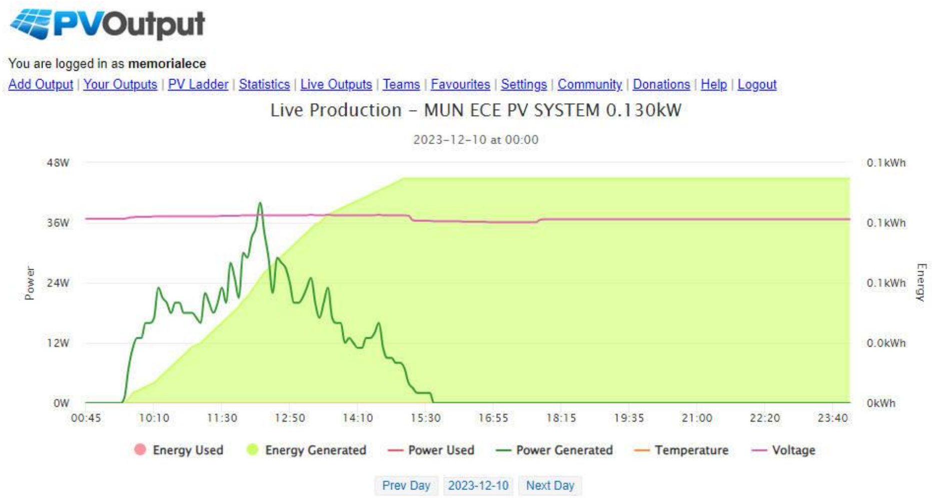


Figure 6. PV panel output power on Dec. 10, 2023, recorded in PVOutput.org.

Meanwhile, the generated energy stopped growing at the same time. The voltage of backup battery also had variations during the day. From 8:15 am to 12:15 pm, the voltage increased slowly from 12.8 V to 13.6 V. At 3:15 pm, at which a 12 V /50 W bulb was turned on, the battery voltage dropped to 12.5 V from 13.4 V immediately. Decreasing steadily, it was 12.1 V at 5:45 pm after 2.5 hours of lighting the bulb. The lighting bulb was turned off thereafter, bringing the voltage back to 12.6 V instantly and finally 12.7 V at the steady state. Data from 14 days ago were automatically reduced to limited parameters as Table 3 lists. All data in Figure 6 are stored in PVOutput.org and can be accessed free of charge after a simple registration process on the website, by searching "MUN ECE PV SYSTEM 130W" and choosing December 10th, 2023 as the date.

The battery voltage discharged at a different rate on Dec. 10 and Dec. 12, 2023. During the a few hours near noon, the output power of the PV panel was greater than that of the afternoon on Dec. 10. Table 5 lists the time when the load was turned on and off, the respective period, the corresponding generated energy, and the battery voltage. Both starting from 12.5 V and ending with 12.1 V, it took 255 minutes for the discharging process on Dec. 12, while 150 minutes for Dec. 10. Energy generated during each period was 0.122 kWh and less than 0.001 kWh.

Table 5. Change of the battery voltage during two days with different PV energy generation.

	Load turned ON	Load turned OFF	Energy generated by the PV panel during the period (kWh)	Period (minutes)
Time	11:10, Dec-12	15:25, Dec-12	/	255
Voltage (V)	12.5	12.1	0.122	/
Time	15:15, Dec-10	17:45, Dec-10	/	150
Voltage (V)	12.5	12.1	< 0.001	/

4. Discussion

Upon the BLE connection was built, the output power from the PV panel was plotted in BTeD interface. Within 55 seconds, any trend of the output power was intuitively observed by this method. The upward and downward change of the output power were easily observed in Figure 5. Thus, the effectiveness of BTeD as the HMI design in the developed SCADA system was verified.

From the power plot recorded in PVOutput.org, the peak power happened around the noon on Dec. 10, 2023, which coordinated with the common solar irradiation pattern. Since it was a day during winter in Canada, the period when solar power was available was relatively short: only between 8:15 am and 3:10 pm, there was output power from the PV panel. At 3:15 pm when the light bulb was turned on, the battery voltage immediately dropped 0.9 V from 13.4 V. This is due to the voltage drop by the battery internal resistance with the increased load. The battery steadily decreased overtime when the blub was on was due to the discharge of the battery. Since the PV panel output power was not comparable to the power consumed by the bulb (50 W), the battery voltage declined at the rate of 0.1 V every 20 minutes. After the bulb was disconnected with the circuit, the battery voltage rose to 12.6 V, and finally 12.7 V during the steady state. During Dec. 12, 2023 noon when the output power from the PV panel was larger, the decreasing rate of the battery was 0.4 (=12.5-12.1) V in 255 minutes, which was slower than 0.4 V in 150 minutes on Dec. 10, 2023. This is attributable to the PV panel which was also charging the bulb, leading to a lesser power consumed from the battery.

The power consumption of the components is listed in Table 6. Nordic Semiconductor® Power Profiler Kit II was used to measure the power consumption of Arduino® UNO R4 Wi-Fi with and without establishing Wi-Fi connection. The power consumption of INA3221 voltage module is from its datasheet. The overall power consumption is therefore between 100.35 mA and 120.35 mA, which is energy efficient compared to commercial products of which the power consumption is at watt level [13–15]. The cost breakdown of the proposed SCADA system monitoring standalone PV systems is also presented in Table 6. In [16–18], the system costs are C$ 107, C$ 210, and C$ 760, respectively. They are less cost-effective than the proposed SCADA system in this paper, which costs only C$ 42.15. The usage of PVOutput.org and BTeD application are free of charge.

Table 6. Power consumption and price breakdown of the proposed system.

Components	Current Consumption	Unit Price (C$)	QTY
Arduino® UNO R4 Wi-Fi	~120 mA (with Wi-Fi connection) ~100 mA (without Wi-Fi connection)	36.99	1
INA3221 Voltage Monitor	~350 μA	5.16	1
Overall	100.35 mA – 120.35 mAre	**C$ 42.15**	

5. Conclusion

In this paper, a new design of HMI and a data storage solution featuring remote, extensive, and low-cost was proposed in the SCADA system for monitoring standalone PV systems. A PV system and its SCADA system were built to verify the effectiveness of this design. The PV system comprised a PV panel, a solar charging controller, a backup battery, and a bulb. The SCADA system consisted of the Arduino UNO R4 Wi-Fi as the RTU, the BTeD as the HMI, the PVOutput.org as the data historian, an INA3221 voltage monitor as the sensor, and a PC as the MTU. By using BTeD, the output power from the PV panel was successfully displayed in the application interface via the BLE connection between the mobile and the RTU. The maximum time allowed for data presentation on the same screen was 55 seconds. The remote and extensive data storage was achieved by PVOutput.org. The PV panel output power and the battery voltage were uploaded to this website via Wi-Fi every five minutes. Data before 14 days were automatically simplified by the website into daily generated energy, peak power, peak time, etc. The recorded solar power matched the solar radiation pattern, and the recorded battery voltage varied accordingly with the load status and the PV output power. This novel design of the SCADA system was revealed to be effective on monitoring the standalone PV system.

Conflict of Interest

There is no conflict of interest for this study.

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