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Development of Stand-Alone DC Energy Datalogger for Off-Grid PV System Application based on Microcontroller

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ABSTRACT

This article presents a microcontroller-based direct current (DC) energy data logger developed by adapting low-cost ATmega328 by measuring the PV system DC and voltage characteristics while simultaneously recording the measured value over time to compute the energy production Watt-hour (*Wh*). The prototype logger has been tested on a live 1 kW standalone PV system where the voltage sensor detects PV series array output voltage ranging between 0–50 VDC by a voltage divider sensing circuit. For accurate sensing of the current output measurement from the PV array, 50A ACS756 hall effect IC was integrated as the current sensor. The data was measured and saved in text format with comma-separated values (CSV) in an SD card, read using Microsoft Excel software. The liquid crystal display (LCD) showed the actual value of the recording process's current, voltage, power, and duration in minutes. The recorded data has been compared to the standard laboratory digital multimeter for calibration manually to justify the measurement value. The error is minimized to 0.6% average by varying the constant float value in the programming code. The advantage of developing this logger is that the development cost is much cheaper than the standard commercial PV energy meter, can be reproduced for other DC application energy measurements, and easily modify the voltage and current range

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to suit the application. Apart from that, this logger also provides high accuracy performance, and its independent characteristic is practical for off-grid or off-site PV system use.

Keywords: Direct current logger, energy logger, off-grid photovoltaic, photovoltaic

INTRODUCTION

The increase in electrical energy power consumption of the declining fossil fuel resources, the environmental pollution issue, and increasing power utility prices have led humanity to depend more on a clean and sustainable energy source. For a long time, solar energy has been a huge renewable energy source that light and heat can be transformed directly into electricity. The photovoltaic system was used globally in various applications, such as buildings, space, agriculture, defense, telecommunications, and electrical gadgets, to reduce costs and easy access to its harvesting process. A complete PV system was equipped with an energy meter or monitoring device. This system is normally equipped or integrated with a larger scale or expensive charge controller and inverters with a dedicated external software system and interfaces. In several situations, off-grid or standalone PV systems normally did not have a data logger system, assessing the power generation generated because of the complexity and higher hardware costs. In the end, the user cannot trace long-term power production, system losses, and failure in the operation of the PV system.

Ronay et al. (2014) and Gertz and Di Justo (2012), in their research, agreed to the term that the solar energy monitoring system is a system that instantly assesses the magnitude of PV system energy characteristics by its embedded potential with an amperage sensor. However, the data can be continuously obtained or stored for long-term use with limited power consumption, either on grid-connected or standalone PV systems. An energy logger can be used in either system, consuming minimal energy and easily accessible by the user. PV system status is commonly monitored using a few types of control and communication technologies. Wired and wireless networking systems are usually used to obtain measuring data from a power meter. Han et al. (2015) developed a microcontroller-based PV control and monitoring device that incorporated a GSM communication module as the way of transmission between the device and a personal computer. However, the whole system is still costly, where the control and monitoring system did not provide a convenient method to retrieve the recorded data, and this device still dissipates extra or external power, which is not practical for remote areas.

In another study, Hadi et al. (2018) built a standalone power logger to measure a solar panel power output by applying Arduino modules proving that such a standalone device is known to be the perfect solution for remote or off-grid PV energy measurement systems and also much cheaper than those on the market for commercial products. However, this method is best used to measure individual or single solar panels in low voltage and current range, limited by the Arduino commercial modules (i.e., 0-25V_{DC} B25 voltage module, 0-20A ACS712 current module) and not suitable for a bigger system. Finally, Mahzan et al. (2017) outline the construction of a data logger for PV monitoring systems that store bulk data from input channels using the Arduino Mega 2560 board, which adapts the ATmega2560 chip. According to their findings, a data logger with an Arduino-based microcontroller is reliable in controlling the PV device. Furthermore, by comparing the data obtained from the proposed data logger with an existing data logger on the market, the proposed data logger achieved about 5% accuracy.

Another power data logger for a PV system, which has been developed by using a microcontroller (micro-C), has been presented by Rehman and Iqbal (2020) adapting ESP32-S2 micro-C, while Gupta et al. (2017) adapted the Arduino UNO, and Borza and Kaplani (2019) adapted the atmega328P board. Figure 1 shows the commercial measurement and monitoring device of PV systems available on the market, with a price starting from RM 600.00 and above.

Figure 1. Commercial PV energy meter and monitoring device

The construction of a prototype DC energy logger was presented in this study, which was developed utilizing a low-cost microcontroller to measure the DC and voltage of a PV system while recording the calculated data over time to calculate the solar energy generated (in kWh). This prototype was then tested and implemented to an established one kWp standalone PV Hybrid Agrivoltaic (HAV) greenhouse system for energy monitoring (Ariffin et al., 2017). The energy logger was integrated by connecting the voltage sensor from the PV array at the PV charge controller's input voltage terminal in parallel, while the current sensor connected in series at the PV array's negative input cable. The logger saved the collected data in an SD card, while the LCD screen displays the voltage, current, power, and duration of the logging progress in real-time. The logged data from the SD card can easily be accessed via MS Excel and will be explained in detail in the next section. Complete PV system for the testing purpose and application is specified in Table 1.

MATERIALS AND METHODS

In this prototype development, the system comprises four elements: the microcontroller as the brain part, voltage detector, current sensor, and data storage. The logger reads the data

Table 1
HAV greenhouse PV system specification

PV Panel Maximum Power	**100 W**
PV Cell Technology	Mono-crystalline Silicon
Panel Quantity	10
Array Configuration	2 panel strings, 5 string parallel
Total Maximum Power (Pmax)	1000 Wp
Maximum Voltage (Vmp)	35.64V in series
Maximum Current (Imp)	28.5A in parallel
Installation Method	Roof-mounted

in the one-minute interval from the sensor circuits and records the data into an SD card. In the meantime, the value measured was displayed on an LCD screen for ease of use to get the PV system information in real-time. This energy logger prototype is specifically designed to measure up to 50 V_{DC} and from 0-50A current using a specific hall effect sensor from the PV array. Table 2 lists out the component used in developing the energy logger, the cost for each component, and the total cost for the whole prototype. Figure 2 represents the process flow in developing the system programming and hardware prototype. Figure 3 exhibits the logger's hardware architecture based on the four main elements above.

Table 2
Component list and cost in Ringgit Malaysia (RM)

No	Item	Qty	U/Price (RM)	Total (RM)
1	Atmel Atmega328P Microcontroller (Arduino UNO)	1	30.00	30.00
2	ACS756 50A current sensor	1	50.00	50.00
3	IIC I2C LCD 2004 (20x4) display	1	25.00	25.00
4	W5100 Ethernet and SD card shield	1	25.00	25.00
5	Voltage divider (100kΩ & 10kΩ resistors)	1	1.00	1.00
6	Plastic Casing	1	10.00	10.00
7	Push button switch	2	4.00	8.00
8	12V cooling fan	1	4.00	4.00
9	Cable & connectors	1	10.00	10.00
			G/Total	153.00

Microcontroller System Hardware and Software

This energy prototype logger uses the ATmega328P-based microcontroller boards (Arduino UNO) consisting of 14 digital input/output (DIO) pins and six analog inputs (AI) for the analog sensor and can be programmed with the IDE (Integrated Development Environment) via a USB type B cable. The measured value is written into an SD card with the built-in SD library by integrating the SD module. The board can be programmed with its specific

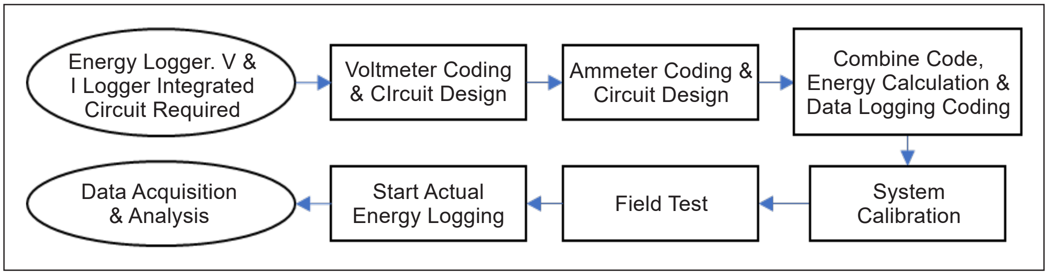

Figure 2. Energy logger design flow showing the steps in developing the software and hardware prototype

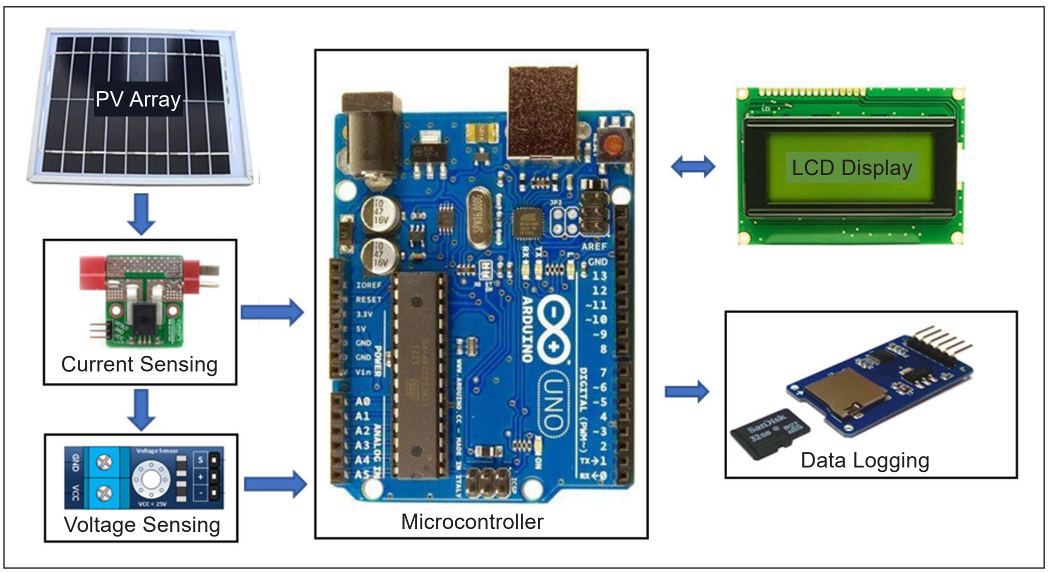

Figure 3. Energy logger hardware architecture, which consists of a microcontroller, current sensor, voltage sensor, and data logger component

software, and usually, the program code is called a sketch. Functionality is placed in the file of the library and applied within the program. The name of their file header with its pre-processor directive is included in the program. For example, float variables are used when calculating voltage, current, and power. This function tends to store real numbers.

Figure 4 represents the programming flow as the system evolves. The first initialization is to test for SD card absence and storage capacity. If the card is not found, it returns to the initialization of the SD card. After the initialization is complete, the system will go into ready mode. The first trigger pulse instruction code will begin measuring and displays the value of voltage, current, and power in real-time. Then, the second trigger pulse is a set of instructions to start the data recording. Next, the microcontroller begins writing the datasets into text format of comma-separated values (CSV) with a pre-programmed string filename. Simultaneously, the LCD screen will show the same information as the above with additional information, duration time in minutes. At any time, once the required data logging time reaches, the data logging cycle will be stopped by giving a third trigger pulse, and the system will be returned to steady mode.

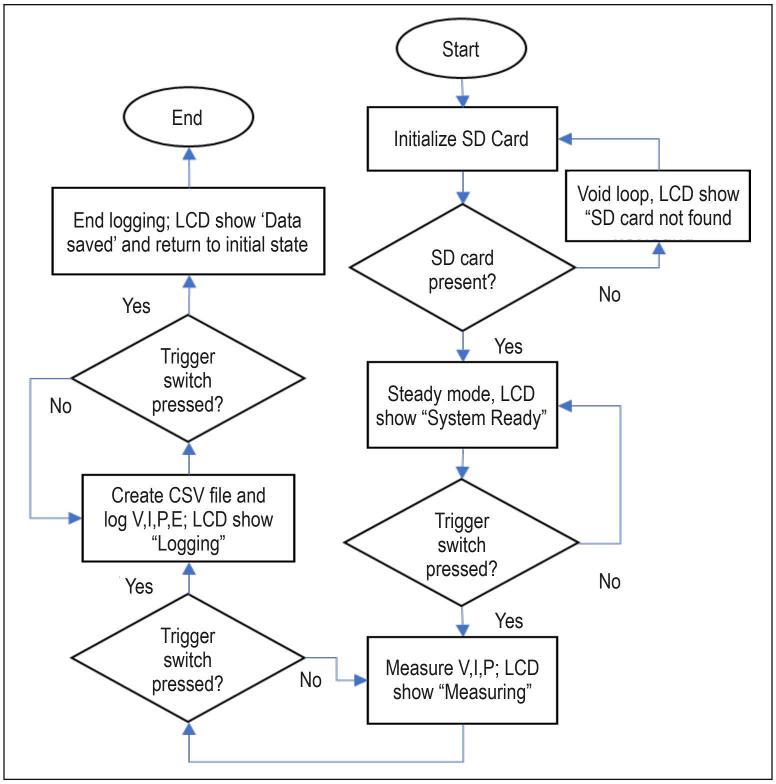

Figure 4. Prototype logger programming flow

Prototype Hardware

The energy logger prototype with LCD, a memory storage module, and the sensor are shown in Figure 5. It has high reliability for embedded systems and very low power consumption.

Voltage Detection. A voltage divider circuit was used as the voltage sensor. Since the ADC analog pin of the microcontroller (for voltage input) is limited to 5V, the divider's voltage output must not be more than that. The voltage divider circuit divides the voltage into two parts, from which one is fed to the Arduino analog input terminal. For a voltage range of 0-50 V_{DC}, the sensor circuit comprises of 100kΩ (R1) and 10kΩ (R2) resistors, where for precise output accuracy, the ratio of both resistors must be minimal. The R2 output voltage was referred to as input for ADC pin A0 on the microcontroller. Figure 6 represent the voltage divider circuit diagram, and R2 output voltage can be written as Equation 1:

$$V_{out} = V_{in} \frac{R_2}{R_1 + R_2} \qquad [1]$$

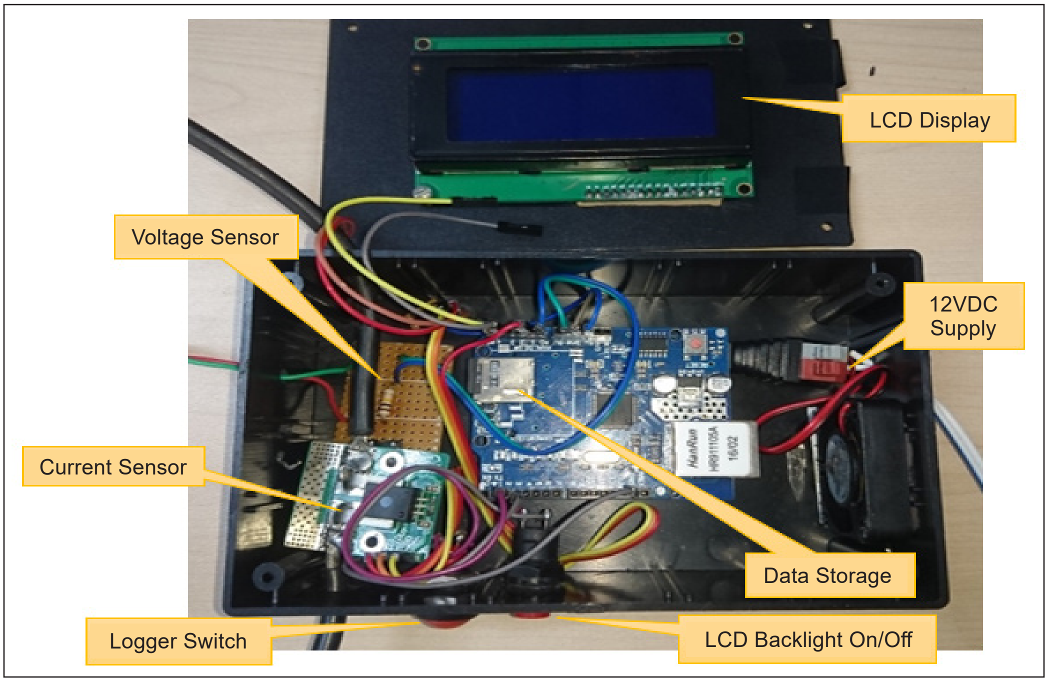

Figure 5. Developed energy logger prototype with memory modules, LCD, and sensors based on ATmega328P microcontroller

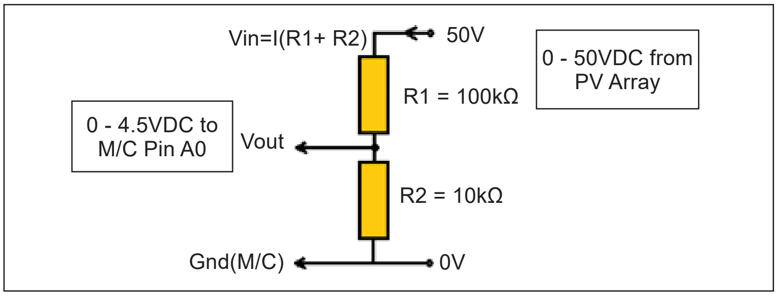

Figure 6. Voltage divider circuit developed for voltage sensing

In this application, if V_{in}=50V maximum, then:

$$V_{out} = 50\frac{10000}{110000} = 4.545V = 4545mV$$

The analog input ADC resolution can be calculated using Equation 2:

$$ADC_{resolution} = \frac{V_{ref}}{(1024-1)} \quad [2]$$

$$ADC_{resolution} = \frac{4545\ mV}{1023} = 4.442\ mV$$

Therefore, 4.442mV will be converted to 1V in the programming code. To protect the microcontroller analog pin, a Zener Diode can be used to avoid high voltage.

Current Sensing. ACS756 Hall Effect current sensor IC has been adapted for DC measurement for high precision sensing. It can measure current up to 50A maximum and can be applied in both DC and AC applications. 'Hall effect' means generating a voltage difference (the Hall voltage) across an electrical conductor, a transverse to an electrical current in the conductor, and a perpendicular magnetic field to the current. A major benefit of adapting this sensor in a system is that its conductive path terminals are electrically isolated from the signal line. Figure 7 exhibits the pinout of the IC module and its standard use. The sensor has a sensitivity of 40mV/A, according to its datasheet. Initially, it produces between 2.4–2.5V analog output from the Vout pin at 0A current (no load) depending on environmental conditions. Since the module can sense up to ±50A current range, the highest voltage output is 4.5V for positive +50A and 0.5 V for negative -50A current measurement.

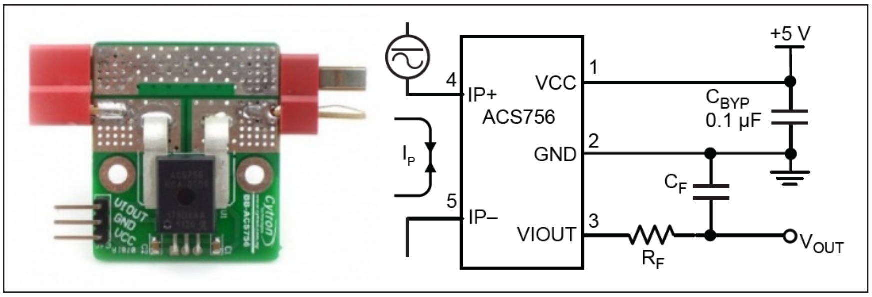

Figure 7. ACS756 Module and typical application

Figure 8 illustrates the schematic diagram for hardware design, which shows the voltage divider and the current sensor connection. IP+ terminal of the ACS756 is connected to the solar charge controller, and the IP- terminal is connected to the negative line from the PV array. The sensor's Vcc pin is connected to the microcontroller's 5V pin. In contrast, Vout is connected to an A1 analog input pin (pin A0 occupied by voltage sensor). The microcontroller converts the analog to a digital signal via its 10 bits ADC, similar to the voltage sensor conversion.

As mentioned earlier, the sensor's sensitivity is 40mV/A, which describes every increment of 1A by PV system array will increase 40mV to Vout pin of ACS756 IC. The sensor output is a voltage that needs to be calculated to transform it to the current value (Ang, 2012). Considering the sensor's ratio and sensitivity in Equation 3:

$$\frac{Change\ of\ Voltage}{I_{(mA)}} = \frac{0.04V}{I_{(mA)}} \quad [3]$$

which the change of voltage can be written as the following:

$$Change\ of\ voltage = (Sensor\ reading - Initial\ reading)\ bits\ \frac{5V}{1024\ bits}$$

The change of voltage is different at the time between the output voltage (sensor reading) and the initial state output voltage, which is about 2.5V. Because 2.5V in Arduino give 510 in 10 bits of ADC, the voltage change can therefore be written as Equation 4:

$$Change\ of\ voltage = (Sensor\ reading - 510)bits\ \frac{5V}{1024\ bits} \quad [4]$$

Combining Equations 3 and 4 gives:

$$I(mA) = \frac{(Sensor\ Reading - 510)bits}{0.04\ V}\left(\frac{5V}{1024\ bits)}\right)(1000mA)$$

Hence,

$$I(mA) = (Sensor\ Reading - 510)(122)$$

$$I(mA) = (Sensor\ Reading - 510)(122)$$

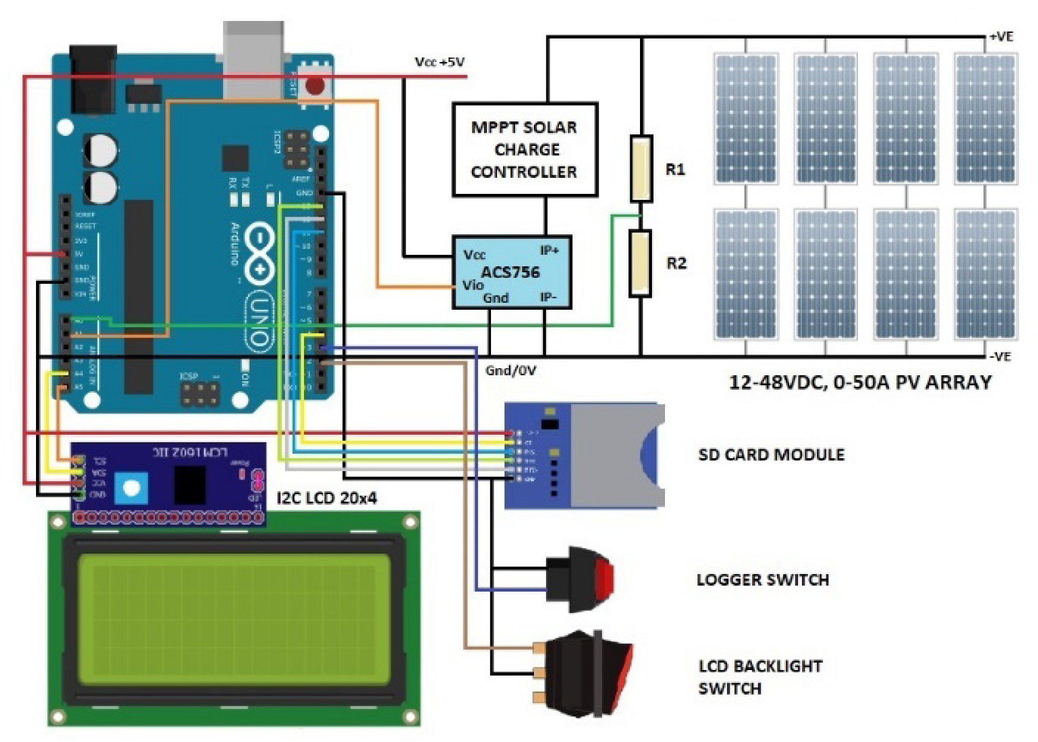

Figure 8. System schematic drawing

Data Logging. The energy logger developed is integrated with an ethernet module with a microSD card slot for storing data with a reading capability of 32 GB to enable bigger data storage and memory backup. When the second trigger button is pressed, this will start the data recording process, and when pressed again, it will stop logging. Measurement's current, voltage, power, and energy values are written to a CSV file in the SD card. By reading the microSD card using the Microsoft Excel application, several files can be found in series based on how many logging cycles a person has taken the readings, each with the filename starting with "datalog" followed by running number as pre-set during programming development.

Power and Energy Calculation. Measurement of power and energy is written in program code performed by the system and automatically written with the measured data in the SD card. For example, to calculate power (Equation 5):

$$P = V \times I \qquad [5]$$

For energy calculation (Equation 6):

$$E = \frac{P\ (average) \times t\ (duration\ in\ minutes)}{60} = kWh \qquad [6]$$

LCD Screen. The LCD screen is the device output panel to display the measured value of voltage, current, power, and duration in real-time. The LCD backlight can be turned on and off by the toggle switch to reduce the power consumption of the logger when not needed (i.e., during daytime).

RESULTS AND DISCUSSIONS

Voltage and Current Sensor Calibration

Once the program was uploaded to the microcontroller, the logger's sensor system was tested using a variable DC power supply and digital multimeter, calibrated for the laboratory instrument standard. A 50W 12VDC bulb as a dummy load was applied to calibrate the current reading. The logger's voltage measurement reading on the LCD is almost similar to the laboratory's power supply voltage display.

Because of ACS756 module produce floating voltage ranging from 2.4 to 2.5V. At the same time, the current is 0A, and a different output sensitivity of 20~40 mV/A due to varying operating temperature, it takes a long procedure to match the readings by repeatedly tuning the constant float value in the programming code. Figure 9 exhibits a dummy load's voltage and current being measured for calibration. The final adjustment calculation between the prototype logger and the laboratory standard instruments resulted in an average deviation of 0.6%, acceptable for most certified calibrated measuring devices where meters cannot

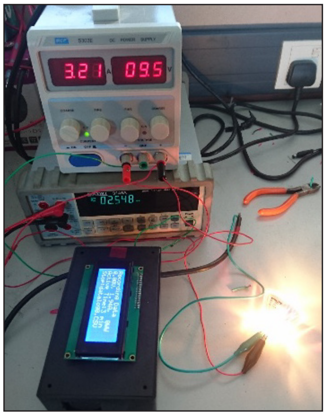

Figure 9. Manual calibration process by comparing prototype logger's voltage and current sensor measurement with standard laboratory DC power supply and current meter

exceed 3% inaccuracy when tested (IEC, 2020; Energy Commission, 2021).

Field Sampling

After the calibration work has been done in the laboratory, a field test experiment has been carried out to assess the energy logger's stability and reliability in real-time and actual conditions. The prototype logger has been installed in line with a specific commercial energy logger to analyze the measured data accuracy. The setup is shown in the Figure 10 schematic diagram below. The commercial energy meter measures the voltage by tapping the positive and negative terminal of the PV array, similar to the prototype logger.

While the prototype logger measures the current through the Hall effect sensor, the commercial energy

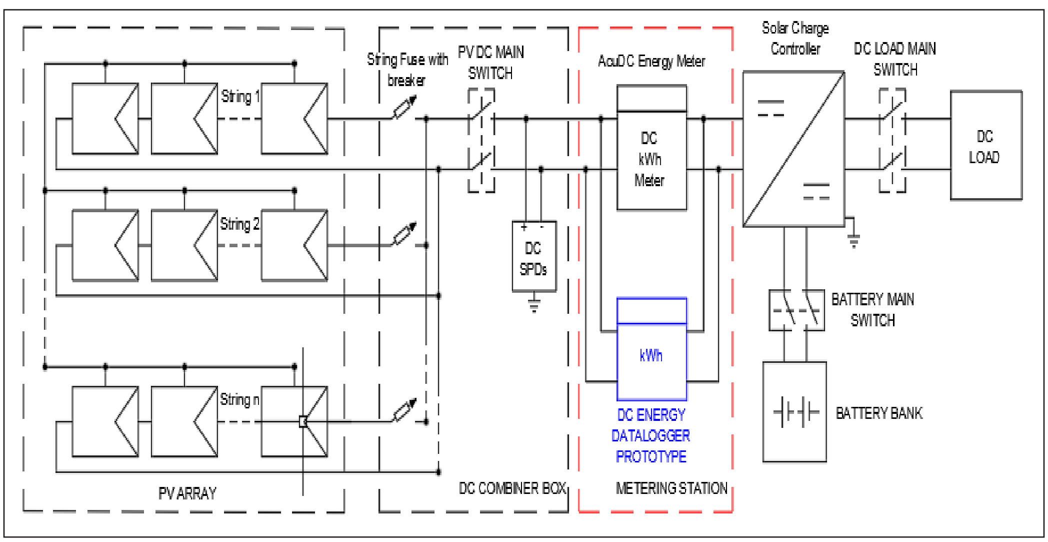

Figure 10. Schematic diagram of measurement setup for prototype logger and commercial energy meter on an existing 1kWp DC PV greenhouse system

meter uses the shunt resistor to measure the current in series at the negative line of the PV array before connecting to the solar charge controller. Figure 11(a) shows the data samples presented using MS Excel, which was copied from the SD memory card, and Figure 11(b) shows the MS Excel data extracted from the commercial energy meter through its specific user interface software, which shows more parameters being measured and calculated by the meter.

Elapse	Time	Voltage	Current	Power	Energy
1	15:35:00	30.03	21.87	656.61	10.94
2	15:36:00	27.23	21.26	578.89	20.59
3	15:37:00	33.89	18.08	612.79	30.80
4	15:38:00	30.51	20.4	622.45	41.18
5	15:39:00	34.16	18.08	617.65	51.47
6	15:40:00	34.49	21.01	724.61	63.55
7	15:41:00	28.04	24.07	674.82	74.80
8	15:42:00	27.5	22.36	614.85	85.04
9	15:43:00	34.38	18.32	629.94	95.54
10	15:44:00	30.08	18.32	551.19	104.73
11	15:45:00	29.54	18.93	559.4	114.05
12	15:46:00	25.94	19.06	494.43	122.29
13	15:47:00	26.64	18.45	491.46	130.48
14	15:48:00	31.1	17.59	547.09	139.60
15	15:49:00	26.37	17.83	470.39	147.44
16	15:50:00	31.16	17.22	536.62	156.39
17	15:51:00	31.69	17.47	553.61	165.61
18	15:52:00	29.49	19.06	561.99	174.98
19	15:53:00	30.73	17.59	540.48	183.99
20	15:54:00	33.3	16.61	553.28	193.21
21	15:55:00	30.13	15.88	478.53	201.18

(a)

Record Number	Time	Voltage (V)	Current (A	Watt (kW)	E_imp (kW	E_exp (kW	E_total (k	E_net (kW	Q_imp (Ah	Q_exp (Ah	Q_total (A	Q_net (Ah)
1396	30-05-19 10:26	17.39	2.693	0.04684	4.52	0	4.52	4.52	264.09	0	264.09	264.09
1397	30-05-19 10:29	17.17	2.597	0.0446	4.52	0	4.52	4.52	264.22	0	264.22	264.22
1398	30-05-19 10:32	17.03	2.648	0.0451	4.52	0	4.52	4.52	264.35	0	264.35	264.35
1399	30-05-19 10:35	17.23	2.861	0.0493	4.52	0	4.52	4.52	264.49	0	264.49	264.49
1400	30-05-19 10:38	16.93	2.877	0.04871	4.52	0	4.52	4.52	264.63	0	264.63	264.63
1401	30-05-19 10:41	16.73	2.946	0.0493	4.53	0	4.53	4.53	264.77	0	264.77	264.77
1402	30-05-19 10:44	16.95	2.608	0.0442	4.53	0	4.53	4.53	264.91	0	264.91	264.91
1403	30-05-19 10:47	17.32	3.098	0.05366	4.53	0	4.53	4.53	265.06	0	265.06	265.06
1404	30-05-19 10:50	17.21	3.324	0.05721	4.53	0	4.53	4.53	265.22	0	265.22	265.22
1405	30-05-19 10:53	17.03	3.222	0.05487	4.54	0	4.54	4.54	265.39	0	265.39	265.39
1406	30-05-19 10:56	17.21	2.999	0.05159	4.54	0	4.54	4.54	265.54	0	265.54	265.54
1407	30-05-19 10:59	17.19	3.051	0.05243	4.54	0	4.54	4.54	265.69	0	265.69	265.69
1408	30-05-19 11:02	17.23	3.065	0.0528	4.55	0	4.55	4.55	265.85	0	265.85	265.85
1409	30-05-19 11:05	17.33	2.961	0.05131	4.55	0	4.55	4.55	266	0	266	266
1410	30-05-19 11:08	17.73	2.697	0.04781	4.55	0	4.55	4.55	266.11	0	266.11	266.11
1411	30-05-19 11:11	17.17	3.009	0.05167	4.55	0	4.55	4.55	266.25	0	266.25	266.25
1412	30-05-19 11:14	17.09	3.143	0.05372	4.56	0	4.56	4.56	266.4	0	266.4	266.4
1413	30-05-19 11:17	17.27	3.152	0.05443	4.56	0	4.56	4.56	266.56	0	266.56	266.56
1414	30-05-19 11:20	17.45	3.294	0.05747	4.56	0	4.56	4.56	266.72	0	266.72	266.72
1415	30-05-19 11:23	17.02	3.486	0.05935	4.56	0	4.56	4.56	266.89	0	266.89	266.89
1416	30-05-19 11:26	16.82	3.646	0.06132	4.57	0	4.57	4.57	267.07	0	267.07	267.07
1417	30-05-19 11:29	16.66	3.715	0.06191	4.57	0	4.57	4.57	267.26	0	267.26	267.26
1418	30-05-19 11:32	16.71	3.669	0.06132	4.57	0	4.57	4.57	267.45	0	267.45	267.45
1419	30-05-19 11:35	16.74	3.482	0.05831	4.58	0	4.58	4.58	267.63	0	267.63	267.63

(b)

Figure 11. (a) Prototype energy logger's CSV data extracted from the SD card read in MS Excel; (b) Extracted data from commercial energy meter user interface software

Energy Analysis

A sample measurement of energy generation from a PV system was recorded using the energy logger for one day from 9:15 AM with 1 minute time interval until 7:00 PM. From the prototype logger's CSV saved data and the commercial energy meter's data, the voltage (*V*) and current (*I*) graph plot has been plotted by MS Excel in Figures 12 and 13, respectively showing small errors between the prototype and the actual energy meter reading.

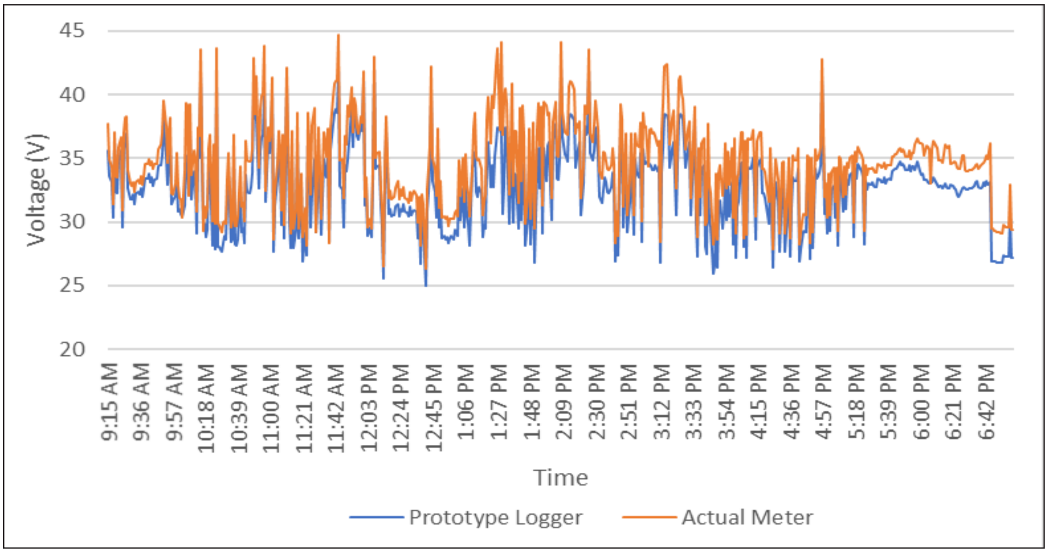

Figure 12. Prototype logger and actual energy meter voltage output over time

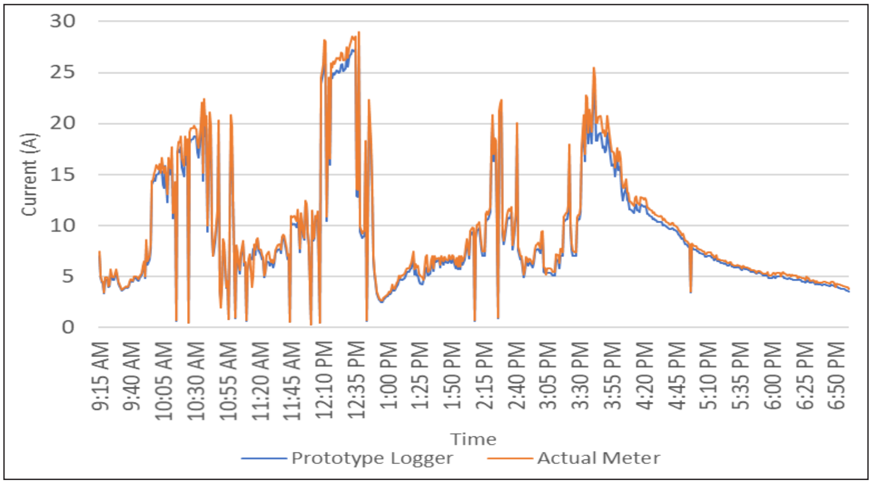

Figure 13. Prototype logger and actual energy meter current output over time

Figure 14 shows the power and cumulative energy in Watt *(W)* & Watt-hour *(Wh)* from prototype and energy meter data. Based on the observation, logged data of the voltage and current characteristic on the prototype logger compared to the actual energy meter is not much different. The deviation calculated was at 0.574% for voltage and 0.531% for current, which is tolerable for standard instrument measurement. Minimizing the voltage divider resistor error tolerance and larger range of ADC bit is suggested to get a more precise value. For the ACS756 current sensor, the error can be reduced more by fine-tuning the constant value in the programming code to match the floating voltage sensitivity due to environmental conditions.

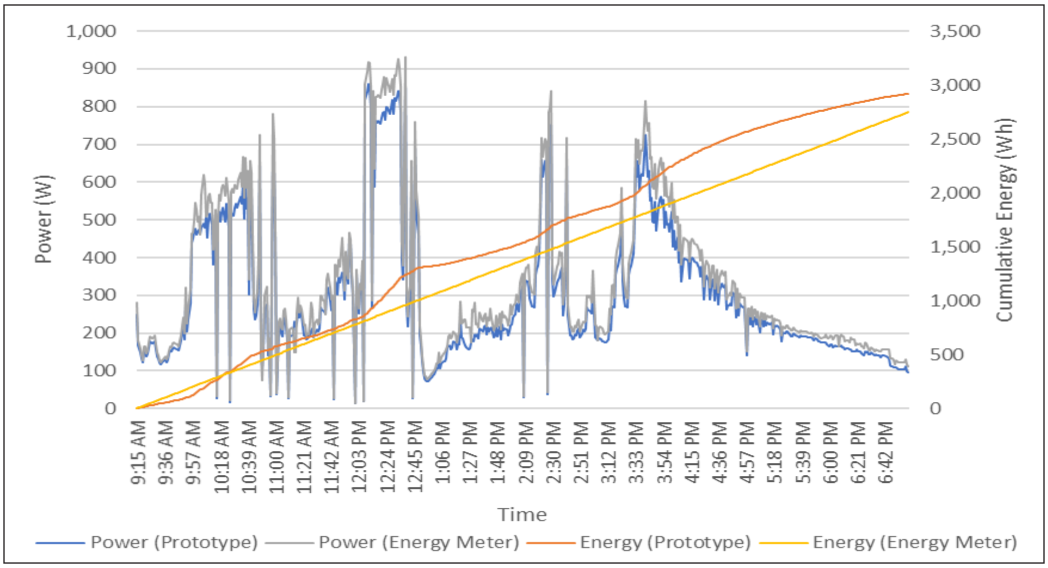

Figure 14. Power and Energy output file from both prototype logger and commercial energy meter.

CONCLUSION

In this article, a microcontroller-based DC energy data logger has been developed using a low-cost ATmega328 microcontroller by measuring the PV system DC and voltage characteristics while simultaneously logging the measured data over time to calculate the energy production in watt-hour (*Wh*). The prototype logger has effectively proven recording and actual DC voltage, current, and power generation on a live one kWp $24V_{DC}$ standalone PV system continuously for a period required. The prototype logger can be reproduced for other DC application energy measurements and easily modified to a larger voltage and current range to suit the application by adjusting the voltage divider circuit and replacing the current sensor module with a higher current limit type. The measured value has been verified using the manual calibration method by comparing the recorded data with the standard laboratory digital multimeter. The error is minimized to ±0.6% average by varying the constant float value in the programming code. The advantage of this logger is that the hardware cost was much cheaper than the standard commercial PV logger, and apart from that, this logger also provides high accuracy performance. Its independent characteristic is very relevant for standalone or off-grid PV system use. Improvement, such as combination with GSM, Bluetooth, or WiFi module for wireless data acquisition (DAQ) and graphical user interface (GUI) development, is being considered for commercialization.

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