Design of a Photovoltaic System for a House in Pakistan and its Open Source Ultra-low Power Data Logger and Controller

By

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Abstract

This thesis presents an open-source, ultra-low powered data-logger for off-grid photovoltaic (PV) applications. An off-grid PV energy system is also designed for a rural house in Pakistan. The real-life power consumption data of this house is collected for the design and simulation purpose. The expected annual output energy of designed system is calculated by using Homer Pro software. Annual solar irradiance, average temperature and other environmental aspects are also considered for simulation of the designed system in Homer Pro. The data-logger is designed to log major parameters of designed PV energy system. Deep-sleep mode of ESP32-S2 microcontroller is used along with voltage, current, and light sensors for logging the data of PV system in an external micro SD card. Data-logger is programmed to operate in deep-sleep and web-portal monitoring modes and a manual or automatic switch is used to select these modes. Real-time PV data can be monitored in a local web-portal programmed in the microcontroller only by switching the toggle switch to on position. The same web-portal is also used to check and download the historical data of a PV system. The energy consumption of the designed system is 7.33mWh during deep-sleep mode and 425mWh during the web-portal monitoring mode. The total cost of the designed data-logger is approximately 30 CAD.

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List of Abbreviations

AC	Alternating Current
ADC	Analog to Digital Converter
CSV	Comma Separated Values
DAQ	Data Acquisition
DC	Direct Current
FSK	Frequency Shift Key
GPIO	General Purpose Input Output
GSM	Global System for Mobile communication
GUI	Graphical User Interface
HTTP	Hyper Text Transfer protocol
HTTP	Hyper Text Markup Language
IDE	Integrated Development Environment
IEA	International Energy Agency
IEC	International Electrotechnical Commission

IoT	Internet of Things
IP	Internet Protocol
LAN	Local Area Network
LCD	Liquid Crystal Display
MCU	Microcontroller Unit
MPLF	MaxPower Low Frequency
MPPT	Maximum Power Point Tracker
MQTT	Message Queuing Telemetry Transfer
PC	Personal Computer
PV	Photovoltaic
RFID	Radio Frequency Identification
RTU	Remote Terminal Unit
SCADA	Supervisory control and data acquisition
SD	Secure Digital
SMTP	Simple Mail Transfer Protocol
SPI	Serial Peripheral Interface

SQL	Structured Query Language
SUN	Smart Utility Network
UART	Universal Asynchronous Receiver-Transmitter
UL	Underwriter Laboratories
VRLA	Polymer-Gel Valve-Regulated Lead Acid
WPMM	Wireless PV Monitoring Module

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1- Introduction

Global energy demand is increasing rapidly due to the high rate of technological advancement and population growth. Electrical power is an essential component for economic growth of a country because modern civilizations, agricultural advancements and industrial expansions are totally dependent on available energy resources. U.S Energy Information Administration (EIA) has predicted that global energy consumption will increase by 50% during 2018 to 2050. All this impact will increase the overall global energy consumption from 608 quadrillion British thermal units (btu) in 2018 to 911 quadrillions Btu by 2050 [1]. This increasing demand of energy is leading towards environmental hazards because major portion of the energy is generally produced by burning the fossil fuel. Figure 1.1 shows the world energy consumption from the year 2010 to 2050. Fossil fuels are non-renewable energy resources and available in limited quantity. At the current consumption rate of fossil fuels, oil reserves will run out in 40 years and gas will not be available after 60 years. Excessive use and environmental impact of using fossil fuel are forcing the society to develop new technologies for producing clean electrical energy from renewable sources such as solar energy, wind energy, biomass energy, hydro energy and geothermal energy [2].

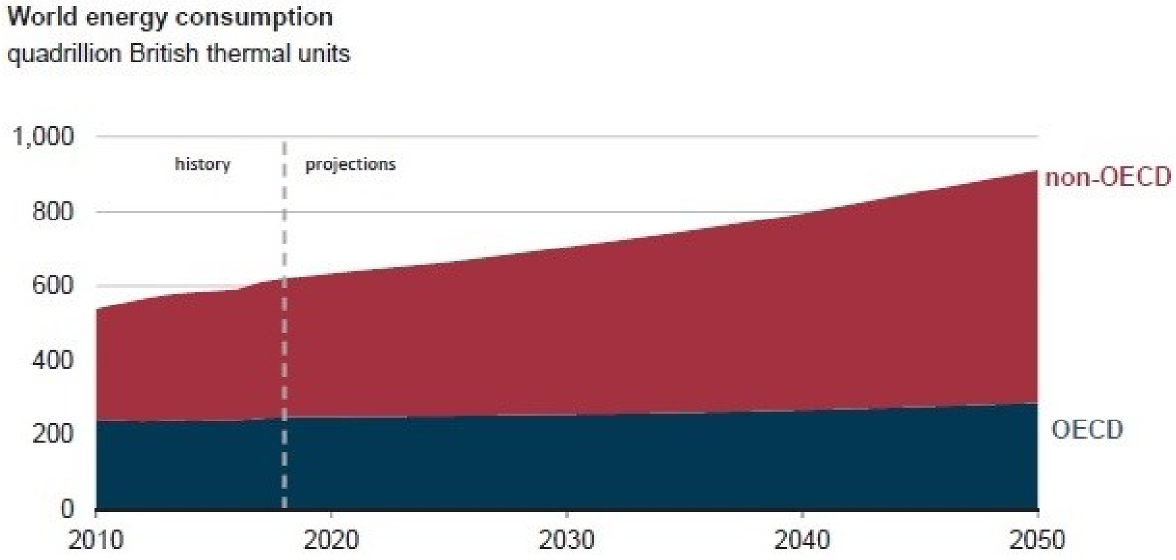


Figure 1.1: World Energy Consumption [1]

Massive investment and infrastructure is required to increase overall capacity of generation plants and utility companies are not willing to invest because the maximum capacity of this upgraded plant will only be utilized in peak time. Most of the consumers are dragged to invest in fuel generators and battery storage systems which inversely affect the economic growth of the country [3].

Renewable energy resources can provide carbon free energy but there are some reservations in adopting these technologies within centralized electrical power system, such as extraordinary initial cost for mega plants, instability due to environmental dependability, location limitations and low efficiency. Centralized electrical power systems also involve high cost of transmission lines, transmission losses and electrical potential conversion losses which pushed the policy makers and electric supply companies to implement the concept of distributed energy systems. Locally installed micro renewable energy systems can easily be synchronized with the centralized electrical power system by the development of micro-grids and all major challenges in adopting renewable energy systems can be resolved by this technology [4].

Hydro and wind energy has a major share in present renewable energy market but solar photovoltaic system is most commonly used for residential applications. Photovoltaic is all about the conversion of solar radiations to electricity by using a semiconductor material. Solar photovoltaic system is usually installed in modular form so it can be modified as per the future load variations. Solar photovoltaic is one of the rapidly growing renewable energy sources and the total installed capacity of global solar energy systems reached about 300 GW by the end of 2016 [5]. The growth factor of the installed capacity of solar energy systems was more than 50 since 2000 and it is increasing day by day. The potential energy of solar is 174 petawatts and only 60% of this energy reaches to earth's surface and rest 40 percent reflects back to the atmosphere. Converting only 0.1% of this energy at 10% efficiency can provide 4 times extra energy as compared to the present global energy consumption [5].

Photovoltaic (PV) is the conversion of solar radiations into electricity using semiconducting materials through photovoltaic effect. A photovoltaic system uses solar modules, each constructed by a number of solar cells, which generate electrical power. PV installations can be ground-mounted type, rooftop mounted type, wall mounted or floating type. The mount may be fixed, or use a mechanical solar tracker to follow the sun throughput the day to harvest maximum energy. Solar maximum power point tracking can be based on a single axis (e.g. to follow sun during the course of the day), or two axis (to also adjust the angle of declination for the time of year) [6]. Solar photovoltaic panel is the most important part of solar PV power system and solar panel is a packaged, connected assembly of PV solar cells available in different voltages and wattages. Most commercial solar panels are produced from crystalline silicon (c-Si) solar cells. Monocrystalline solar panels, polycrystalline solar panels and amorphous solar panels are three basic types of solar panels in the market [7].

The basic difference in these panels is their output efficiency. Solar radiation has an energy capacity of 1000 W/m^2 which is called solar constant and output efficiency of a solar panel means that how much energy the specific solar panel can generate out of this solar constant. Presently, monocrystalline are considered more efficient than polycrystalline and amorphous, then polycrystalline and amorphous are at the end in terms of efficiency. Selection of solar panels is mostly carried out as per the availability of space or area for the installation. Monocrystalline are mostly used in roof-top installations due to their higher ability to generate more power in lesser area [8].

More than 100 countries are using solar photovoltaic including China, Japan and the United States. Germany has the world's largest solar photovoltaic installations and getting more than 7% to its national electricity demands from solar power. Solar is one of the most significant renewable sources and has the highest potential to provide a carbon free source of energy. PV systems have long been used in specialized applications as off-grid or stand-alone systems but grid-connected PV systems are used since last few decades. Off-grid systems are suitable for remote areas where grid supply is not available. Appliances connected to the stand-alone system can be designed for DC source to reduce the overall costing of the system and inverter loses as well. On the other hand, grid-tied solar PV system can be synchronized with the utility grid and extra power generated from this system can be provided to the main grid through net-metering system. Presently, the most common installation type of solar PV system is Grid-tied because they can act as micro-grids to provide the extra energy back to the main utility grid. Solar PV modules were first mass-produced back in 2000, when German environmentalists and the Euro-solar organization got funding from government for a ten thousand grid-tied roof solar installation program [9].

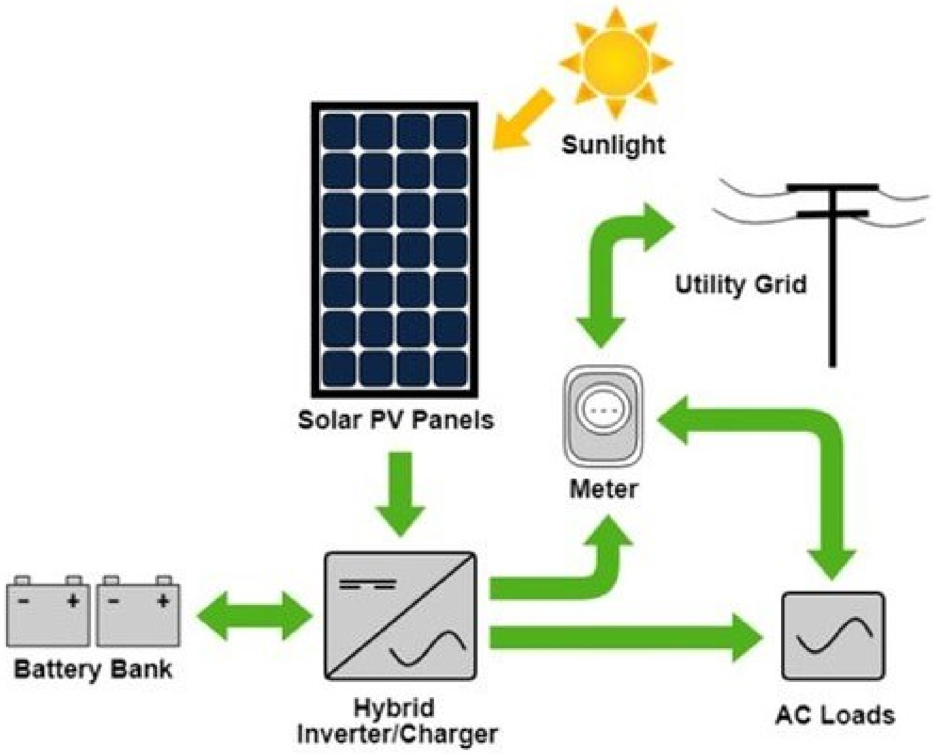


Figure 1.2: Solar Photovoltaic with Reverse Metering System [9]

Figure 1.2 shows a general layout of a grid-tied solar PV systems. Grid-tied solar PV systems are good for urban areas where over 20% of the population doesn't have the access to electricity. Many more in rural areas of developing countries have access to only a limited amount of electricity and they have to face power outage problems regularly. Presently, more than 900 billion people are suffering with the lack of electricity [10].

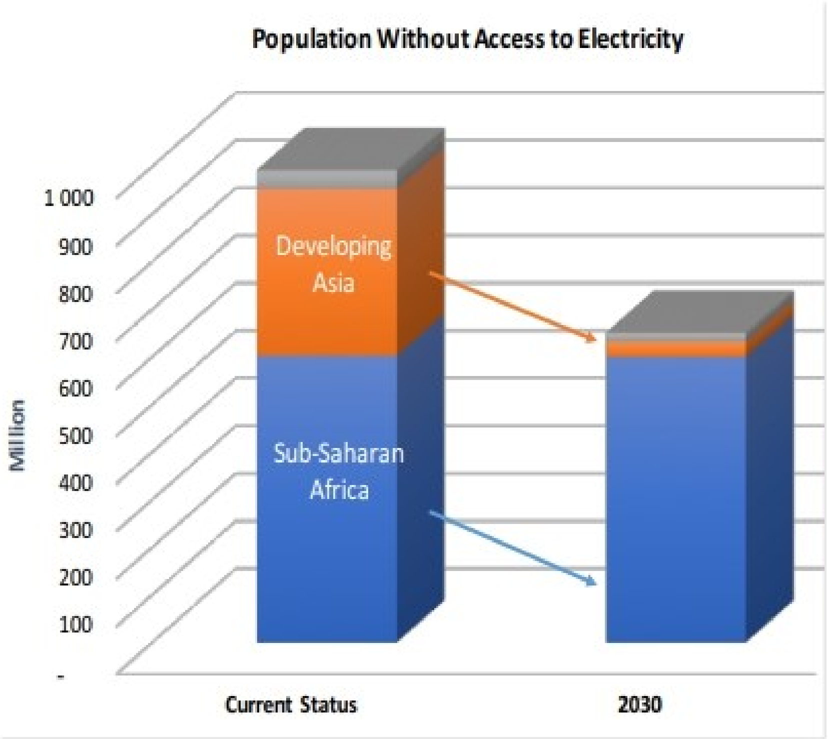


Figure 1.3: People without access to electricity [10]

As per a report by International Energy Agency (IEA), 0.6 billion people will still be facing this problem at the end of 2030 unless there are some disruptive changes in electrification policies. Basic healthcare and education systems are also dependent on electricity so these communities have to face a poor living standard without access to electricity [10].

Stand-alone solar PV system can be a good solution for the electrification of these remote areas. Installation of stand-alone solar PV units is increasing because many communities are adopting this technology to overcome energy crises in remote areas [10]. Stand-alone solar power unit consists of solar panels, batteries, charge controller and DC to AC inverter. Fuel generators are mostly used in stand-alone solar power installations for emergency backup. Solar panels provide electricity to all appliances and also charge the batteries in day time. This system generally produces low electricity in cloudy weather and can't fully charge the batteries. A backup generator then operates to fulfil the power requirements of that remote user. Figure 1.4 shows a general layout of stand-alone solar power unit.

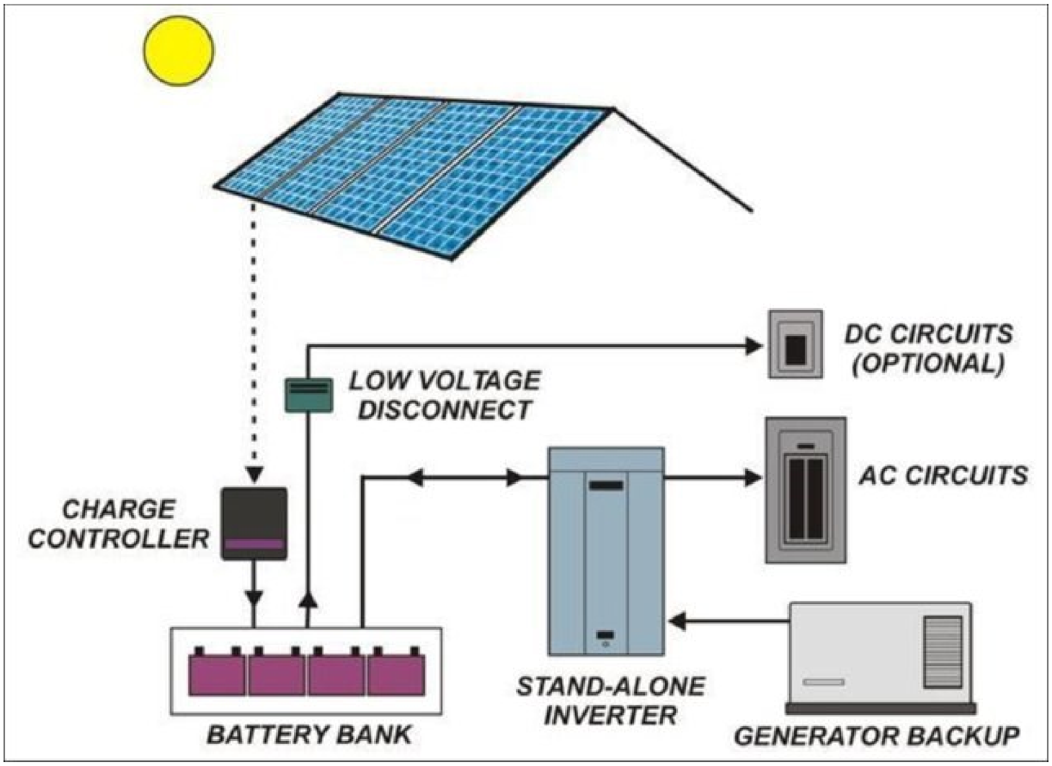


Figure 1.4: Stand-alone solar power unit [42]

Stand-alone solar PV energy units are getting famous now a days and many of research groups are working to improve this technology. Collecting the system behavior data can be used for the improvement of the system. This thesis designs an open source ultra-low power data logger and controller for a PV system. The proposed data logger constantly records all important parameters including energy, light intensity and temperature of a stand-alone PV system without consuming much energy from the system.

1.2- Literature Review

The environmental impact of energy production and consumption from fossil fuels has transferred the focus of governments and researchers towards improving the efficiency of renewable energy technologies to fulfil the globally increasing energy demands. PV energy generation is increasing significantly and considered as the most promising and consistent source of alternate energy. Capital cost of solar power units is comparatively higher than other conventional sources and maximizing the effectiveness of these plants has become more important to compete with the present energy market. Maximization of efficiency and reliability of renewable energy resources can be achieved through constant monitoring of these energy units. Monitoring and data logging the efficiency of solar PV power units allows the operator to evaluate and improve the overall performance of the system. There are many data logging and monitoring solutions available in market by PV inverter manufacturers for grid-tied and larger PV units but most of them are expensive, complicated and only compatible with their own inverters. Commercial data monitoring devices for smaller and stand-alone PV units are hard to find so researchers are constantly developing several products to find a low cost and reliable solution for this remotely installed PV units.

Some of the research projects are reviewed as following to discover the objective and goal for the development of a new open source ultra-low-power data logger and control system which can operate without any internet connection for a remotely installed stand-alone solar PV unit.

1.2.1- Research Based Systems

Researchers have been working on photovoltaic data loggers since a long time. The author has proposed a data logging system for solar powered street light in [11] using voltage sensor, current sensor and battery control unit to record the data of solar PV production and battery charge capacity by using ATmega328 microcontroller. All data is stored in local SD card after every minute which can be extracted by using a computer for monitoring and analysis purpose. This is a simple and low cost data logging solution to monitor basic data of a solar street light and this data can be used to improve the maintenance and design quality of a solar powered street light.

A monitoring and data logging systems is developed in [12] by using a microcontroller and a single-board computer. This data logger is specifically designed for an off-grid solar photovoltaic unit installed in a remote house. Current sensor and voltage divider are used to detect current and voltage of the system and this all data is processed by STM32 microcontroller. A Linux based single-board computer receives the data from STM32 and transmit it to a remote server through internet after every five minutes. This single-board computer can also store the data to its local SQL database in case of internet connection failure. This data logger is suitable for monitoring the important parameters of the small solar system with maximum current up to 25 A and voltages up to 55 V and also it is very suitable for performance analysis and fault detection of remotely installed off-grid solar PV units.

Work presented in [13] introduces a PV analyzer with lower manufacturing cost by using voltage sensor, current sensor, temperature sensor, variable rheostat and Arduino UNO. The Arduino UNO gets the data from all sensors and transfers it to a locally installed computer, where Parallax Data Acquisition tool is used to log the data in excel sheet. This analyzer logs the power output of a solar PV unit and also records the parameters that affect the performance of the system like temperature and humidity. The measurement accuracy of this analyzer is almost equal to a good quality millimeter. As per the author, Total cost of this analyzer is 22 CAD which doesn't include the cost of the computer.

[14] designed and installed a solar PV data logger based on a free software and hardware as an experimental prototype in various remote sites. This data logger measures 14 parameters of a stand-alone solar PV unit and stores it to a cloud space using 3G technology. This monitoring system allows user to check the performance of the solar PV unit remotely by using web or mobile application because data logger is always connected to the cloud with the help of IoT based Arduino Ethernet controller. Data logger also meets the measurement accuracy standard described by international electro-technical

commission IEC61724. All measured data is stored in local MySQL database which is hosted in a server located in the University of Jaén and in an open source IoT analytics platform service ThingsSpeak that allows inserting, visualizing and analyzing live data streams in the cloud. Total cost of this IoT based data logger is 200 CAD and this system also has to bear a regular cost for 3G connection.

A low-cost data logger for stand-alone photovoltaic unit is presented in [15]. This data logger is capable of measuring major electrical and meteorological parameters of PV system and logging all parameters in local SD card. This data logger measures all parameters with very high accuracy and meets the accuracy requirements defined by international electro-technical commission (IEC61724). Arduino UNO is used to measure all feedbacks from sensors and log required data in a local memory card. This data logger is specially designed for remote locations and don't require any telecommunication network or maintenance. This data logger has been tested under natural environment. The cost of final developed data logger is 116 CAD which is very low as compared to other commercially available data loggers for PV installations.

[16] introduces the integration of Internet of IoT to improve the solar measurement systems for small off-grid solar PV units. Arduino UNO microcontroller is used to collect data from all sensors and store this data to an open source cloud based IoT platform called ThingSpeak. All required real time or historical parameters of Solar PV system can be viewed remotely by using an open source smartphone's application called "Things View".

This data logger also fulfils the requirements of IEC61724 with a measurement accuracy of above 98%.

In [17], the author has used Raspberry Pi microcontroller to develop a low cost monitoring system to monitor the real-time parameters of a small standalone solar PV system. The designed monitoring system can extract, store and display the real-time parameters including voltage, current and ambient temperature of a solar PV system. The author used voltage divider to detect voltages, current sensor (ACS712 – 30A) to measure current and a temperature sensor (LM35) to measure the value of ambient temperature. All the analog data from sensors is converted to digital by using an analog to digital converter (MCP3008) between sensors and Raspberry Pi microcontroller. A graphical user interface (GUI) is designed by using Node.js software in a computer for graphical representation of real-time data from all the sensors. The real-time data from this monitoring system can be used for solar PV analysis and this remote-monitoring system can also be used for bigger Solar PV projects after some modifications.

The author developed a Labview based monitoring system for grid connected solar PV system in [18]. The author used current and voltage sensors to collect data of solar PV system and then converted this data to 0-10 V signals with the help of an electronic measurement card. Developed PV monitoring system also consists of electronic measurement circuits, solid-state relays as circuit breakers, Labview data acquisition card for data-logging, monitoring and controlling of the system. Analog input data acquisition (DAQ) card NL USB-6221 is receiving the analog signals from electronic measurement circuit and transmitting to computer. Data logging and monitoring interface is designed with the help of Labview software to collect all major parameters of grid connected PV system including solar PV voltage, solar PV current, grid voltage, grid current, grid frequency, load current and load power. The author obtained all experimental results by installing this monitoring system on a 1.2 kW grid connected solar PV system. Results show real-time data of solar PV unit but the computer must be powered-on all over the time to log continuous data of installed system.

Author designed electronic monitoring and data-logging system in [19]. The deigned system can be used to monitor individual PV module in a PV power plant and it can provide all electric parameters of each PV modules down to the cell sub-string level. This monitoring and data-logging can help in detection of failure modes and the estimation of PV degradation with the passage of time. The author used two processors in this system. One of them is dedicated for data acquisition and the other is used for the communication of the data to remote monitoring platform. This system records many parameters of the PV module including current, voltage, PV module temperature and environmental parameters. The sampling rate of data acquisition is adjustable from 1 to 65 s for each parameter. Author used current, voltage and temperature sensors to get all required parameters and compared them with expected output of solar panels to estimate the degradation of solar panel. Communication processor is gets data from data acquisition processor through RS-485 protocol and transmit this data using Bluetooth protocol to nearby monitoring system. Author has also used radio frequency module for long-range data transmission. The designed system can use the IoT features by developing the existing firmware and further improving the functionalities.

In [20], the author has developed a cost-effective wireless PV monitoring module (WPMM) which can be used to monitor the parameters of each solar panel in a large solar PV system. Author has proposed a method to connect PV monitoring module to each solar panel in solar power system and connect all these modules to a RTU by using frequency shift key (FSK) method. This RTU collects the data from all PV monitoring modules and transmit this data to a centralized data-logger. Author used a PC and smart phone to monitor the solar PV data from data logger. PV monitoring module consists of a shunt resistor for current monitoring, a voltage divider circuit for voltage monitoring, an analog to digital converter for signal conversion, a power generation circuit to directly power-up the module by using PV energy and a communication module for the transmission of collected data to remote terminal unit (RTU). Author used 8051 d microcontroller unit to achieve cost effective solution for analog to digital conversion and wireless communication. This study described the implementation method of the wireless PV monitoring module for PV monitoring at panel level to achieve the cost-effective solution and good performance.

The author in [21] used IoT technology to develop PV monitoring system for solar power generation unit. This research shows that it is possible to develop an efficient IoT based PV monitoring system at low cost. Author used an inexpensive Raspberry pi hardware to develop IoT gateway and adopted the Message Queuing Telemetry Transfer (MQTT) protocol at IoT gateway and smart phone. This PV monitoring system is using PV end node to collect energy data from each solar panel including output voltage, output current and PV temperature. All collected data is shared with IoT gateway through smart utility network (SUN) communication network. A Raspberry pi hardware is used as IoT gateway including MQTT broker module and MQTT publisher module. The MQTT broker module is responsible for registration management and data transmission between a publisher and a subscriber. The MQTT Publish module is used for the actual PV monitoring data collection and this data collection is done by periodic requests of data transmission to PV end node. The user can easily monitor the PV data remotely by logging into MQTT publisher platform developed by author.

Authors in [22] developed an IoT based PV monitoring system using battery less Radio-frequency identification technology (RFID) for remote monitoring of temperature of PV cells and their health state. In this research paper, the developed PV monitoring solution is used for real-time measuring the temperature of the hot spots of PV cells and sending the measured data over the net using a Simple Mail Transfer Protocol (SMTP) to central data-logging and monitoring stations for proper action in case of abnormalities such as over-temperature of solar cells. The basic components of this system are RFID tag Gen2 with embedded temperature sensor, RFID reader with transmit power 500 mw, Middleware, MySQL database and SMTP email server for sending email alerts on hotspots. Author used RFID based temperature sensors to detect the temperature of each PV module. The collected data is then transmitted to a databased developed on cloud technology with the help of reader and middleware. The designed system showed excellent results in terms of early detection of PV overheat and prompt transmission of alerts.

In [23] the author used ATMega16 microcontroller for monitoring and controlling of a solar PV system. Major components of this system are current sensors, AVR microcontroller ATMega16, TTL to USB converter module and computer. In this system, the author used current and voltage sensors to collect power flow data in microcontroller and operated two relays to control the power flow of solar panels towards load and battery. All collected data is transmitted to a local computer by using TTL to USB converter. MATLAB software is installed in this computer for monitoring and data-logging purpose. Microcontroller also shows the power consumption data at a locally installed LCD. The designed system is tested on 25 Watts solar panels and the self-consumption of this system is much more than the output power of solar panels.

Author of [24] designed a cost-effective online wireless monitoring system for domestic solar PV generators. The designed PV monitoring system provides online wireless monitoring for important performance and controlling parameters of a standalone solar PV system including solar irradiance, ambient temperature, the PV surface temperature, output power, the battery charge level, and PV surface status. The basic components of this system are current sensor, voltage sensor, ambient temperature sensor, irradiance sensor, camera, Arduino microcontroller, wireless transceiver (WiFi module), router and a computer for remote monitoring. Microcontroller collects all the data from sensors and transmit it to a remotely installed monitoring platform with the help of wireless module and router. The camera is equipped with its own wifi connection and connected directly to the router to reduce the processing time. The router acts as an access point and any computer connected with this router can view all energy data and images. The designed system has a web-based display to provide the efficiency, output power, nominal power, power variation plot, battery charge level, nominal battery level, and a picture of the PV panels. The motive of this study is provide all energy parameters and health status of solar PV generators to the user.

Author in [25] developed an IoT based remote real-time energy monitoring system to monitor the basic parameters of solar power generator. The basic components of this system are voltage sensor, current sensor, Arduino UNO, ESP8266 module, cloud database and web-based monitoring platform. Experimental setup is installed on an 80 Watts solar panel under standard test conditions for testing purpose. Voltage and current sensors are used to collect the output of photovoltaic module and the output signal from sensors is converted from analog to digital with the help of ADC port of microcontroller (Arduino UNO). ESP 8266 is collecting this accumulated data from microcontroller and transmitting it to cloud database. An open source IoT application things board is used to store and retrieve data from hardware setup using the HTTP protocol over the Internet. The energy data of PV panel including current, voltage and power can be monitored globally with the help of this monitoring system. The results show very small error between local and online monitored parameters. This PV monitoring system helps in continuous remote monitoring of basic parameters of a solar panel and results in improved efficiency of the power plants.

Another low-cost IoT based solar PV monitoring system is introduced in [26]. The basic components of this system are voltage transducer, Hall Effect current sensor, temperature sensor LM35, SIM900A GPRS module and Arduino Uno microcontroller. MATLAB software is used for the development of programming codes and a web-based design is used for visualization of collected data. Voltage is sensed by using voltage divider circuit, hall-effect sensor is used to measure the current and LM35 is used to get temperature of solar panels. The data collected by all sensors is processed by using Arduino Uno microcontroller and sent to SIM 900 GSM module through serial communication. The GSM module sends all collected data to a remotely installed dedicated computer system through internet. This computer is programmed to store all data for future reference and review. This stored data can also be viewed anywhere using internet connection on an IP setup by the GSM module. The designed system can measure and store the output voltage, output current and ambient temperature of PV module. User can also perform comparison of data with previous database and reference values. This PV monitoring system can also send SMS alters in case of any fault or abnormal behavior of solar PV generator.

Allafi and T. Iqbal presents a small PV power system monitoring and data collection system in [27]. The author designed a web server based on ESP32 which can monitor PV current, battery current and PV voltage and battery voltage data. This system is designed with the help of low-cost sensors, a microcontroller ESp32, wifi and an SD card reader. ESP32 collects energy data from sensors and saves it as text file in SD-card. The text file is saved only for a week and microcontroller updates all data with the new one after this time. The web server is designed in ESP32 and stored in SD card so the user can easily access the web page file via a laptop, cellphone, or tablet by using wifi connection. There is an option in web page to download stored data and the user can easily download the stored data in text file through that option in web page. This web page can also be accessed remotely by using internet and results show that the web server delivers the real time data and can be used for the monitoring of a small solar energy system.

In [28], authors describe the development of a microcontroller-based photovoltaic energy data-logger using a low-cost ATmega328 microcontroller. The developed system can measure and log the voltage and current of PV system to calculate the energy generated by the system over specific time. The designed system has been installed on a 1 kWp standalone solar power system for testing purpose. The voltage sensor in designed system can measure the DC voltage rage of 0-50 V using a voltage divider circuit and a hall-effect sensor ACS756 is used to measure the output current upto 50 A. All measured data is stored in comma-separated values (CSV) format which can be viewed in MS Excel software. Author has also designed a local LCD to show the real time values of voltage, current, power and time stamps of data-logging. Authors also compared all measured data with a digital multi-meter for calibration and adjusted the measurements as per the output of multi-meter to get zero error in readings. All measured data is stored in an SD card in CSV format with a name of “datalog” which can easily be extracted by using any laptop or computer. The designed data-logger is very suitable for standalone PV applications.

Authors in [29] designed a data-logging and monitoring system for a 1.6 kWp single-phase grid-connected solar Photovoltaic system. Author used voltage sensor for output voltage measurement, current sensor for output current measurement, microcontroller Arduino Uno for data processing, real time clock, internal memory for data storage, telemetry 3DR radio and computer interface for online monitoring. A smart application on a local computer is developed to show the graphical trends of collected and logged data. Author has also developed a local LCD to show real-time output measurements of operational solar power unit. The designed system is installed on an existing 1.6 kWp grid-tied solar power unit for testing purpose and calibrated with the help of class 0.2 standard laboratory instrumentation. The designed data logger successfully measured and logged the current, voltage and power data for one week testing period and user was able to determine the efficiency of solar power system with the help of this data-logging and monitoring system.

In [30], authors explained different methods to develop low-cost data acquisition and storage systems for PV energy systems. The data-loggers discussed and developed in this study are data-logger using Arduino excel, data-logger using node MCU and data-logger using Ethernet shield. Author used voltage sensor for output voltage measurements and hall-effect sensor ACS712 for current measurements for all types of data-loggers. Arduino Excel based data-logger is developed by using a computer, Data acquisition circuits which consists of Arduino, sensors, and software named “Robert Valgolio”. Arduino collects data from sensors and stores it in internal memory. Rebert Valgolio software is used to extract this data from Arduino with the help of USB cable. The node MCU based data-logger uses node MCU and ESP8266 for data acquisition and transmission. Node MCU collects data from sensors and transmit it to ESP8266 using 12C/UART communication. ESP8266 is equipped with wifi so it is used to transmit this data to online cloud database. This data-logger is designed by using IoT technology and stored data can be monitored remotely by using web-based monitoring technique. In Ethernet shield based data-logger, the author used XAMMP server to build database and Arduino shield is used to collect and transfer data to database through local Ethernet connection. A webpage is also developed to monitor this data remotely from any point of time. Author claims that all three types are less expensive types of data-loggers for PV systems and data-logger with Arduino shield and WiFi module is the least expensive among these three types.

1.2.2- Result of Literature Review

In the light of literature review in previous section, it is evident that researchers are working to improve the data logging and monitoring systems for PV systems. There are many systems which required data communication wire to extract data from data-logger and some of the data-logging systems can communicate wirelessly to the user for data extraction. RS232, RS485 and Ethernet are the common communication protocols in wired data-logging systems. WiFi and Bluetooth are used for wireless communication in some data-loggers. Most of the data-loggers are designed only for local access but some of them and using IoT technology and can be accessed remotely through internet. Local LCD, webpages, desktop applications and mobile applications are mostly used to display data in data-logging systems.

Self-power consumption of data-logging system increases by adding more and more features in the system. As per the previous literature review, we can say that the focus of most of the researchers is to provide technological advancements in data-logging and monitoring systems for PV energy units. This advancement leads to the addition of more components in the system, leading towards the extra power consumption of the system itself. Some of the authors have also discussed this issue and tried to reduce the power consumption of data-logging and monitoring systems. As we know that solar PV systems are normally installed at remote location and have a limited energy capacity, so reducing the power consumption of a data-logging and monitoring system for PV energy unit can be supportive in this field.

1.3- Research Objectives

This research work introduces an open source ultra-low power data logger and controller for a PV system to overcome the extra power consumption of previously developed data-logging and monitoring systems. Followings are the basic objects of this thesis.

1.3.1- Literature Review

In this section, the literature review of previously developed PV data-logging and monitoring systems will be carried out which will help to understand the previous research work in this field. This literature review will also show the gaps in PV data logging and monitoring systems.

1.3.2- Grid-tied Solar PV System Design for a House

In this section, a sample house will be selected for the designing of grid tied solar PV system with battery backup. Load calculation of the house will help to get the exact size of the required PV system. A house in rural area of Pakistan will be selected for this purpose. The designed system will also provide a robust solution against extensive Load shedding in rural areas of Pakistan.

1.3.3- Designing of PV Data-Logger

An ultra-low powered data-logger for PV energy units will be designed to log the power generation and consumption data of any solar PV unit. Ultra low power mode of a latest microcontroller ESP32-S2 will be used for this purpose. The designed data-logger will be able to locally store basic parameters of solar PV unit and user will be able to extract that data by connecting through WiFi or cable.

1.3.4- Designing of Data-Extracting Platform

A web-based platform will be designed to extract all logged data in microcontroller. This platform will help the user to access all logged data wirelessly or through wire connection to microcontroller. User will also have the option to reset all data with the help of this platform.

1.3.5- Results and Conclusions

As the main motive of this research is to develop an ultra-low powered data-logger for PV system so the power consumption of the designed system will be measures and compared to the previously developed systems. Results will also include the data logging samples of the designed system.

CHAPTER 2: DESIGN AND SIMULATION OF SOLAR PV SYSTEM FOR A RURAL HOUSE

2.1- Site Description

Pakistan is a developing country and its energy demand is increasing with rapid growth of population. Presently, the demand of electricity in Pakistan is higher than its production capacity and country is facing load shedding in different areas. The most affected areas of the country are rural areas, which are facing more than 10 hours electricity outage per day. The designing and simulation of a grid-connected solar PV system for a house in a village of Pakistan is being done in this chapter. The selected location is facing almost 10 hours of load shedding daily so a battery backup is also designed to keep system operational in the absence of grid power. Figure 2.1 shows the aerial view of selected location and red marking indicates the roof of the house.

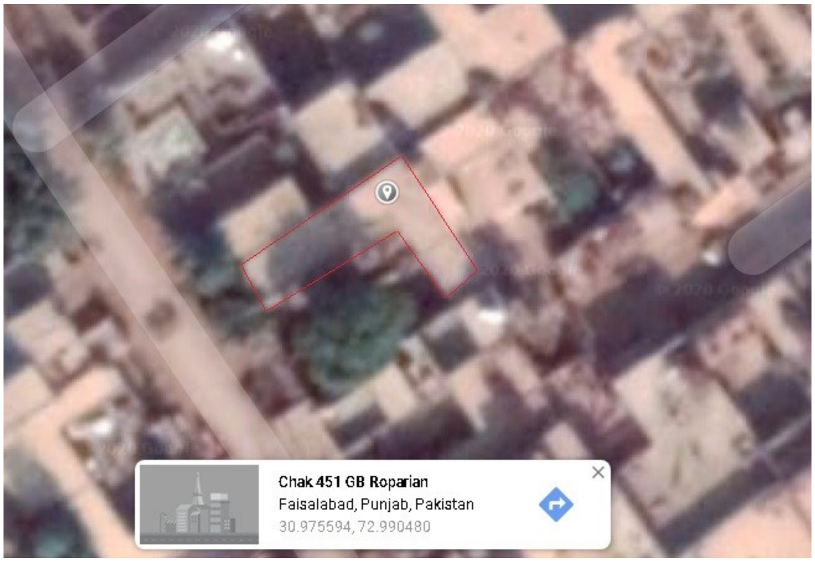


Figure 2.1: Site location

This house consists of 2 bedrooms, 1 drawing room and 1 kitchen. Total covered area of this house is almost 3,000 square feet. Total electric appliances in the house are 3 ceiling fans, 6 LED lights, 1 water pump and 1 television. The of villagers of Pakistan are living very simple life and they mostly use natural resources in daily life like fresh water, daylight and tree shades. There are total 7 family members living in the house. As per the electricity bill of the house, average monthly electricity consumption of this house is 40 kWh. The electricity consumption is higher in summer due to the use of ceiling fans. Figure 2.2 shows the monthly electric power consumption of the house for one year.

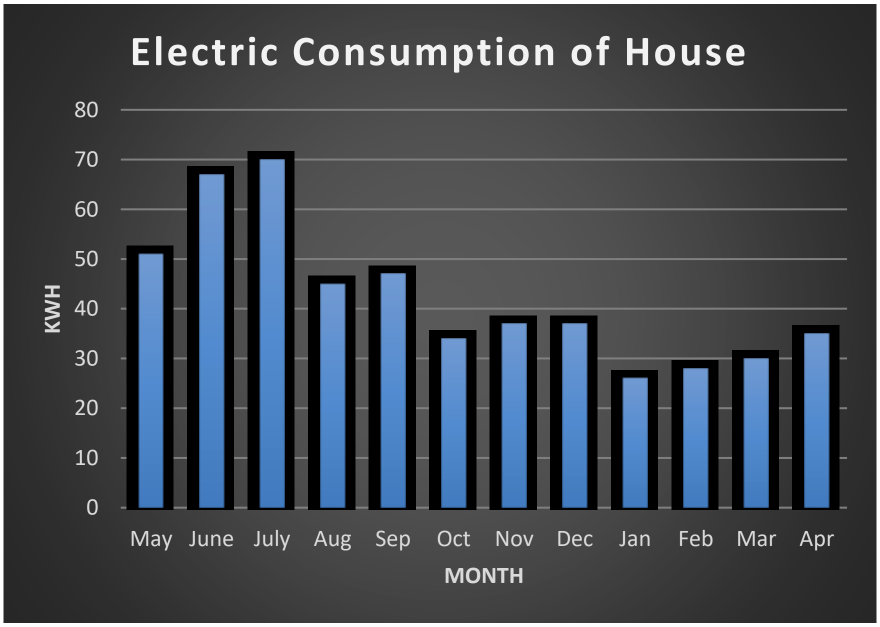


Figure 2.2: Monthly electric consumption of the house

May, June and July are peak months of summer so electric consumption is high for these months due to the use of electric fans. All the appliances are operating at 220 VAC. This site has a good potential for solar energy with an average annual solar irradiance of 5.27 kWh/m^2/day as shown in the figure 2.3.

Choose Data Source: ● Enter monthly averages ○ Import from a time series data file or the library

Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.607	3.496
Feb	0.619	4.357
Mar	0.601	5.239
Apr	0.597	6.097
May	0.608	6.770
Jun	0.602	6.890
Jul	0.576	6.470
Aug	0.610	6.372
Sep	0.634	5.774
Oct	0.665	4.939
Nov	0.632	3.785
Dec	0.574	3.075

Annual Average (kWh/m²/day): 5.27

Downloaded at 6/25/2020 10:50:07 PM from:
National Renewable Energy Lab database.
National Solar Radiation Database
CellNumber: 321131
CellDimensions: 40km x 40km
CellMidpointLatitude: 31.046
CellMidpointLongitude: 72.799

Scaled Annual Average (kWh/m²/da 5.27

Figure 2.3: Solar Irradiance data of site

The solar irradiance data is extracted by using Homer pro software at exact location of the site. Homer pro uses the database of National Renewable Energy Lab. The average annual temperature of selected site 24.18 °C which is also being calculated by using homer pro software as shown in Figure 2.4.

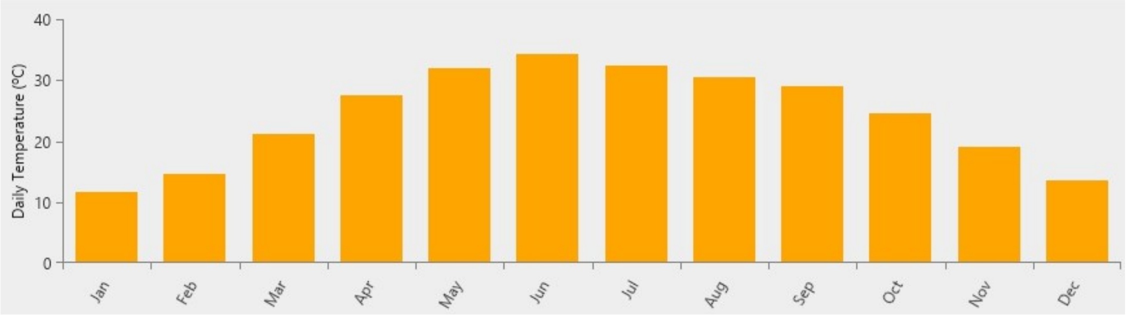


Figure 2.4: Average temperature of the site

2.2- Solar PV System Design

The selected house has a very small electric load and also located in a region where solar energy is widely available throughout the day so most suitable solar PV system for this location is "Stand-alone Solar PV system with battery backup". The battery backup can support the system in case of any power outage. Special inverters are available in the market to support this kind of system with internal solar charge controllers. These inverters can also act as grid-tied system in the presence of grid and provide the electric supply from solar panels. These inverters act as stand-alone system in the absence of utility grid and supply the electricity from battery bank. The priority of the energy source can also be adjusted in the inverter. The energy from Solar PV will be the first priority in the designed system and battery backup will be used at night. The Grid supply will only be used in case of emergency if the solar PV is not available (night or cloudy day) and battery is also below 50% charging capacity. Following are the basic components of this Solar PV system.

1- Solar Panel
2- Inverter
3- Battery Bank

2.3- Component Description and Sizing

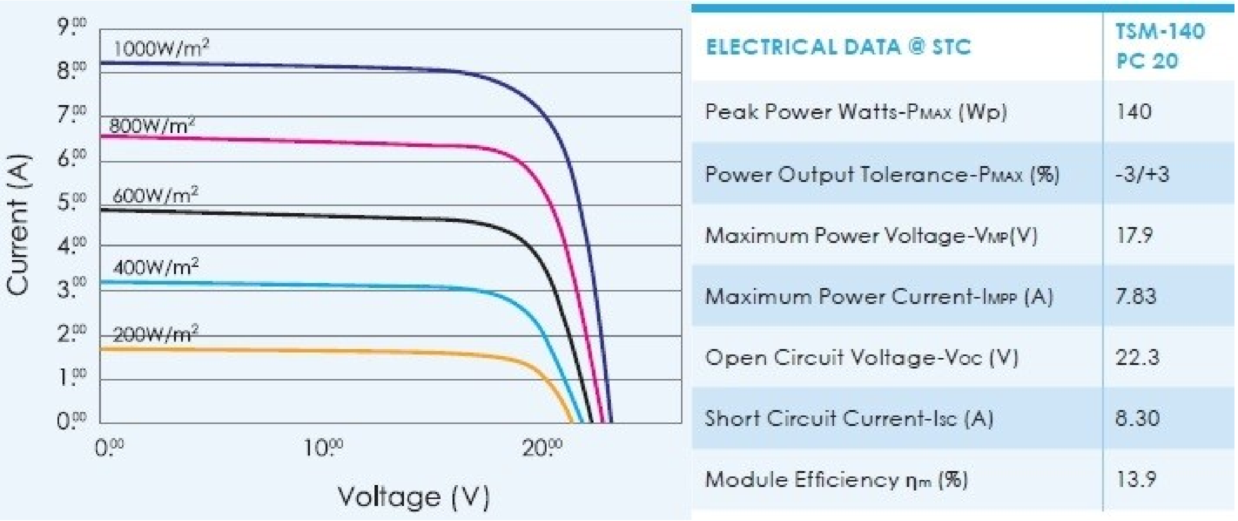
All the components of this research are selected as per the availability in the local market. Followings are some basic components of grid-tied solar PV system with battery.

- Solar Panels
- Battery bank

- Inverter & charge controller
- PV combining and protection box
- Frames to mount Solar PV system
- AC & DC power cables
- Grounding Pits
- Energy meter or monitoring device

2.3.1- Solar Panel

Solar panel is a basic component of a solar PV power system. Selection of a solar panel mostly depends on the quality, price and availability in local market. The selected site has a large area available on roof-top so area for solar PV installation is not an issue for this site. A polycrystalline solar panel TSM-140 PC 20 by Trina solar is selected for this project [31]. This is a 36 cells, 140 watt solar panel with 17.6VDC operating voltages. This panel can bear snow loads up to 5400 Pa and wind loads up to 2400 Pa. This specific solar panel shows high performance under low light conditions specially in Cloudy days, mornings and evenings. It is independently certified by international certification bodies and manufactured according to international quality and environment management system ISO9001, ISO14001. This module is 13.9% efficient with IEC 61215, IEC 61730, TÜV-Rheinland, UL 1703, IEC 61701 and IEC 62716 certificates. This is a 140 Wp solar panel with a power temperature coefficient of 0.43% per ^{0}C. The average temperature for this site is higher than ambient temperature in summer so the output of solar panel will be effected by temperature in summer. The Figure 2.5 shows some technical specifications and power curve of this solar panel [31].



ELECTRICAL DATA @ STC	TSM-140 PC 20
Peak Power Watts-PMAX (Wp)	140
Power Output Tolerance-PMAX (%)	-3/+3
Maximum Power Voltage-VMP(V)	17.9
Maximum Power Current-IMPP (A)	7.83
Open Circuit Voltage-Voc (V)	22.3
Short Circuit Current-Isc (A)	8.30
Module Efficiency ηm (%)	13.9

Figure 2.5: Technical data of solar panel [31]

As per the energy requirement of the selected house, the solar panel has to provide 40 kWh per month. Simple calculations can be performed for the sizing of solar panels. As per given data,

Monthly energy consumption of the house = 40 kWh

Daily energy consumption of the house = E = 40/30 = 1.34 kWh

Average daily solar irradiance of the location = R = 5.27 kWh/m^2/day

Efficiency of battery bank = μ_B = 80%

Efficiency of Inverter & charge controller = μ_I = 90%

Efficiency of solar panel = μ_m = 13.9%

$$\text{Required area} = \frac{Daily\ Required\ Energy}{Solar\ Irridiance \times PV\ Efficiency \times Battery\ Efficiency \times Inverter\ Efficiency \times Fixed\ panel\ efficiency}$$

$$\text{Required Area} = \frac{1.34}{5.27 \times 0.7 \times 0.9 \times 0.8 \times 0.139}$$

$$\text{Required Area} = 3.63\ \text{m}^2$$

As per the calculations, more than 3.63 m^2 area of solar panel is required to run this house 100% on solar. The size of our selected solar panel is 1.005 m^2 so total required solar panels can be calculated by following formula.

$$\text{Number of solar panels} = \text{Total area required} \div \text{area of single solar panel}$$

$$\text{Required Area} = 3.63\ \text{m}^2$$

$$\text{Size of one solar panel} = 1.005\ \text{m}^2$$

$$\text{Solar Panels required for the project} = \frac{3.63}{1.005}$$

$$\text{Solar Panels required for the project} = 3.6 = 4\ \text{solar panels}$$

The calculation shows that 4 solar panels are required to fulfil the requirement of the house. The inverter will decide the bus voltage of solar panels. Small systems are mostly designed at 12 VDC but this kind of residential system has the potential of increase in demand in future so 24 VDC system is recommended for this house so it can be upgraded in future.

2.3.2- Battery Bank

Rechargeable batteries are normally used to store energy from solar panels. In grid-tied solar PV system with battery backup, battery bank stores the extra energy from solar panels throughout the day and this energy can be used in the night time and also in cloudy weather. Battery cannot return the full amount of energy that is normally used to charge the battery which means the efficiency of battery is not 100%. Energy wastage occurs in batteries during charging and discharging process. There are many types of batteries in the market and their life spam, efficiency and price varies along with their type. The most commonly used batteries for small solar PV installations are Polymer-Gel Valve-Regulated Lead Acid (VRLA) batteries. These batteries are in middle range as compared to price and life cycle. 2 days of emergency backup is enough for selected site because local grid can also provide the power in constant cloudy days. Battery bank required for this system can be calculated by simple formula.

Efficiency of battery bank = 80%

Depth of discharge = 70%

Required backup = 2 days

Daily Energy consumption = E = 1.34 kWh

Efficiency of Inverter = 93%

Total Energy of battery =

$$\frac{Daily\ Required\ Energy \times number\ of\ days}{Battery\ Efficiency \times Depth\ of\ Discharge \times Inverter\ Efficiency}$$

$$\text{Total Energy of battery} = \frac{1.34 \times 2}{0.8 \times 0.7 \times 0.93}$$

Total Energy of battery = 5146 Wh

As the rated voltage of the system are 24 VDC so 2 batteries will be used in series. The size of battery can be calculated by following formula.

$$\text{Size of battery} = \frac{Total\ energy\ of\ battery}{System\ bus\ voltages}$$

$$\text{Size of battery} = \frac{5146}{24}$$

Size of battery = 214 AH

As the calculation shows that two batteries of 214 Ah capacity can provide 2 days backup to selected house. Narada AcmeG series 12NDF215 is selected for this project which is a 12 V, 215 Ah VRLA battery. Total two batteries can provide the backup of 2 days for this house. Narada is one of the leading brand and followings are some technical features of selected battery.

- AGM-Acid Valve-Regulated Lead Acid battery
- Part of models adopt CCPP technology
- Front terminal design suited for 19”/21” cabinet•
- Strong handles for easy operation
- Patent Terminal sealing & front access
- Self-regulating pressure relief valve with flame arrester
- Terminal cover for insulation with flexible access
- Flame retardant ABS case (UL94 V-0, optional)
- Centralized H2 gas vent kit
- Low self-discharge rate
- Comply with IEC, IEEE, UL, EN, CE standards, etc.
- Design life at 25°C (77°F): 12+ years

2.3.3- Inverter

The size of inverter always depends on the total load of the system. Table 2.1 shows the total load of the house.

Sr.	Item	Load(W)	Qty	Total load
1	Light	20	4	80 W
2	Fan	80	3	240 W
3	Water Pump	550	1	550 W
4	Television	100	1	100 W
			Total	970 W

Table 2.1: Total load of the house

As per the total load of the house, the capacity of selected inverter must be higher than 970 W. The inverter for this system would also support battery backup and grid connection. MPLF (Low Frequency Inverter) 1 kW solar inverter is selected for this project. This is a 1000 W inverter so the system can be upgraded in future by simply adding solar panels and battery bank. This inverter has a pure sine wave output and supports 24 VDC battery bank. The supply priority of this inverter can be programmed between PV, battery and grid. The user can easily adjust the charging voltage and current of this inverter. This inverter has some programmable multiple operation modes such as Grid-tie, off-grid and grid-tie with battery backup.

Sr.	Item	Specification
1	Max. PV Array Power	1200 W
2	Rated Output Power	1000 W
3	Maximum PV Array Open Circuit Voltage	55 VDC
4	MPPT Range @ Operating Voltage	15 VDC ~ 55 VDC
5	Nominal Output Voltage	230 VAC
6	Nominal Output Current	4.5 A
7	Power Factor	> 0.8
8	Maximum Conversion Efficiency (DC/AC)	93%
9	Frequency Range	50 Hz/60 Hz (Auto sensing)
10	Maximum Solar Input Current	40 A
11	Output Waveform	Pure sine wave
12	Efficiency (DC to AC battery)	93 %
13	Battery Voltage	24 VDC
14	Maximum battery Charge Current (Solar)	40 A

Table 2.2: Technical specifications of the inverter [32]

Table 2.2 shows the technical specifications of the selected inverter. This data shows that the bus voltage of solar panels must be between 15 VDC – 55 VDC. This inverter is equipped with an efficient MPPT change controller which can support upto 1200 W solar panels. Figure 2.6 shows the general overview of the designed system. The net-metering feature will be used in future because presently there are not enough solar panels installed on roof-top to generate extra energy.

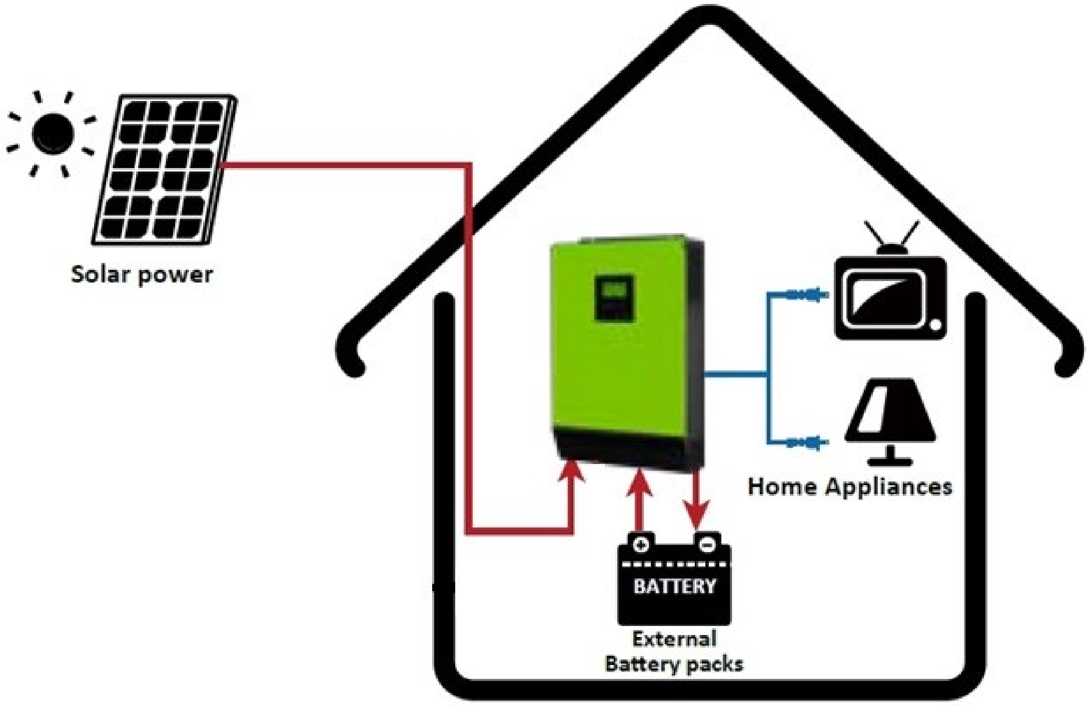


Figure 2.6: Operation layout of the designed PV system

2.4- System Layout and Technical Specifications

The sizing of three major components of solar PV system is being carried out in previous section. Total four solar panels of 140 watts each are required to fulfil the electrical needs of the house. The DC bus of the system is 24 V so two panels will be connected in series to charge the batteries. Figure 2.7 shows the overall layout of the designed system. Solar panels are directly connected to the inverter.

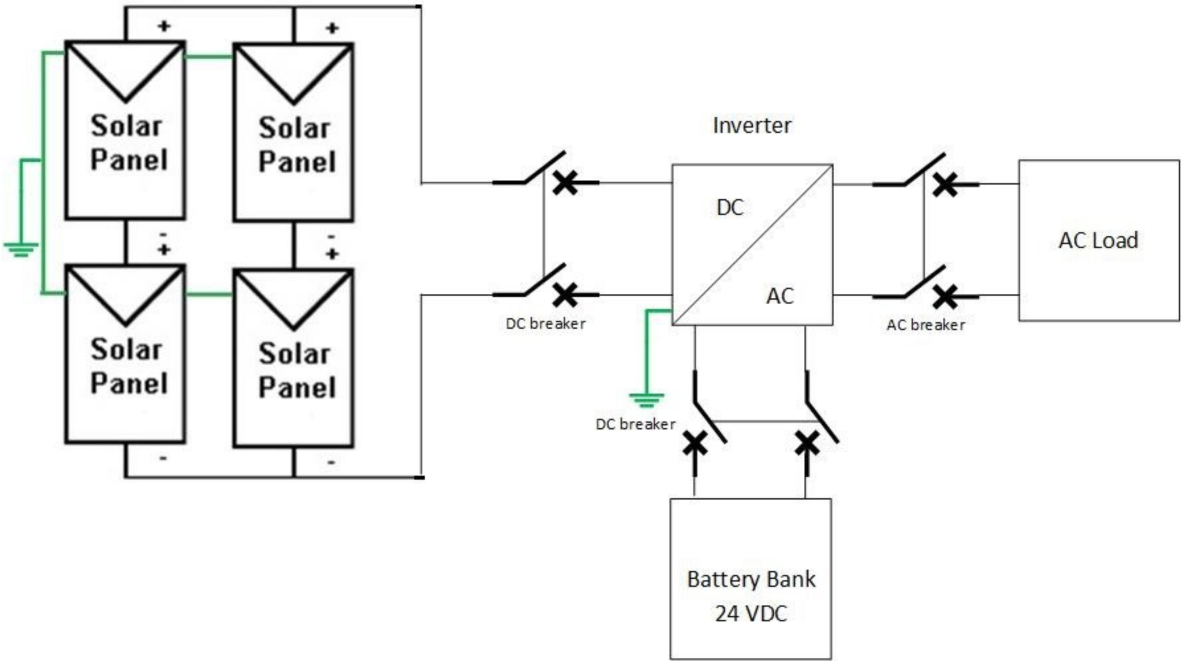


Figure 2.7: System layout

The charge controller of inverter is charging the batteries and also providing power to the inverter for running load. The battery bank is used to store extra energy from solar panels in day-time and provide energy in the absence of sun light. This system can also provide power to the local utility grid but this is only possible if batteries are fully charge and solar panels generate more than the consumption of the user. Table 2.3 shows some technical specifications of the designed system. This system can support 2 KW load and solar panels can also be extended in future for system extension.

Sr.	Item	Specs
1	PV voltage	44.6 V_{Dc}
2	PV current	15.66 A
3	Battery Voltage	24 V
4	Battery capacity	250 Ah
5	Battery Backup	2 days
6	Max output Power	1 KW

Table 2.3: Technical specifications of the designed system

Figure 2.8 shows the placement of solar panels on roof of the house. Space is not a problem for this system because a large space is available on rooftop of this house.

Figure 2.8: Solar panel placement on rooftop

2.5- Steady-state Analysis of Designed System

The steady state analysis of designed system will show the expected output of the system. Homer software is used to perform steady state analysis of solar PV system. Figure 2.9 shows the Homer design of the system. The total load of the house is designed as 1.34 kWh per day as per the calculations in previous section. In this design, a solar panel of 140 W is being used to find the exact quantity of solar panels to run the electric load of house through PV system. Two batteries are providing power backup to the system in the absence of sun light and an inverter of 1 kW is providing constant power supply to the house. Grid is also present in that area but the grid is not included in the design because it will only be used in case of emergency. The designed system will help to provide a constant and green energy to the house throughtout the year.

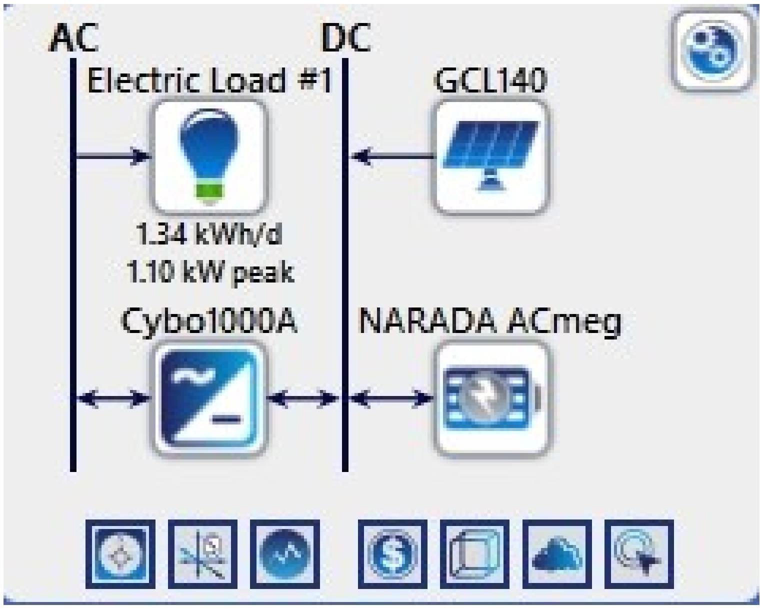
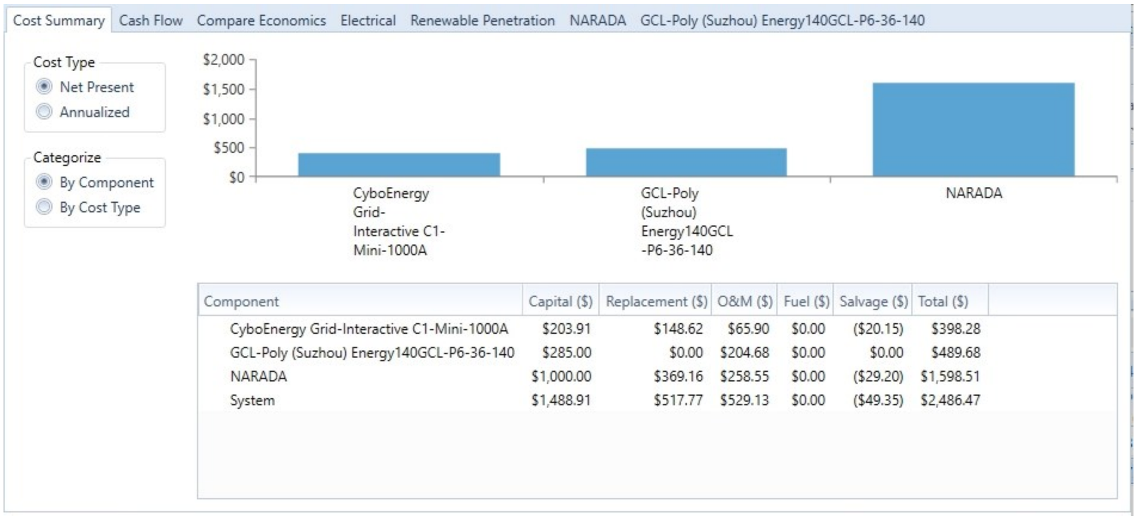


Figure 2.9: Homer design of the system

The local resources such as solar irridiance, temperature and wind speed are also calculated with the help of Homer software by selecting site location and source of the data in software. Figure 2.10 shows the initial cost of the designed system as per the local market.



Cost Type

● Net Present
○ Annualized

Categorize

● By Component
○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
CyboEnergy Grid-Interactive C1-Mini-1000A	$203.91	$148.62	$65.90	$0.00	($20.15)	$398.28
GCL-Poly (Suzhou) Energy140GCL-P6-36-140	$285.00	$0.00	$204.68	$0.00	$0.00	$489.68
NARADA	$1,000.00	$369.16	$258.55	$0.00	($29.20)	$1,598.51
System	$1,488.91	$517.77	$529.13	$0.00	($49.35)	$2,486.47

Figure 2.10: Initial cost of the system

The most expensive part of this system is battery bank because it is being designed to provide the backup for 2 days. The total cost of this system is 2486 USD as per the simulation results of HOMER software. Figure 2.11 shows the cash flow of the designed system for next 25 years. This shows that the software has done the cost analysis of the system for next 25 years.

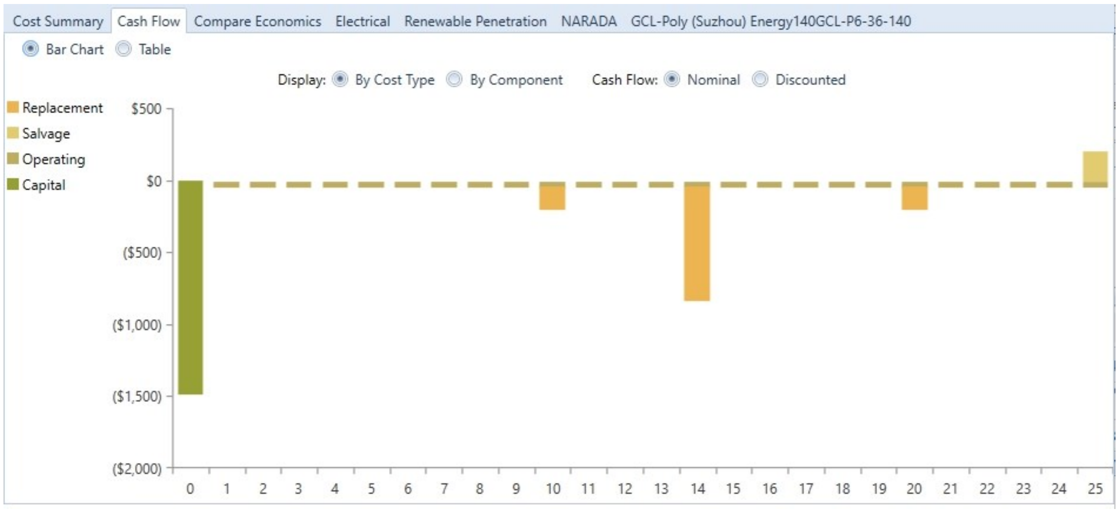
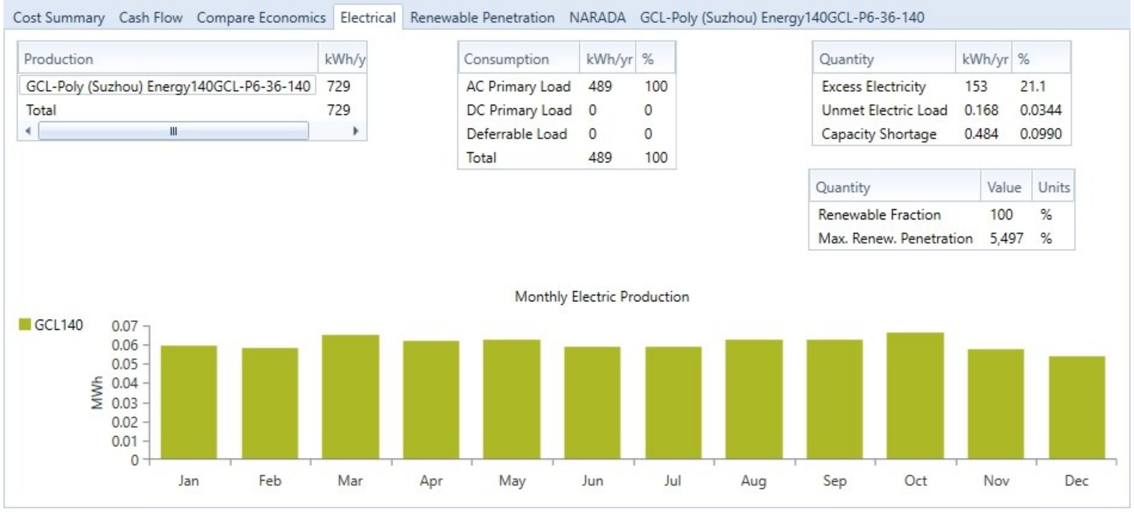


Figure 2.11: Cash flow of the designed system

Figure 2.12 shows the monthly electrical production of the designed system.The results show that the designed system is producing 729 kWh per year and the total requirement of the house is 489 kWh. Normally, Homer overestimates the output of solar panel by neglecting the losses due to fixed solar panels. As a result of this over estimaition, results show extra energy production from solar panels.



Production	kWh/y
GCL-Poly (Suzhou) Energy140GCL-P6-36-140	729
Total	729

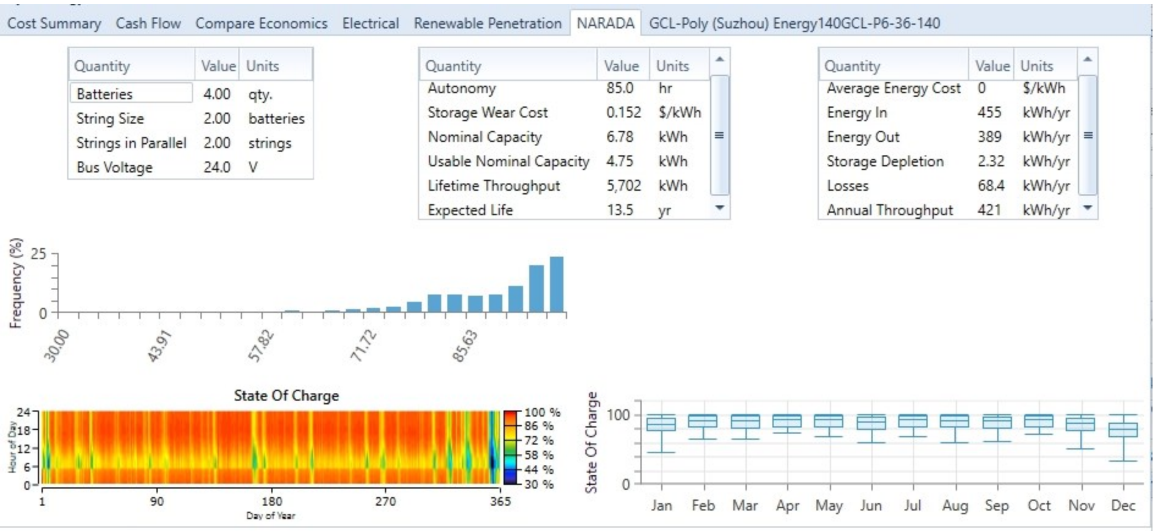
Consumption	kWh/yr	%
AC Primary Load	489	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	489	100

Quantity	kWh/yr	%
Excess Electricity	153	21.1
Unmet Electric Load	0.168	0.0344
Capacity Shortage	0.484	0.0990

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	5,497	%

Figure 2.12: Electrical analysis of the designed system

Figure 2.13 shows the usage of battery per year. The results show that battery bank will store 455 kWh/year from solar panels and provide 389 kWh/year to the load. Simulation results show that there are total 68.4 kWh/year losses in the battery bank which means the battery bank is 85% efficient.



Quantity	Value	Units
Batteries	4.00	qty.
String Size	2.00	batteries
Strings in Parallel	2.00	strings
Bus Voltage	24.0	V

Quantity	Value	Units
Autonomy	85.0	hr
Storage Wear Cost	0.152	$/kWh
Nominal Capacity	6.78	kWh
Usable Nominal Capacity	4.75	kWh
Lifetime Throughput	5,702	kWh
Expected Life	13.5	yr

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	455	kWh/yr
Energy Out	389	kWh/yr
Storage Depletion	2.32	kWh/yr
Losses	68.4	kWh/yr
Annual Throughput	421	kWh/yr

Figure 2.13: Annual battery usage

2.6- Conclusion

Energy concumption data of a rural house in Pakistan is collected from electric bill of previous year. The designed system is cost effective and easy to install. All the components used in this research are readily available in local market. Real-time solar irridiance, temperature and load data of selected location is used for the Homer simlation. The results of Homer simulation show that the designed PV system is capable of running the selected rural house throught the year without any involvement of local utility grid. The designed system is producing 729 kWh per year to run the electric load of selected house and charge the batteries as well. The battery bank of designed system can provide a power backup for consective 2 days during cloudy weather. The total cost of designed system is 2486 USD as per the simulation results of HOMER software. This cost includes the initial cost of all components and maintenance cost for next 25 years.

CHAPTER 3: COMPARATIVE ANALYSIS OF COMMERCIAL PV DATA-LOGGERS

3.1- Introduction

There are many products available in market to log and monitor the data of PV energy system. Every product is designed for specific type of applications. Majority of the products focus on mega PV projects which includes grid-tied PV projects. These projects are normally installed at remote locations so most of the products also offer remote access to the user. This chapter deals in commercially available Solar PV data-loggers and their basic features.

3.2- Commercial PV Data-Logging and Monitoring Systems

Followings are some major PV data-logging and monitoring systems with complete description.

3.2.1- Photovoltaic Data-Logger by ECO EYE SMARTPV

Eco-Eye is a UK based company which deals in energy monitoring devices for domestic and commercial applications. This company has also developed Eco Eye Smart PV system to monitor the performance of PV energy systems [33]. Eco Eye SmartPV is an efficient and smart energy monitoring solution for PV energy projects. The company usually sell it as a full PV monitoring solution which is compatible with single phase, 50 Hz and 240

VAC systems. The complete system includes current sensor for grid connection, current sensors for PV connection, voltage sensor for PV connection, smart PV display, data transmitter, memory card, AA battery and connection cables. This system has monitoring and data-logging capability. SmartPV can calculate energy generated by PV, energy used in the building and net energy from or to local utility grid. There are indication lights on the monitoring device which shows that either the energy from PV is running the load or grid is also involved to share extra load. Thses indication lights also identify the extra generation from PV by green signal. This device can store the data directly to internal memory card and can also transmit data to locally connected computer with four second resolution.

Eco Eye SmartPV is an effective tool for any kind of solar installation and easy to install. The stored data of memory card can easily be viewed by inserting the memory card into a card reader. There is also an option to retrive data with the help of USB data cable. There is a software named Trax analysis which can be used to set electricity rates. This software can provide monthly electricity generation from PV system, electricity purchased from local utility grid and net budget reports of electric consumption of the building.

This system can dislay the data for PV generation in kW, grid usage in kW, net usage in kW, desired graphs, present date, present time and real time temperature. Total price of this system is 140 CAD which does not include shipping and installation cost. Figure 3.1 shows the complete package of Eco Eye SmartPV monitoring system.

Figure 3.1: Eco Eye SmartPV monitoring system [33]

3.2.2- Geo Solo II PV Monitoring System

Green Energy Options Ltd has introduced a smart solar monitoring system named Geo Solo II PV. This is a web-enabled in-home PV monitoring system which can display the kWh generated by the solar panels, credits earned by feed-in terrif and carbon emission reduction by using renewable energy resource. Geo Solo II shows the real-time and historical data of solar panels and can also be accesed remotely to get the update of installed system. This system can guide to turn on heavy electric load with a green finger indication on the display screen. This indication shows that solar panels are generating sufficient load to support large electric appliances like dish washer, electric heater, air conditioner and water pump etc.

Geo Solo II PV monitoring system is one of the poineers in UK to provide color display screen with trends and graphs. The differnet color schemes of every parameter helps to read any solar data very easily and without any waste of time. The installation of this system is very easy and can be done without any kind of additional wiring or modifiction of existing system. This system uses a LED sensor to detect the data from pulse signal of generation meter and provides very accurate and efficient energy data. Geo Solo II has an internal temperature sensor to show the real-time temperature data of the house. This system can be installed on both single phase and three phase configurations. There are three major parts of this system which are LED sensor, data transmitter and colored display screen. LED sensor detect the pulse output signal of generation meter and sends it to data transmitter. This data transmitter is powered by a battery which can provide power to this transmitter upto two years. Colored display screen gets data from transmitter and shows it in colored patterns. Figure 3.2 shows a sample display screen of Geo solo II PV monitoring system. The commercial price of the basic model of this system is 128 CAD. This company also provides online access to their device with an online service called Energynote. Energynote provides the real-time power generation data, historical trends and graphs of each solar parameter, hints and tips for the improvement of installed system, money earned by feed-in tariff and carbon emission reduction graphs.

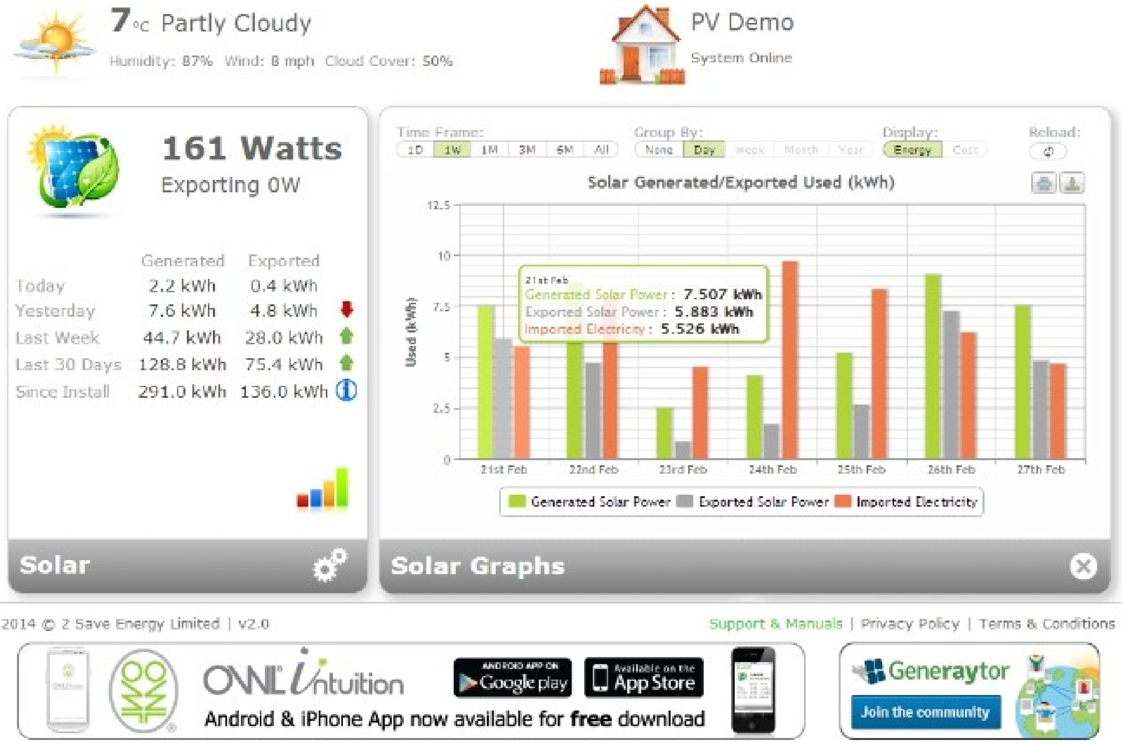
Figure 3.2: Geo Solo II PV monitoring system [34]

3.2.3- Intuition PV Monitoring System

A UK based company "The OWL" has developed a PV energy monitoring system named as Intuition PV monitoring system. The OWL is basically expert in wireless energy monitoring and heating control systems. This designed system helps to monitor the overall PV generation including energy exported to the grid and internal energy consumption of the building. This system provides online access to the system with the help of smart mobile app and just require internet connection for remote access of data from any location. This energy monitoring system shows the 12 seconds interval of energy generation and consumption trends. It also shows the improvements in power consumption trends of the user which leads in energy saving by better power consumption habits. The tariff settings can easily be configured by the user. This system provides the data regarding power consumption of the building and impact of installed PV system on monthly utility bill. Figure 3.3 shows the basic hardware of this PV monitoring system.

Figure 3.3: Basic hardware of Intuition PV monitoring system [35]

Intuition PV monitoring system provides graphical representation of both historical and real-time data of PV energy system. These graphical trends provide data to the user regarding energy generation of solar panels which can help to determine the accurate time for apply electrical load to the system. Figure 3.4 shows the sample graphs of intuition PV monitoring system.



7 °C Partly Cloudy

Humidity: 87% Wind: 8 mph Cloud Cover: 50%

PV Demo

System Online

161 Watts

Exporting 0W

	Generated	Exported
Today	2.2 kWh	0.4 kWh
Yesterday	7.6 kWh	4.8 kWh
Last Week	44.7 kWh	28.0 kWh
Last 30 Days	128.8 kWh	75.4 kWh
Since Install	291.0 kWh	136.0 kWh

21st Feb

Generated Solar Power : 7.507 kWh

Exported Solar Power : 5.883 kWh

Imported Electricity : 5.526 kWh

Figure 3.4: Graphical trends of Intuition PV monitoring system [35]

The operating frequency of this PV monitoring system is 433 MHz and its operating range is upto 30 m. The in-build battery can last for more than 14 months. The sensors provided by the company are suitable to measure upto 71 A current. The system is suitable to operate between 0 ˚C to 40 ˚C temperature and 25% to 95% non-condensing relative humidity. The cost of basic unit of this energy monitoring system is 166 CAD.

3.2.4- SolarFox Solar Display System:

SolarFox solar display system is a product of German company SOLEDOS GmbH used worldwide for visual representation of PV energy systems. Solarfox displays the power flow of a building along with the PV generation. This system can show the data and indications at the time of high production from PV system as compared to the energy consumption. This sytem also shows the charging capacity of the batteries and net energy flow of the local utility grid. Direction of current flow is also showed by visual animations which attracts the attention of the observers. Figure 3.5 shows some common visual graphs of this system.

Figure 3.5: SolarFox Solar visual graphs [36]

SolarFox can display visual graphs of different PV systems regardless of their location. Multiple systems at different location can be displayed at a single location by using this product. The basic model SF-100 series is designed to display PV energy data without any involvement of high end hardware equipment. The hardware of this system includes a LED dislay screen, control computer SC-1000 with software, 15° tilting wall mount, Cable and accessories, Internet connection, online management and individual content including user guide.

The self power cosumption of this system is 44.7 kWh per year which is very high for domestic and other small scale PV energy system. This value is calculated by considering 10 hours use per day. The main drawback of this system is that this is only compatible with some selected inverters and can't be used with any kind of PV energy system. SolarFox solar display system is only suitable for large scale PV projects with a selected raneg of inverters. Figure 3.6 shows the linking plan for Solarfox solar display system. This diagram shows that a single display system can be connected to multiple PV energy systems by using internet conection.

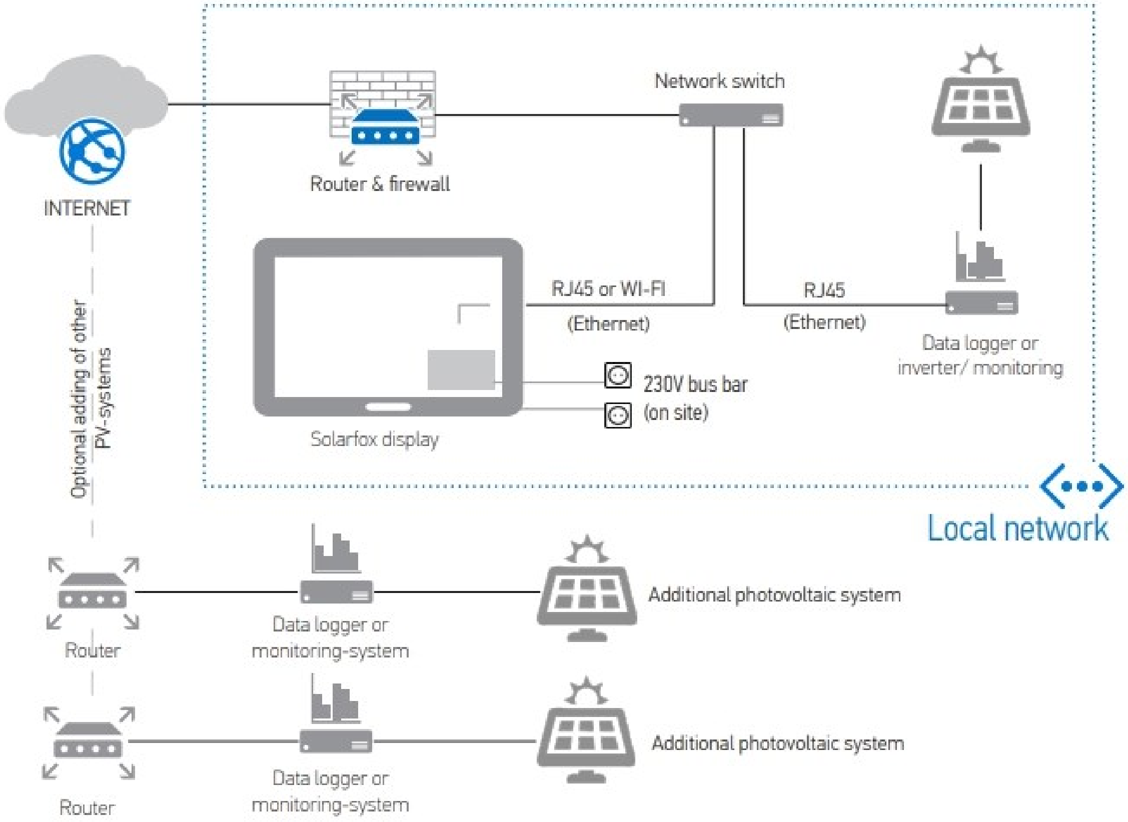


Figure 3.6: Linking plan for SolarFox solar display system [36]

3.2.5- PV Monitoring Platform by SolarEdge

SolarEdge has designed an IoT based PV data logging and monitoring platform which extract basic data from PV energy systems including faults, energy production and system performance upto individual solar panel level. This monitoring platform does not require any extra sensors, wiring or data transmitters for logging and monitoring data from PV system. This platform can only work with inverters designed by SolarEdge. Electrical and financial performance of PV energy system can be fully visible and easy to monitor with the help of this platform. Figure 3.7 shows some simple display screens of this monitoring platform.

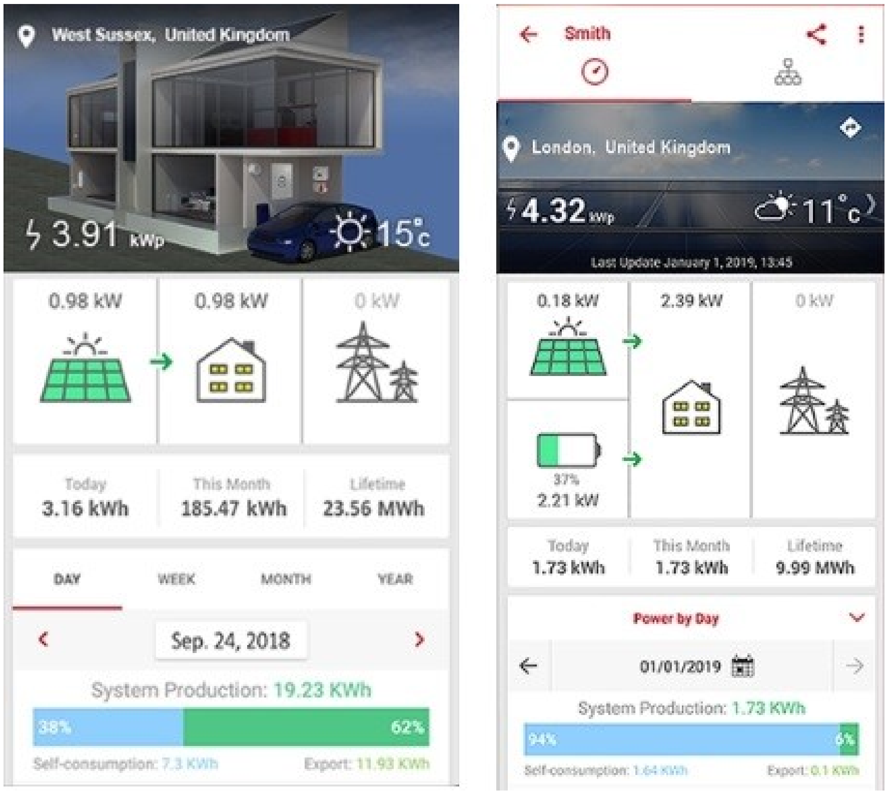
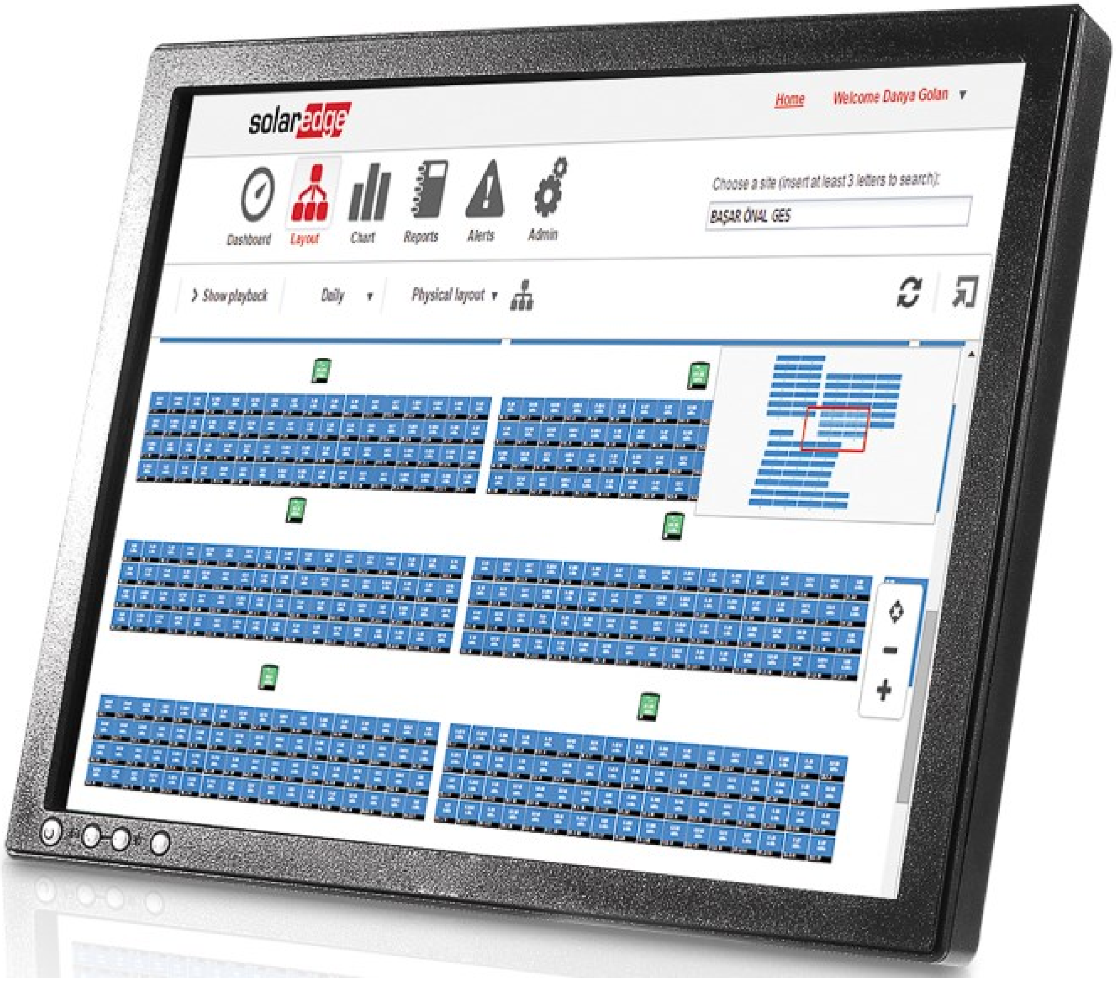


Figure 3.7: Display screens of SolarEdge monitoring platform [37]

This platform can be equipped with a comprehensive reporting and analysis tool having the ability to send automatic reports on scheduled time. Monitoring system can also generate automatic alerts regarding any kind of fault in the PV energy system. Monitoring system provides easy remote access to high resolution historical and real-time data to computer, smartphone, or tablet. This special feature of this system enables the user for any kind of remote fault detection and troubleshooting of the PV energy system.

SolarEdge monitoring platform covers all domestic, commercial and industrial PV energy systems. This system can track the PV production, regular power consumption of the building and net energy to or from local utility grid. SolarEdge monitoring platform is compatible with both single and three phase electric power system. The basic version of this platform is free for 25 years.

Figure 3.8 shows SolarEdge monitoring platform including display screen for a commercial PV energy system. It can be clearly seen in the picture that all solar PV modules are visible at locally installed screen. The performance monitoring and fault detection at individual module level is very easy by using this monitoring system. This monitoring platform provides multiple options for PV energy data sharing and public display of all measured data. The physical layout of the designed site can be edited very easily as per required by user with the help of SolarEdge Mapper application or online layout editor.



Choose a site (insert at least 3 letters to search): BAŞAR ÖNAL GES

Figure 3.8: SolarEdge Monitoring system for commercial application [37]

3.2.6- Tigo PV Monitoring System

Flex MLPE TS4-M is an integrated modular junction box based PV monitoring system designed by Tigo Energy. Tigo Energy also provides a smart website and mobile app for remote monitoring of installed PV energy system. Figure 3.9 shows hardware nmodule of Flex MLPE TS4-M monitoring system.

Figure 3. 9: Hardware module of Tigo PV monitoring system [38]

Tigo monitoring system helps to detect faults and diagnose performance issues remotely. This system also has the ability to send fault alets which helps to maintain the maximum up time of PV energy unit. Tigo Energy has been upgrading its monitoring system to meet the requirements of various types of PV installations. This PV monitoring module is usually installed at back of solar panel. This system sends automated emails and sms messages regarding daily or monthly energy production of the PV system. Tigo monitoring system shows energy, power and reclaimed power data for each module with 15 minutes interval. Smart website of Tigo Energy shows graphs for all historical and real time data of PV system. Figure 3.10 shows a sample display of smart website of Tigo Energy.

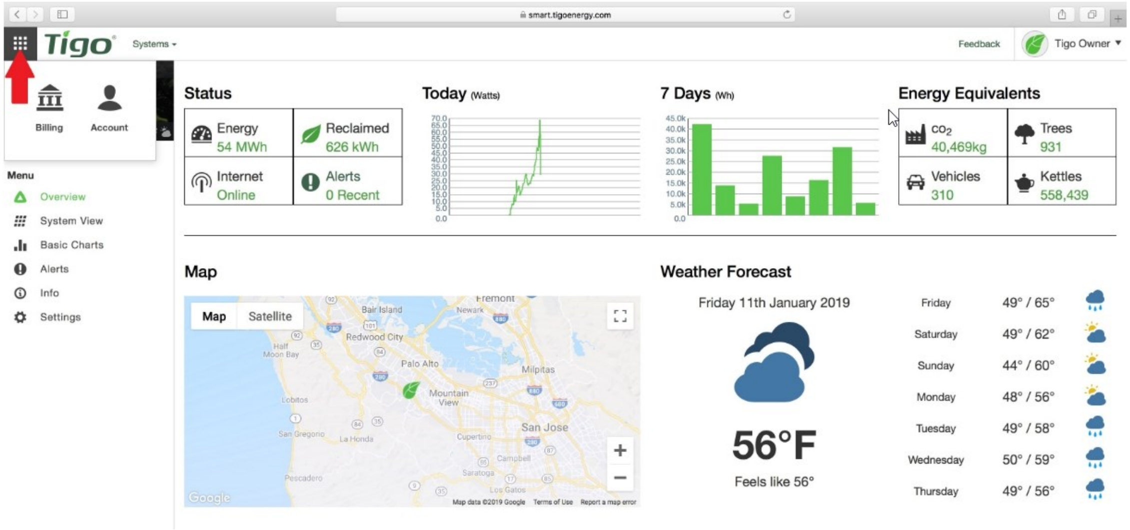


Figure 3.10: Smart web view of Tigo Energy [38]

3.2.7- Enlighten Monitoring System by Enphase Energy

Enlighten software and mobile application are the products of Enphase energy. The main purpose of Enlighten monitoring system is the efficient management of installed PV energy system. MyEnlighten web application helps to remotely track the overall energy of whole PV system, energy production data of each panel, health of the PV system and energy consumption trend of the building. Web application can also share the PV production data with family and friends with the help of a very simple and easy to use interface. Enlighten monitoring system can only be connected with enphase microinverters to get PV production data. Figure 3.11 shows a simple PV data representation in Enphase Enlighten web portal. The plus signs in this diagram can show the further details of selected data.

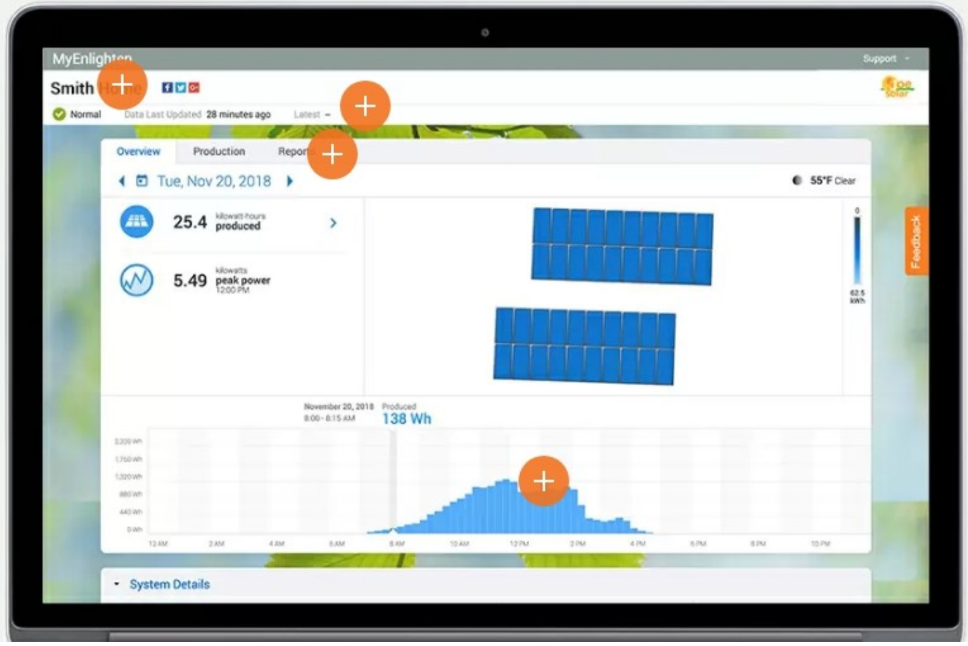


Figure 3.11: MyEnlighten web portal [39]

3.3- Conclusion

Some major and leading PV data-logging and monitoring systems has been discussed in this chapter. Table 3.1 shows the price overview of all these systems.

Sr.	Monitoring System	Manufacturer	Price
1	SmartPV monitoring system	ECO Eye	140 CAD
2	Geo Solo II PV	GEO	128 CAD
3	Intuition PV monitoring system	OWL	166 CAD
4	SolarFox Solar display system	SOLEDOS GmbH	180 CAD
5	SolarEdge PV monitoring system	SolarEdge	433 CAD
6	Tigo PV monitoring system	Tigo Energy	389 CAD
7	Enlighten PV monitoring system	Enphase	20 CAD/year

Table 3.1: Price comparison of PV monitoring systems

Comparison of commercial PV data-logging and monitoring systems show that most of available systems are very expensive and can only work with specific equipment. Very less open source PV data-loggers are availabel in market so there is still need for new inovations in this field. Not even a single system is suitable for small PV energy systems. To overcome the high cost, limited range of aplication, installation efforts and high self-power consumption of commercially available PV data-loggers, this thesis introduces an open-source ultra-low powered PV data-logger to be used for small domestic PV energy units.

CHAPTER 4: PV DATA-LOGGER DESIGN AND HARDWARE STRUCTURE

4.1- Introduction

Data-logging and monitoring system is very important for a smooth and efficient operation of a PV energy unit. Data-logging and monitoring system can be used to determine the schedule of periodic maintenance of a PV system. Troubleshooting of any kind of fault in PV energy system can be done quickly with the help of data-logger. Normally, majority of PV data-logging and monitoring systems display current, voltage, power and energy of a PV unit at their local screen. Some modern monitoring systems can also be integrated with internet and transmit all data to a remotely installed control and monitoring unit. Energy companies can easily monitor and maintain their remotely installed PV units with the help of these monitoring systems. Data stored by data-loggers can be accessed by using GSM, USB, RS232, RS485, Wifi or Bluetooth connections. Wireless connections of data-loggers are more convenient as compared to wired connection types. Most of the data-loggers use analog and digital sensors to collect data from solar panels, batteries and inverters. Environment related data like temperature, solar radiation, wind speed and ambient temperature can also be monitored by some advanced data-loggers.

Some of the commercial data-logging and monitoring devices are very expensive and complex in design as discussed in previous chapters. The self-power consumption is also a major drawback of these modern data-loggers. The expensive and advanced data-loggers are not suitable for stand-alone domestic PV energy units; so, a simple, low cost data-logger with ultra-low power consumption is proposed in this research. This chapter will further discuss the design, hardware components, programming algorithm, self-power consumption and operation of an ultra-low powered PV data-logger that is designed for a stand-alone domestic PV energy unit.

4.2- Description of Data-Logger

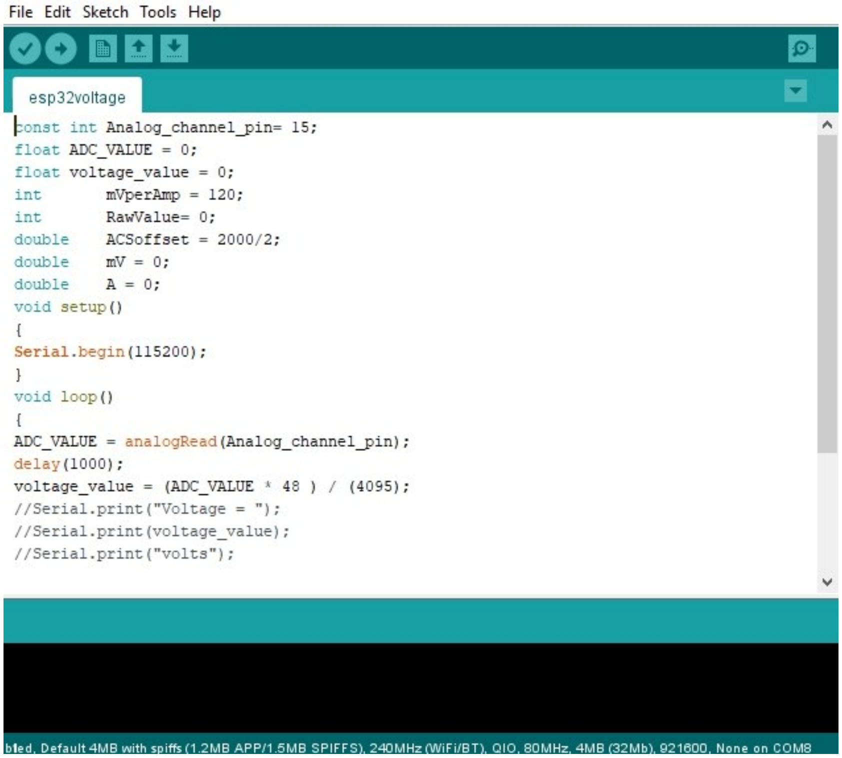
Deep sleep mode of a latest microcontroller ESP32-S2 is used to develop a low-cost data-logger for off-grid PV applications with ultra-low self-power consumption. Arduino IDE software is used for the programming of microcontroller. Current, voltage and light sensors are used to get the real-time PV data. The designed data-logger can be used to monitor and store the real-time data of PV voltage, PV current, PV power, PV energy and light intensity. Three analog to digital converter (ADC) pins of microcontroller are used to collect analog data from all three sensors. All the data collected by sensors is stored in the form of text file in an external micro SD card. A local web-based monitoring platform is also designed by using HTML coding to monitor all the data collected by data-logger. The same web-page can also be used to download and delete the stored data in memory card. A toggle switch is used to switch between web-monitoring and deep-sleep modes of data-logger. A LED light is used to show the status of local web-server of data logger. Followings are the basic components used for the designing of this data-logger.

1- Arduino IDE
2- ESP32-S2 microcontroller
3- Memory card reader
4- ACS712 current sensor (20A)

5- Voltage sensor (Voltage divider)
6- Light sensor (Light dependent resistor)

4.2.1- Arduino IDE

Arduino integrated development environment (IDE) is a microcontroller programming tool which can be run on both Windows and Linux operating systems. Arduino IDE is specially designed for Arduino microcontroller but other controllers can also be programmed by using this software after adding the libraries of those specific controllers. The basic programming language used in Arduino IDE is C and C++. Library of ESP32-S2 is loaded in Arduino IDE for the programming of designed data-logger. Figure 4.1 shows the programming platform of Arduino IDE.



```
const int Analog_channel_pin= 15;
float ADC_VALUE = 0;
float voltage_value = 0;
int       mVperAmp = 120;
int       RawValue= 0;
double    ACSoffset = 2000/2;
double    mV = 0;
double    A = 0;
void setup()
{
Serial.begin(115200);
}
void loop()
{
ADC_VALUE = analogRead(Analog_channel_pin);
delay(1000);
voltage_value = (ADC_VALUE * 48 ) / (4095);
//Serial.print("Voltage = ");
//Serial.print(voltage_value);
//Serial.print("volts");
```

```
bled, Default 4MB with spiffs (1.2MB APP/1.5MB SPIFFS), 240MHz (WiFi/BT), QIO, 80MHz, 4MB (32Mb), 921600, None on COM8
```

Figure 4.1: Arduino IDE

Arduino IDE also provides some basic sample programs of almost any kind of sensor. These sample programs can be very helpful for the learning of basic microcontroller programming and testing. User has to select the accurate port and model of microcontroller before burning the written program into microcontroller.

4.2.2- ESP32-S2 Microcontroller

ESP32-S2 designed by ESPRESSIF is a single core WiFi enabled microcontroller which includes the features of high performance, low power consumption mode and large number of I/O (input and outputs). ESP32-S2 supports a large amount of peripherals, which includes 43 programmable GPIOs (General Purpose Inputs and Outputs) with an ability to be configured as USB OTG (Universal Serial Bus On-The-Go), LCD interface, camera interface, Serial Peripheral Interface (SPI), I2S interface, Universal Asynchronous Receiver-Transmitter (UART), ADC, Digital to analog converter (DAC) and other common features. ESP32-S2 has configurable LCD and capacitive touch GPIOs to provide HMI (Human Machine Interface) features for touchpads and other touch screens. The development board used in this project is designed by Liligo and model of this board is LILYGO® TTGO T8 ESP32-S2-WOOR V1.1. Table 4.1 shows technical specifications of ESP32-S2-WOOR development board.

Sr.	Item	Specification
1	Chipset	ESPRESSIF-ESP32-S2-WROOM
2	Flash	4 MB
3	SRAM	320 kB SRAM
4	Buttons	Boot, Reset
5	USB to TTL	CH340C
6	Modular Interface	UART, SPI, I2C, PWM, I2S, ADC, WiFi, SD Card
7	On-board Clock	32.768 kHz crystal oscillator
8	Working voltage	2.7 V-3.6 V
9	Working temperature	-40 ℃ ~ +85 ℃

Table 4.1: Technical Specification of ESP32-S2

Each pin of this microcontroller can be programmed for different applications, depending on the pin configuration chart. Figure 4.2 shows the pin configuration chart of LILYGO® TTGO T8 ESP32-S2-WOOR V1.1.

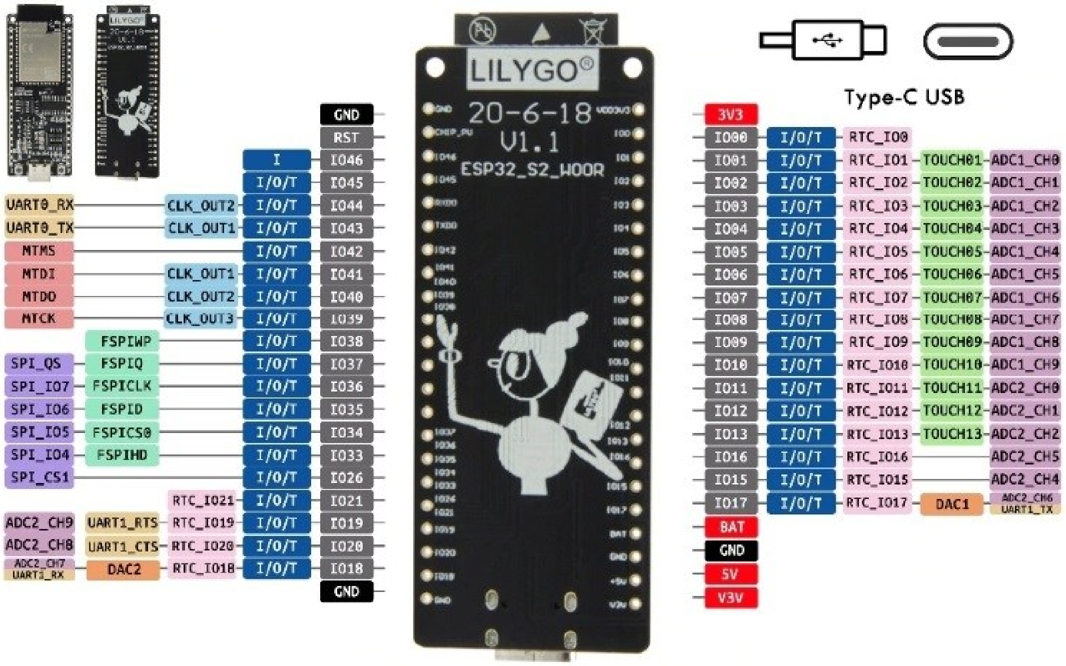


Figure 4.2: Pin configuration map of ESP32-S2-WOOR development board

The basic purpose of selecting this microcontroller is its ultra-low-power co-processor. This co-processor acts as main CPU (central processing unit) during deep-sleep mode. Only the data stored in RTC memory can be processed during deep-sleep mode. The power consumption of this board is 25 µA while only using RTC memory and RTC clock during deep-sleep mode.

4.2.3- Memory Card Reader

The internal memory of ESP32-S2 is not enough to store the data for a long time so an external micro SD card is used for logging the data collected by ESP32-S2. For that purpose, a micro SD card module is attached to the fast serial peripheral interface pins (FSPI) of the ESP32-S2-WOOR board which are from IO34 to IO37. This module provides an onboard pop-up micro SD card interface, where the memory card can be installed easily. The operating voltage of this micro SD card module is 3.3 V, so VCC and GND pins of the module are connected to 3V3 and ground pins of the microcontroller. The operating current of this module is 80 mA at a 3.3 V supply. The selected micro SD card module supports a maximum 32 GB memory card. Figure 4.3 shows the block diagram of pin connections of the micro SD card module with the ESP32-S2-WOOR development board. This diagram clearly indicates that CS pin of memory card is connected to FSPICS pin of microcontroller. This specific pin is responsible for data communication to and from memory card.

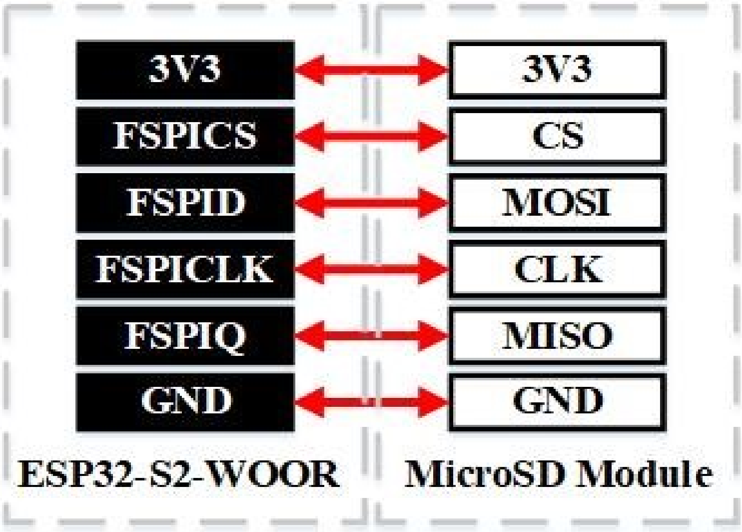


Figure 4.3: Pin configuration of micro SD card module

Figure 4.4 shows the micro SD card module used for the designing of data-logger. This figure also shows the six pins of card reader. Two pins are dedicated for power supply and other four pins can be used for data reading and writing to the micro SD card.

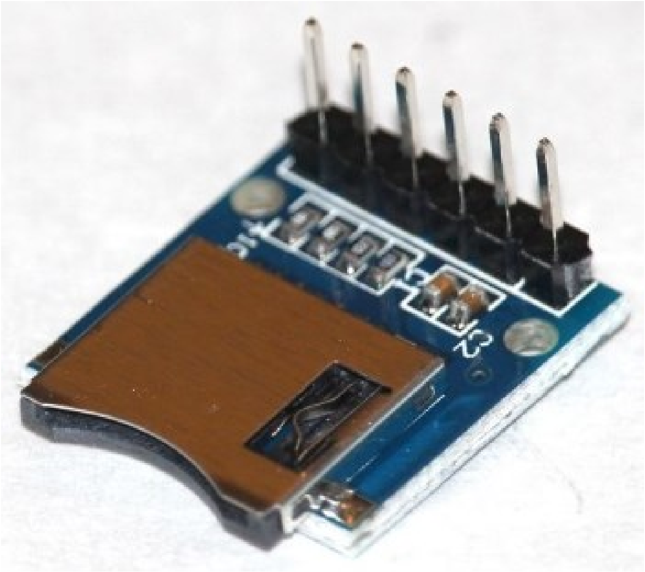


Figure 4.4: Micro SD card module for microcontroller

4.2.4- Current Sensor ACS-712 (20 A)

ACS712 Hall current sensor is used to measure the DC current from solar panels. It is a compact hall effect-based current sensor to measure linear current with a voltage isolation level of 2.1 kV(RMS). A current conductor of low resistance is used in this sensor. The selected current sensor can measure a maximum of 20 A with a scale factor of 100 mV/A at a supply voltage of 5 VDC. The analog signal measurement range of ESP32-S2 is 3.3 VDC, so this sensor is being powered up by using the 3.3 V pin of the microcontroller by adjusting the scale factor to 66 mV/A. The main chip used in this sensor is ACS712ELCTR-20A-T. Figure 4.5 shows the connection diagram of the ACS712ELCTR-20A-T chip and the physical appearance of the whole sensor.

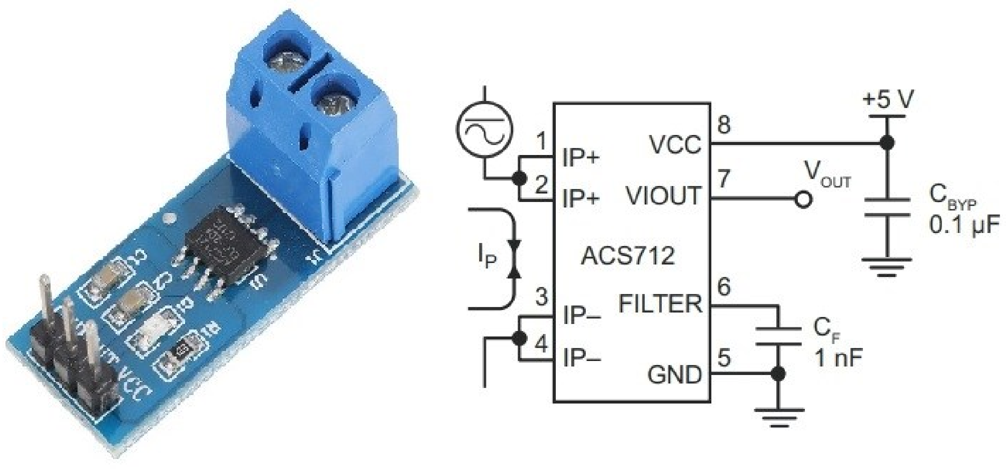


Figure 4.5: Sensor board and connection diagram of ACS712ELECTR-20A-T

4.2.5- Voltage Sensor

ESP32-S2 provides 13 bit ADC inputs with a maximum read value of 3.3 V, which means the processor will read 8191 while applying 3.3 V to its selected ADC pin. A voltage divider circuit is used to sense the DC bus voltages of the PV energy unit. The voltage divider is designed to convert 36 V to 3.3 V, which means this system is suitable to measure a full 36 V dc bus. The resistances can be calculated by the following formula.

$$V_{out} = (V_{in} \times R2) \div (R1 + R2)$$

The values of R1 and R2 are 10 k Ω and 1 k Ω, respectively, to convert 36 V to 3.273 V. Figure 4.6 shows the circuit diagram of the voltage divider for the designed system.

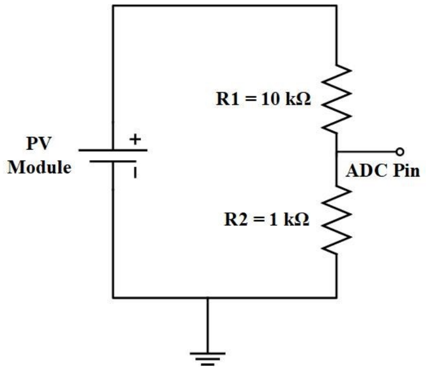


Figure 4.6: Voltage divider circuit

4.2.6- Light Sensor

A light-dependent resistor (LDR) is used as a light sensor in the designed data-logger. The resistance of LDR is inversely proportional to the light. The resistance of this particular LDR is 400 Ω in 1000 lux and 9 KΩ in 10 lux of applied light [40]. A voltage divider by using 10 kΩ resistance and LDR is designed to detect light intensity. Figure 4.7 shows an

LDR along with its circuit diagram. The voltage source is the 3.3 V pin of the microcontroller, so the potential at the ADC pin will increase along with increasing light intensity.

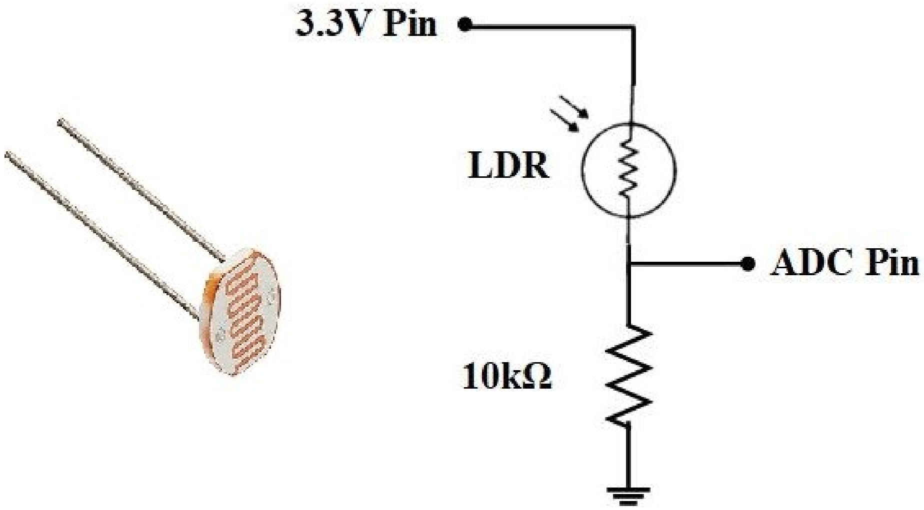


Figure 4.7: Light-dependent resistor and a voltage divider to sense light intensity

4.3- Design and Programming of Data-logger

ESP32-S2 collects data from voltage, current, and light sensors through the first three pins of ADC1 and stores in an external memory card installed in a micro SD card module. 3V3 pin of development board is used to provide power to all sensors and memory cards. IO11 pin of the microcontroller is used to connect a toggle switch for selection between deep-sleep and monitoring modes of data-logger. A light-emitting diode (LED) is connected to the IO12 pin to show the status of the webserver of the data-logger. Figure 4.8 shows the block diagram for the pin configuration of the microcontroller.

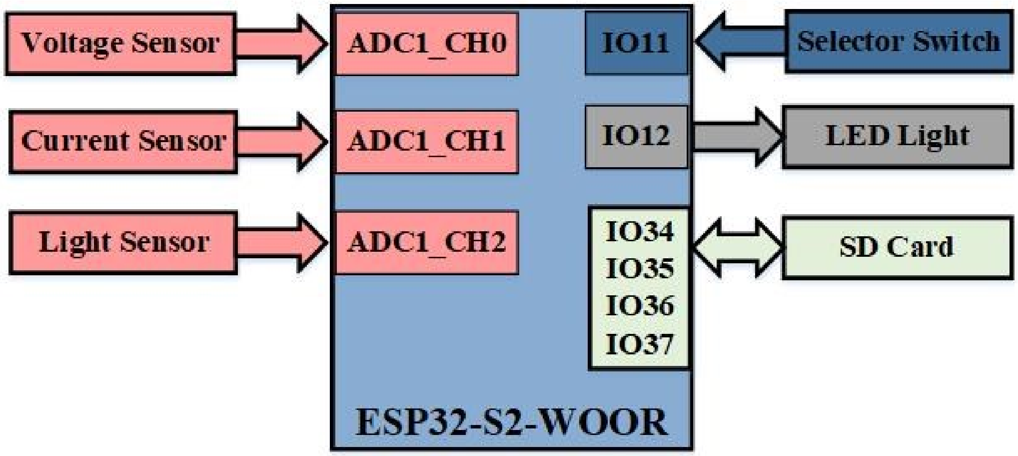


Figure 4.8: Pin configuration of ESP32-S2-WOOR board

All the components of the data-logger are assembled on a breadboard for testing purposes, as shown in Figure 4.9.

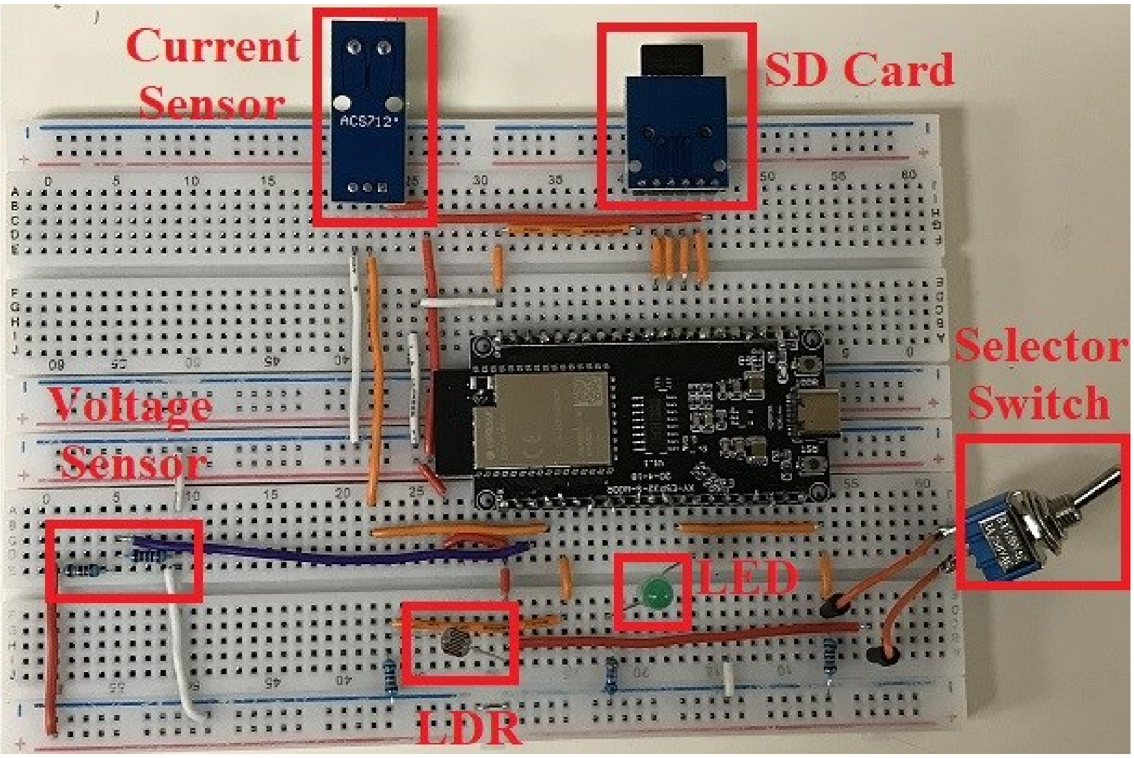


Figure 4.9: Breadboard model of data-logger

Figure 4.10 shows the programming flow chart of the designed data-logger.

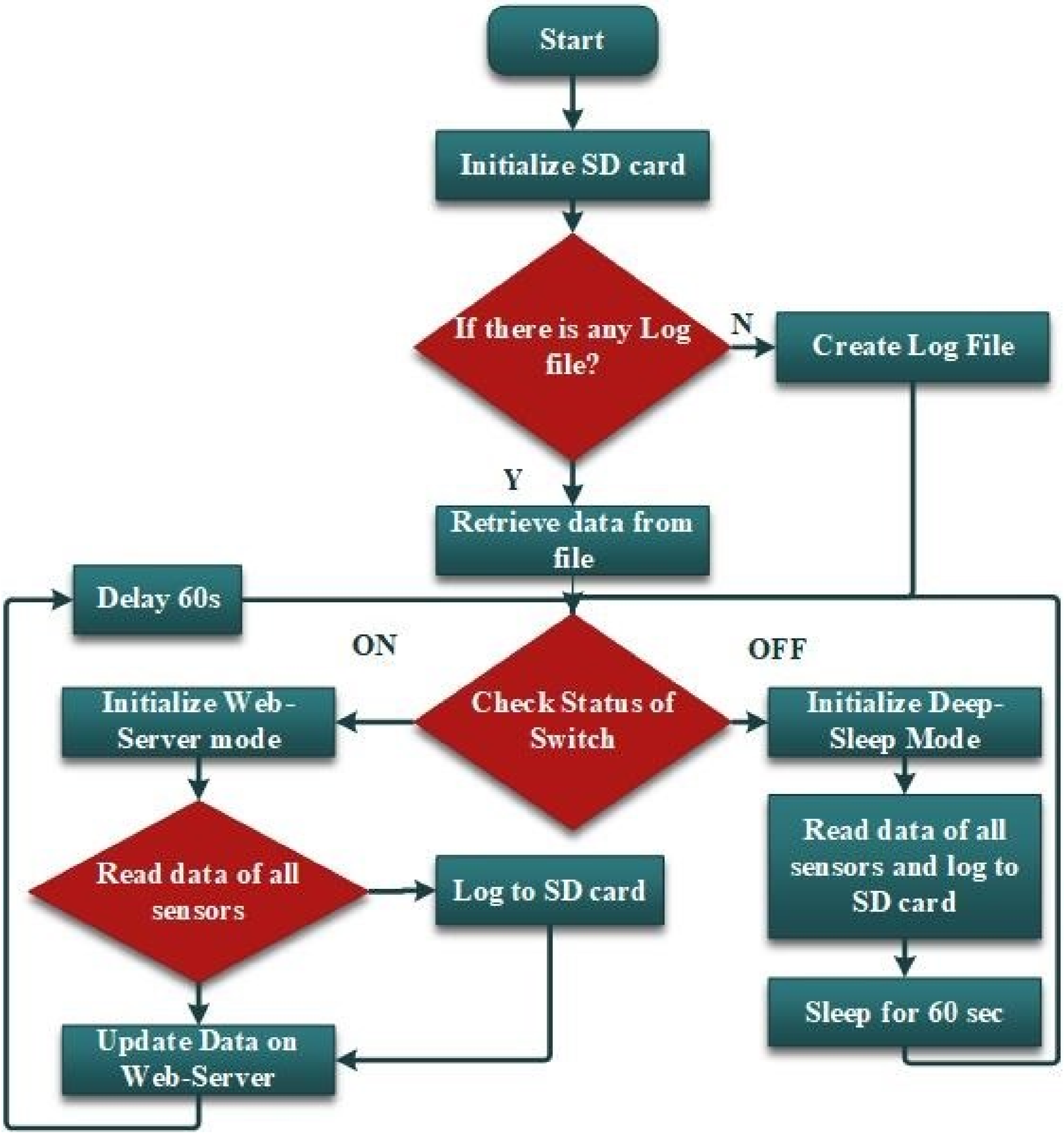


Figure 4.10: Basic algorithm of data-logger

It can clearly be observed by figure 4.10 that the data-logger is programmed to operate in two different modes by using the different positions of toggle switch.

1- Deep-sleep Mode
2- Monitoring Mode

4.3.1- Deep-Sleep Mode

The data-logger will operate in deep-sleep mode if the toggle switch is in off position. This mode is also called power saving mode because the self-power consumption of data-logger is near to zero during deep-sleep mode. The data-logger is programmed to wake-up for one second in every 60 seconds cycle to get the readings of PV system. RTC memory is the only memory of microcontroller that remains powered-up during deep-sleep mode so the energy measurement data of PV system is stored in RTC memory of microcontroller. The microcontroller also stores the collected PV data to external memory card during one second of wake-up time.

4.3.2- Monitoring Mode

The data-logger operates in monitoring mode if the toggle switch is at on position. This mode can also called web-server mode because a local web-server is programmed in data-logger by using HTML codding. The microcontroller initializes a local web-server for monitoring and data management purpose by detecting the on position of toggle switch. The microcontroller is assigned with a local IP during monitoring mode and any device connected to the data-logger through WiFi can be used to access the designed web-portal of data-logger by using the assigned IP of microcontroller. The PV data of locally installed PV system can be monitored and managed by using this web-portal. The designed web-portal shows the dials for monitoring the real-time PV power, PV voltage, PV current and light intensity. The data stored in memory card can be downloaded or deleted by using this web-portal. Figure 4.11 shows the main page of designed web-portal.

Figure 4.11: Web portal of data-logger

The time interval of data-logging, refresh rate of web-portal, sleep time of data-logger and voltage measuring range of data-logger can also be adjusted in monitoring mode of data-logger. The self-power consumption is very high during monitoring mode because all the parts of data-logger operates at full capacity during this mode. Monitoring mode is only recommended to be used for downloading data from data-logger or fault analysis of PV system.

4.4- Lab Testing Setup of Data-Logger

The photovoltaic test system consists of 2 solar modules of 140W each. Both modules are connected to a 12V battery unit through a maximum power point tracker (MPPT) based charge controller. Figure 4.12 shows the control scheme of the installed system along with the data-logger. The MPPT controller adjusts the output of the DC-DC converter after sensing the current and voltage feedbacks of solar panels. The same current and voltage feedback is also connected to the data-logger for monitoring and data-logging purpose.

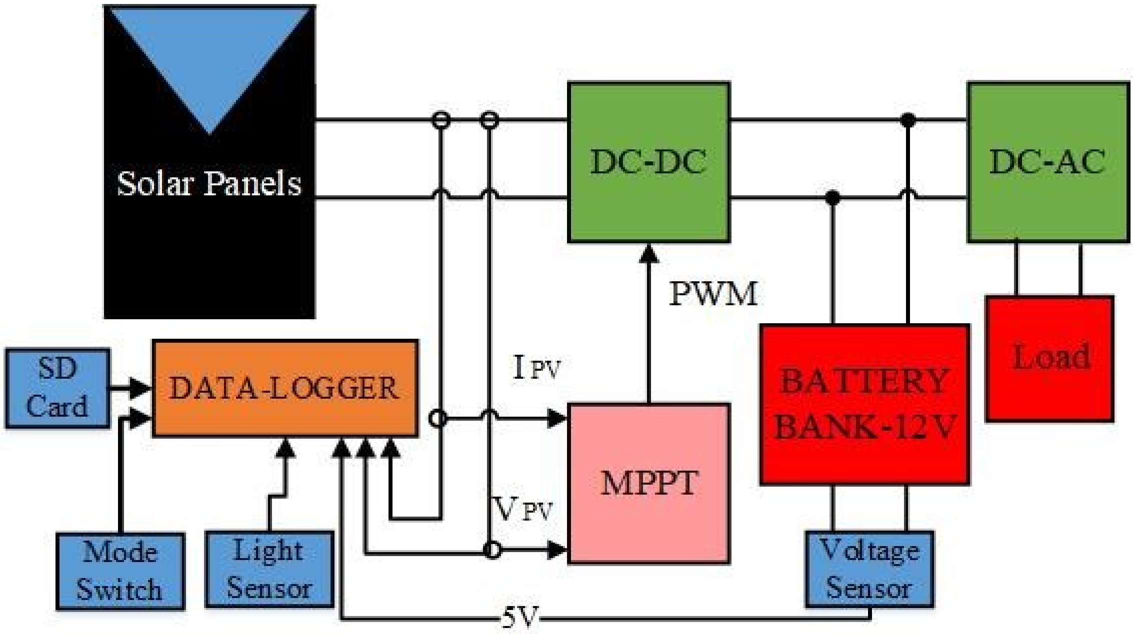


Figure 4.12: Control and data-logging of isolated PV system

Figure 4.13 shows the hardware connection setup of the designed data-logger. The data-logger is connected to one PV incoming bus to log and monitor the data of that specific panel. The laptop is connected to the data-logger through a WiFi connection and showing the web portal of the designed system.

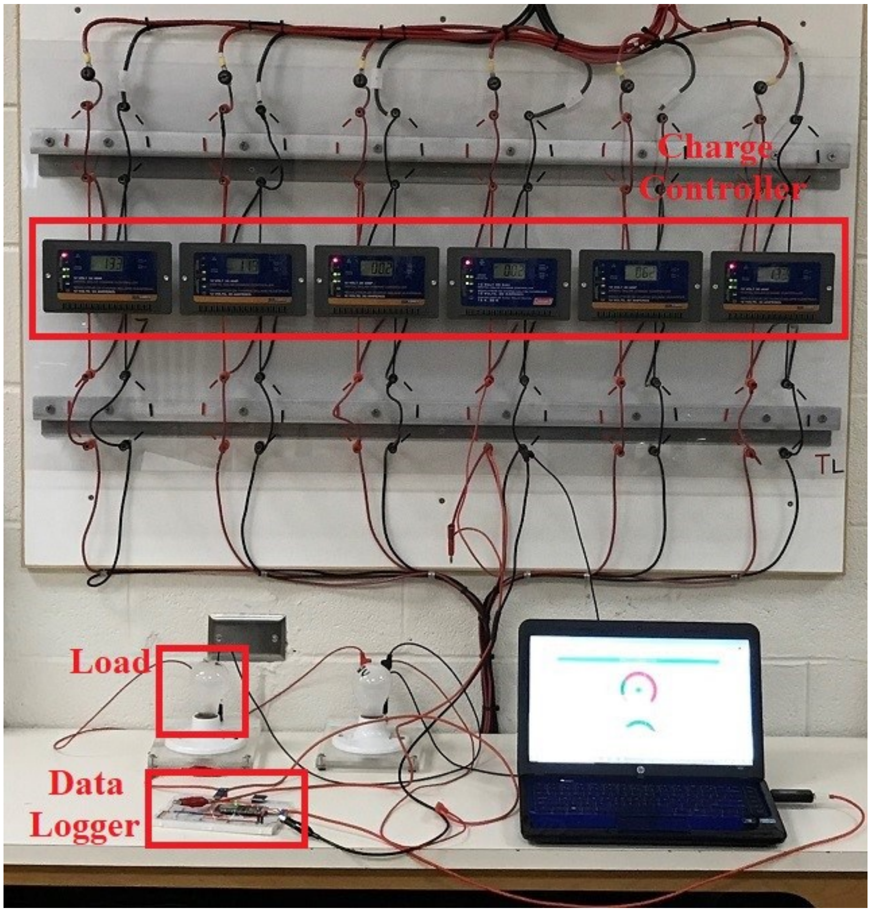


Figure 4. 13: Hardware testing setup

The data-logger showed 98% accurate readings and logged the power, energy, voltage, current and light intensity data all over day in both monitoring and deep-sleep operatin modes.

CHAPTER 5: RESULTS AND CONCLUSION

5.1- Introduction

Design of a PV system for a rural house in Pakistan has been presented An open source ultra-low power data-logger and controller for an off-grid PV application is also designed in this research. The designed system is installed on a PV system in lab for testing purpose. All the operations and functions of designed system are tested in lab. This chapter describes the test results, self-power consumption, costing and future prospective of designed data-logger.

5.2- Energy Consumption of Designed Data-Logger

The main motive of this research is to reduce the self-power consumption of a PV data-logger. ESP32-S2 has a feature of deep-sleep mode during which the self-power consumption of this microcontroller is near to zero. This mode is also called power saving mode. The central processing unit, major portion of the RAM, all digital and analog peripherals of microcontroller remains off during deep-sleep mode. Only RTC memory, RTC clock, RTC controller, RTC peripherals, and ultra-low power processor can be used during this mode. The current consumption of microcontroller in designed deep-sleep mode is 2 5µA at 5 VDC [41]. This data has been extracted from the datasheet provided by the manufacturer of this microcontroller. The datasheet of this microcontroller also shows its self-power consumption in other operating modes. Current consumption of 25 µA means that the power consumption of selected microcontroller in deep-sleep mode is 0.125 mW.

A USB based energy meter is used for measuring the power consumption of designed data-logger. Figure 5.1 shows the self-power consumption of data-logger during monitoring mode. This figure shows that 86 mA is the maximum current that this data-logger can consume.

Figure 5.1 Self-Power consumption during monitoring mode

The test results show that the current consumption of the designed data-logger is less than 1 mA during deep sleep mode. The energy meter which is used for power measurement of designed system cannot measure a current less than 1 mA so it shows a current consumption of 0.000 mA during deep-sleep mode. Figure 5.2 shows the current consumption of designed data-logger during deep-sleep mode.

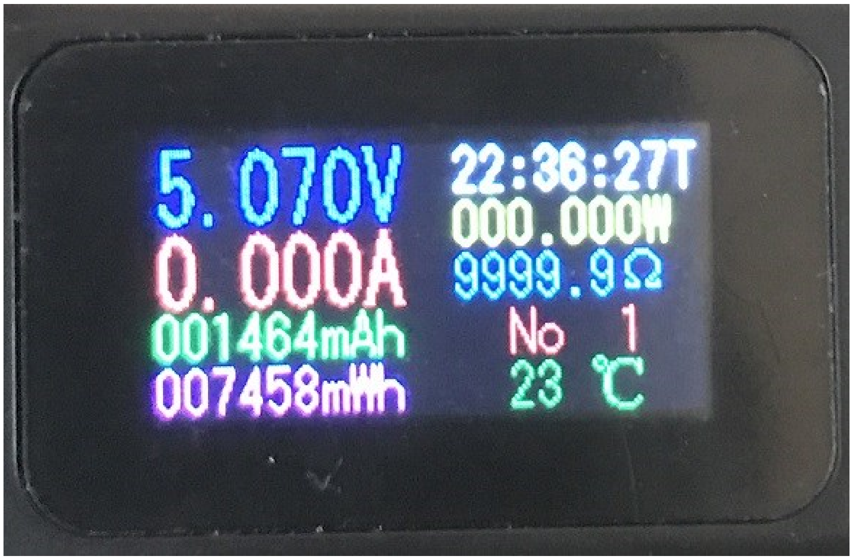


Figure 5.2 Self-power consumption during deep-sleep mode

The data-logger is programmed to wake-up for 1 s during each 60 s cycle and the current consumption during wake-up time is 27 mA to 35 mA as shown in figure 5.3.

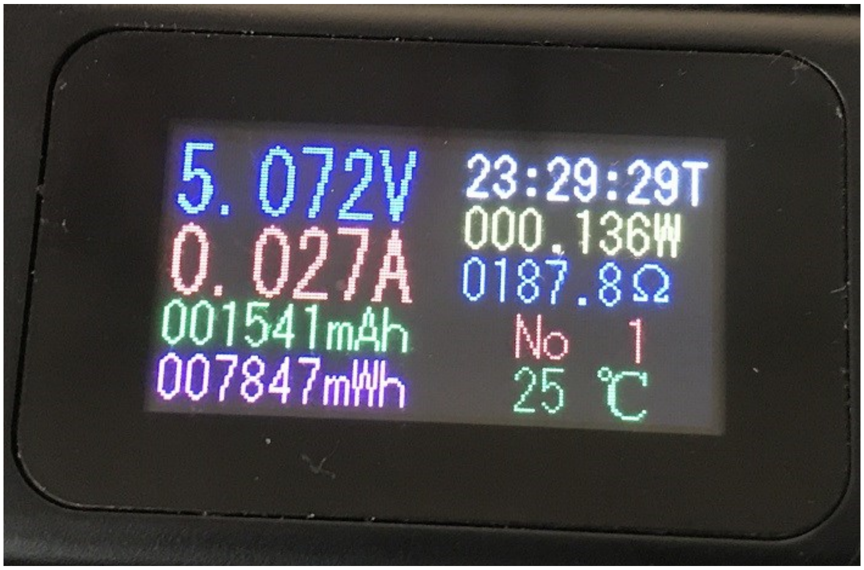


Figure 5.3 Self-power consumption during wakeup time

The power consumption of the data-logger can be calculated by the following formulas.

Nominal Voltage = 5 V

Current consumption during deep sleep = 0.9 mA

Power consumption in deep sleep = $P_1 = 5 \times 0.0009 = 4.5$ mW

Current consumption during wakeup = 35 mA

Power consumption during wakeup = $P_2 = 5 \times 0.035 = 175$ mW

Time of each cycle = T = 60 s

Total cycles per hour = 60

Hourly deep sleep time = $T_1 = 59$ min

Hourly wakeup time = $T_2 = 1$ min

Energy consumption of deep sleep time = $E_1 = (T_1 \times P_1)/60$

$E_1 = (59 \times 4.5)/60 = 4.42$ mWh

Energy consumption of wakeup time = $E_2 = (T_2 \times P_2)/60$

$E_2 = (1 \times 175)/60 = 2.91$ mWh

Total hourly energy consumption = $E = E_1 + E_2$

$E = 4.42 + 2.91 = 7.33$ mWh

Annual Energy = $7.33 \times 10^{-3} \times 24 \times 365$

Annual Energy consumption = 64 Wh

The calculation shows that the designed data-logger is consuming only 64 Wh per year, which is ultra-low for a PV data-logger. 64 Wh power consumption means that a battery of 5 V, 8 Ah can run this data-logger for more than six months without any external power source.

5.3- Cost of Designed Data-Logger

The designed data-logger is cost effective because all of its components are not much expensive. Table 5.1 shows that the total cost of designed data-logger is not more than 30 CAD.

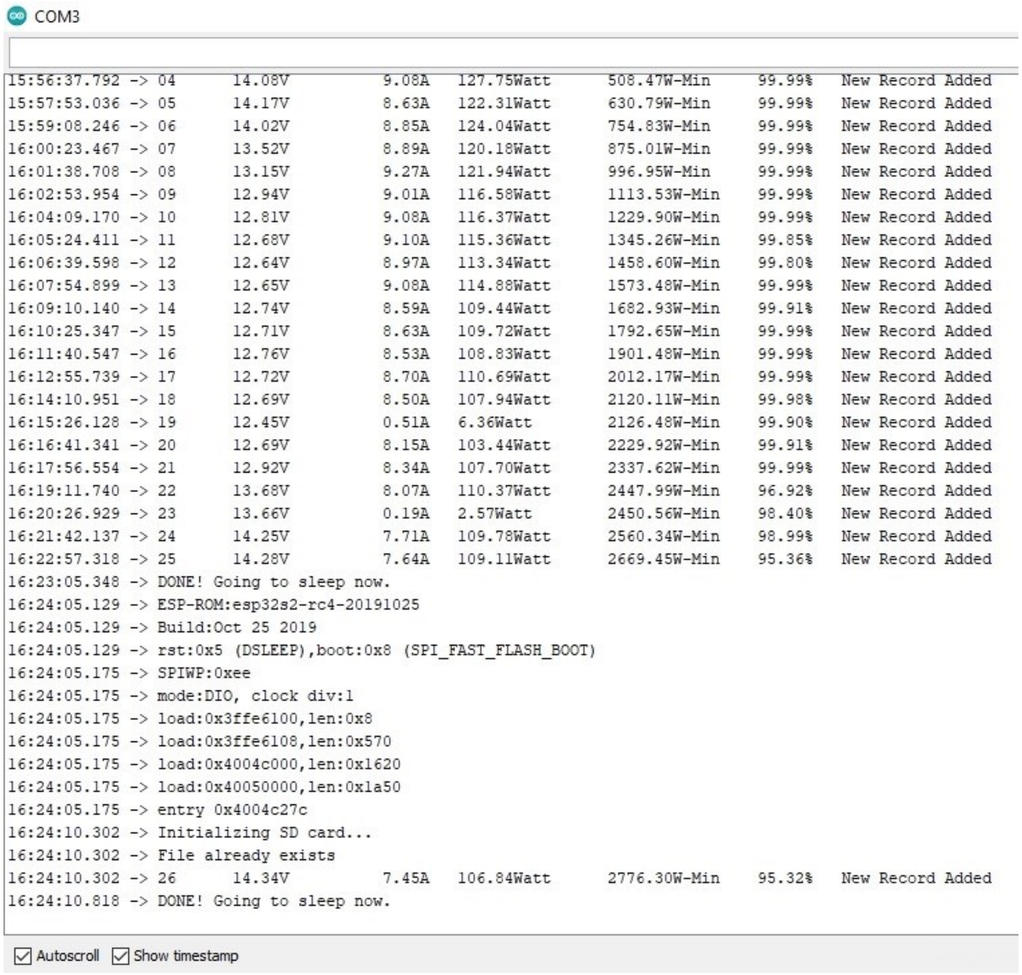
Sr.	Components	Price C$
1	ESP32-S2-WOOR	6.60
2	Card reader	0.50
3	Memory card	5.50
4	Current sensor	1.50
5	Light sensor	0.10
6	Voltage sensor	0.10
7	Selector switch	0.60
8	LED light	0.10
9	Miscellaneous	15.00
	TOTAL	30.00

Table 5. 1 Costing of designed data-logger

All the components are ordered online from China. This data-logger provides a very simple design with less possible components. The most expensive part of this data logger is microcontroller with a total price of 6.60 CAD which does not include the delivery cost to Canada. The cost of this data-logger can be reduced more while ordering the components on bulk quantity. The cost analysis results show that this research provides a cost effective PV data-logging solution along with ultra-low self-power consumption. The main reason for not providing local LCD display is to reduce the cost and power consumption of this data-logger.

5.4- Testing Results

There are three different ways to extract and monitor the logged data from data-logger. Real-time operation of data-logger can be monitored by using Arduino IDE software. The data-logger must be connected to a computer through USB cable for this purpose. The monitoring mode of Arduino IDE shows all the operation of data-logger. Figure 5.4 shows the operation of data-logger in Arduino IDE.

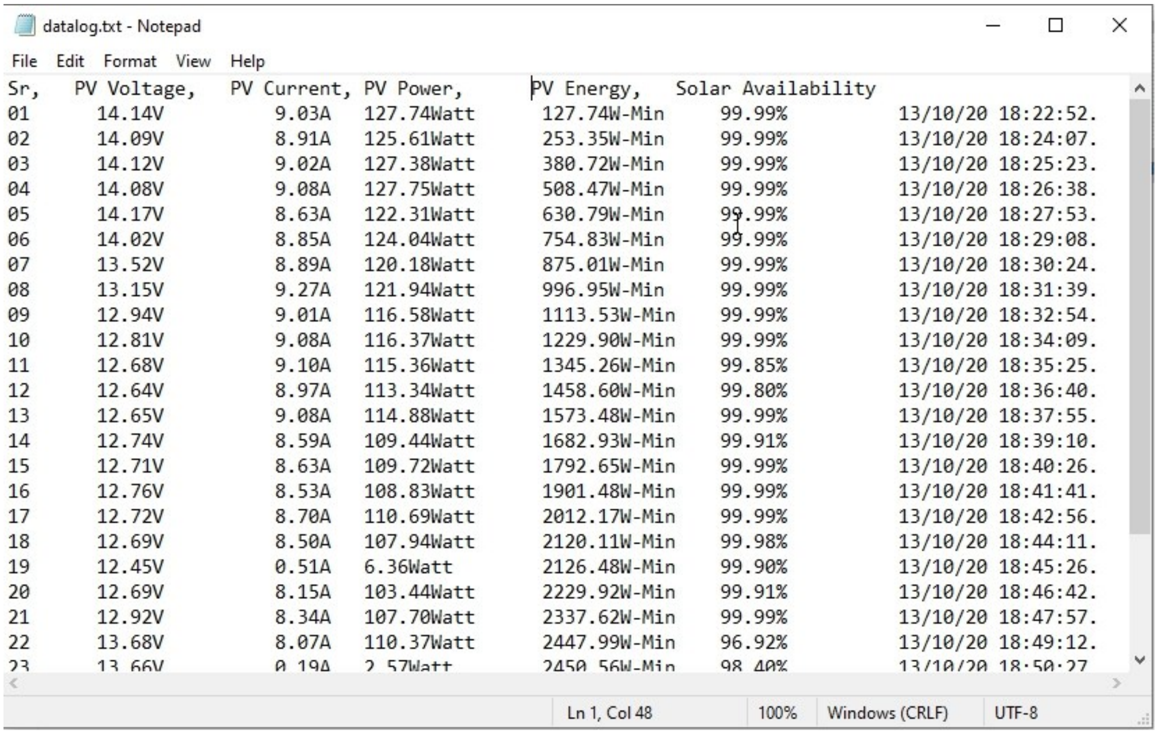


```
15:56:37.792 -> 04      14.08V          9.08A   127.75Watt      508.47W-Min     99.99%   New Record Added
15:57:53.036 -> 05      14.17V          8.63A   122.31Watt      630.79W-Min     99.99%   New Record Added
15:59:08.246 -> 06      14.02V          8.85A   124.04Watt      754.83W-Min     99.99%   New Record Added
16:00:23.467 -> 07      13.52V          8.89A   120.18Watt      875.01W-Min     99.99%   New Record Added
16:01:38.708 -> 08      13.15V          9.27A   121.94Watt      996.95W-Min     99.99%   New Record Added
16:02:53.954 -> 09      12.94V          9.01A   116.58Watt      1113.53W-Min    99.99%   New Record Added
16:04:09.170 -> 10      12.81V          9.08A   116.37Watt      1229.90W-Min    99.99%   New Record Added
16:05:24.411 -> 11      12.68V          9.10A   115.36Watt      1345.26W-Min    99.85%   New Record Added
16:06:39.598 -> 12      12.64V          8.97A   113.34Watt      1458.60W-Min    99.80%   New Record Added
16:07:54.899 -> 13      12.65V          9.08A   114.88Watt      1573.48W-Min    99.99%   New Record Added
16:09:10.140 -> 14      12.74V          8.59A   109.44Watt      1682.93W-Min    99.91%   New Record Added
16:10:25.347 -> 15      12.71V          8.63A   109.72Watt      1792.65W-Min    99.99%   New Record Added
16:11:40.547 -> 16      12.76V          8.53A   108.83Watt      1901.48W-Min    99.99%   New Record Added
16:12:55.739 -> 17      12.72V          8.70A   110.69Watt      2012.17W-Min    99.99%   New Record Added
16:14:10.951 -> 18      12.69V          8.50A   107.94Watt      2120.11W-Min    99.98%   New Record Added
16:15:26.128 -> 19      12.45V          0.51A   6.36Watt        2126.48W-Min    99.90%   New Record Added
16:16:41.341 -> 20      12.69V          8.15A   103.44Watt      2229.92W-Min    99.91%   New Record Added
16:17:56.554 -> 21      12.92V          8.34A   107.70Watt      2337.62W-Min    99.99%   New Record Added
16:19:11.740 -> 22      13.68V          8.07A   110.37Watt      2447.99W-Min    96.92%   New Record Added
16:20:26.929 -> 23      13.66V          0.19A   2.57Watt        2450.56W-Min    98.40%   New Record Added
16:21:42.137 -> 24      14.25V          7.71A   109.78Watt      2560.34W-Min    98.99%   New Record Added
16:22:57.318 -> 25      14.28V          7.64A   109.11Watt      2669.45W-Min    95.36%   New Record Added
16:23:05.348 -> DONE! Going to sleep now.
16:24:05.129 -> ESP-ROM:esp32s2-rc4-20191025
16:24:05.129 -> Build:Oct 25 2019
16:24:05.129 -> rst:0x5 (DSLEEP),boot:0x8 (SPI_FAST_FLASH_BOOT)
16:24:05.175 -> SPIWP:0xee
16:24:05.175 -> mode:DIO, clock div:1
16:24:05.175 -> load:0x3ffe6100,len:0x8
16:24:05.175 -> load:0x3ffe6108,len:0x570
16:24:05.175 -> load:0x4004c000,len:0x1620
16:24:05.175 -> load:0x40050000,len:0x1a50
16:24:05.175 -> entry 0x4004c27c
16:24:10.302 -> Initializing SD card...
16:24:10.302 -> File already exists
16:24:10.302 -> 26      14.34V          7.45A   106.84Watt      2776.30W-Min    95.32%   New Record Added
16:24:10.818 -> DONE! Going to sleep now.
```

☑ Autoscroll ☑ Show timestamp

Figure 5.4 Data monitoring in Arduino IDE

Initial rows in figure 5.4 shows that the data-logger is operating in web-monitoring mode and logging the data after every 60 seconds cycle. After 25th cycle the data-logger goes into deep-sleep mode because the toggle switch is turned off. The data-logger wakes-up after every 60 seconds and check the logged file in SD card. The data-logger analyze the previously logged data and calculates the consistent serial number for new data-entry. The text file of logged data in SD card can be downloaded by using SD card reader or web-portal. Figure 5.5 shows the text file downloaded by using web-portal of data-logger.



```
Sr,   PV Voltage,   PV Current, PV Power,      PV Energy,   Solar Availability
01      14.14V          9.03A   127.74Watt      127.74W-Min     99.99%          13/10/20 18:22:52.
02      14.09V          8.91A   125.61Watt      253.35W-Min     99.99%          13/10/20 18:24:07.
03      14.12V          9.02A   127.38Watt      380.72W-Min     99.99%          13/10/20 18:25:23.
04      14.08V          9.08A   127.75Watt      508.47W-Min     99.99%          13/10/20 18:26:38.
05      14.17V          8.63A   122.31Watt      630.79W-Min     99.99%          13/10/20 18:27:53.
06      14.02V          8.85A   124.04Watt      754.83W-Min     99.99%          13/10/20 18:29:08.
07      13.52V          8.89A   120.18Watt      875.01W-Min     99.99%          13/10/20 18:30:24.
08      13.15V          9.27A   121.94Watt      996.95W-Min     99.99%          13/10/20 18:31:39.
09      12.94V          9.01A   116.58Watt      1113.53W-Min    99.99%          13/10/20 18:32:54.
10      12.81V          9.08A   116.37Watt      1229.90W-Min    99.99%          13/10/20 18:34:09.
11      12.68V          9.10A   115.36Watt      1345.26W-Min    99.85%          13/10/20 18:35:25.
12      12.64V          8.97A   113.34Watt      1458.60W-Min    99.80%          13/10/20 18:36:40.
13      12.65V          9.08A   114.88Watt      1573.48W-Min    99.99%          13/10/20 18:37:55.
14      12.74V          8.59A   109.44Watt      1682.93W-Min    99.91%          13/10/20 18:39:10.
15      12.71V          8.63A   109.72Watt      1792.65W-Min    99.99%          13/10/20 18:40:26.
16      12.76V          8.53A   108.83Watt      1901.48W-Min    99.99%          13/10/20 18:41:41.
17      12.72V          8.70A   110.69Watt      2012.17W-Min    99.99%          13/10/20 18:42:56.
18      12.69V          8.50A   107.94Watt      2120.11W-Min    99.98%          13/10/20 18:44:11.
19      12.45V          0.51A   6.36Watt        2126.48W-Min    99.90%          13/10/20 18:45:26.
20      12.69V          8.15A   103.44Watt      2229.92W-Min    99.91%          13/10/20 18:46:42.
21      12.92V          8.34A   107.70Watt      2337.62W-Min    99.99%          13/10/20 18:47:57.
22      13.68V          8.07A   110.37Watt      2447.99W-Min    96.92%          13/10/20 18:49:12.
23      13.66V          0.19A   2.57Watt        2450.56W-Min    98.40%          13/10/20 18:50:27
```

Figure 5.5 Data logged in Text file

The total capacity of SD card is 16 GB and this card can easily store the PV data for years without any trouble. The SD card can easily be replaced by another card (32 GB Maximum) to increase the storage capacity of data-logger.

5.5- Conclusions

Data-logging and monitoring system plays a very important role in continuous, efficient and effective operation of a PV solar energy unit. User can easily manage the maintenance and cleaning schedule of a PV system by using the stored data. Cleaning period of solar panels at specific location can be determined by comparing the PV output and sunlight availability data of data-logger. Historical data of this data-logger can be used to improve the designing and implementation of new solar PV systems for that specific region. Regular maintenance, cleaning and quick fault detection of a solar PV unit by using a data-logger ensures the smooth and trouble-free operation for many years.

Energy consumption data of a rural house in Pakistan is collected for the designing of an off-grid PV energy unit. The simulation results of designed system shows that the selected house can run throughout the year only by the energy produced by the PV energy unit. All the components of designed PV energy unit are readily available in local market so there will be no trouble in maintenance of this system in future. Annual data of solar irradiance and temperature is also considered to determine the expected output of designed system. The designed system consists of four solar panels of 140 W each, two batteries to create a battery bank of 24 VDC and an inverter of 1 KW with inbuilt charge controller. Each solar panel provides 17.2 VDC and two solar panels are connected in series to get them in the MPPT range of charge controller. Solar panels can provide power to the load and charge batteries at the same time. The expected life of battery bank is 12 years at normal room temperature. The simulation results show that the designed system is cost effective and efficient for selected rural house.

In this thesis, an open-source, ultra-low power, low cost and efficient data-logger and monitoring system is also developed for an off-grid PV energy system. This data-logger stores all required parameters of PV system in external memory card. This data can be accessed by using a web-portal from any device connected to the data-logger through WiFi connection. A latest microcontroller ESP32-S2, current sensor, voltage sensor and light sensor are used to develop this data-logger. The total cost of prototype is only around 30 CAD. Moreover, the switching between power saving and monitoring mode is handled by using a simple toggle switch. The annual energy consumption of designed data-logger is only 64 Wh/year which is considered as ultra-low energy consumption. The testing results clearly show that all the objects of this research are achieved efficiently.

5.6- Future Works

An energy efficient and open source data logging and monitoring system is developed for off-grid PV energy systems with limited access to technology and resource due to global pandemic of COVID-19. Some of the features are also kept very simple due to time constraint for this research work of the Master’s Program. Followings are some of the recommendations that can be performed on this system in future to improve its effectiveness.

5.6.1- Better Graphics of Web-Portal

Presently, web-portal of this system is designed to show real-time and historical data of PV system. It shows the dials for each reading from PV system. For future work, some trendcharts and graphs of historical data can also be designed by using some advanced HTML features for better representation of data.

5.6.2- Data Management Settings

The present design of data-logger stores all PV data in a single text file in memory card. An option in setting page of web-portal can be designed to select the size and time spam of each text file so the user can easily select the size of each text file to be stored in memory card like monthly, weekly, seasonal, or yearly data etc.

5.6.3- Centralize Database for Multiple Data-Loggers

The developed data-logger only stores PV data in local memory card. An online database can be designed to store the data from multiple data-loggers to collect data from different locations. This kind of structure can help the PV energy system installation companies to enhance their maintenance services in future.

5.6.4- Load Management

The designed data-logger only store the basic parameters of PV system. A load management system can be designed by controlling the connecting load as per the capacity of battery bank. Data-logger can be used to turn off the non-essencial load during cloudy days or night time if the storage of battery bank is below selected levels.

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