EcoCharge – "Smart 1kW MPPT Solar Controller"

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Abstract— ***The increasing need for cleaner forms of energy, mainly solar energy, calls for special efforts to design energy harvesting and management systems that are effective and cheap. The present work is thus compelled to report the construction and operative testing of Eco Charge– a 1kW MPP tracking solar charger controller based on Arduino and ESP32 for wireless networking and online monitoring. It also utilizes the P&O algorithm for MPPT to achieve maximum efficiency in the photovoltaic power conversion operating at different environmental variations whenever required. The main feature of Eco Charge which enhances the usability is the use of ESP32 which allows the user to monitor and operate the system using the internet. This is increasingly becoming a necessity for solar energy applications as it enables end users to view system operational status, energy generated, and environmental conditions from anywhere across the globe over the internet. In addition, the charge controller is also designed to be less expensive compared to the existing industrial MPPT charge controllers by applying the concepts of hardware and software open source, hence encouraging usage of solar systems on individual discrete or small scale. The hardware construction of Eco Charge consists of an Arduino microcontroller as the CPU, which is interfaced with a series of voltage and current sensor arrays that are constantly updated with the output of the solar panel and the battery status. The site-specific Maximum Power Point Tracking (MPPT) technology uses such information to manipulate the duty cycle of a buck-boost converter, maximizing the solar panels' output power on the load connected. The electrical products in this engineering project, especially the development board Arduino, have been selected due to its low price, simple execution and a large number of additional libraries and peripheral devices. Furthermore, with the integration of the ESP32 module into the system, it enables the users to utilize wi-fi communication, thereby improving the functionality of the system and easily integrating it into IOT systems. Use of the online based controls allows users to manage the system from any part and so improves the performance of energy consumption in the system. From the experimental findings, it can be observed that the energy harvesting efficiency of the solar cells was considerably increased as compared to conventional charge controllers that do not have MPPT included in them. In a series of tests conducted by Eco Charge, an improvement of up to 20% in power was registered depending on temperature effects and other characteristics of a solar panel. Additionally, the system could still stay operational amidst variations. Apart from energy saving, Eco Charge offers users high value wireless monitoring, which provides them with information about the trends in energy generation and other appropriate system failures like low battery or malfunctioning sensors. Such integrated IoT surveillance features are beneficial for the solar energy applications as they permit a longer outlook on the installed systems especially in rural or off grid conditions where routine repair works would be difficult. All in all, it is noteworthy that Solar Charge offers the client an adequate, flexible and modern solution for the management of solar power generation. The novel fusion of MPPT contenders with IoT observant features leads to rejection of closed source design of solar chargers, making startups and individuals reliant on alternative energy sources.***

Indexed Terms- Maximum Power Point Tracking (MPPT), Solar charge controller, Arduino, Espressif System 32 (ESP 32), Battery Storage System.

I. INTRODUCTION

In light of the emerging global perspective to totally adopt renewable forms of energy, solar power has emerged as one of the solutions in combating carbon footprints and the overwhelmed demand for clean energy. Solar energy is one of the most widely distributed energy sources and the most environmentally safe with the possibility to be used on a large scale. However, one of the significant factors that hinder efficient usage of solar energy systems is the reliability and consistency of solar power generation with regard to weather patterns, solar intensity, and the temperature. Those can vary considerably the available energy output of a solar panel, and therefore results in waste of a lot of useful available solar energy. In order to tackle this problem, the Maximum Power Point Tracking (MPPT) has been created in order to allow solar energy systems to be used optimally by making the operating point of the solar energy system as close as possible to the operating point of the solar panels. This is the shortfall of the available MPPT device where it is never utilized comprehensively in a portable, DIY solar power device or devices owing to the intricacy and expense that accompanies its usage. In addition, a large number of the currently available solar charge controllers do not come with any sophisticated options like performance monitoring, remote control, real time monitoring etc. that make performance optimization possible and warranty. Conversely, MPPT technology is one area in which the efficiency of solar power systems can be greatly enhanced, but in many of the cheap mass-produced solar charge controllers available today, either MPPT is not implemented at all, or when it is, it is poorly implemented, particularly in DIY applications. This results in more loss of energy and a decreased efficiency of the solar system in question. Also, lack of integrated monitoring systems renders it hard to evaluate changes in the system and adapt its features to the users' needs based on these changes. Previous approaches entail physical changes, which can be which it is possible to monitor and manage the device remotely. Many systems that are currently available necessitate on-site intervention with the purpose of overseeing the generation of energy and altering parameters, which makes them quite suitable for home users or those who are managing a number of generators at various sites. Furthermore, security and privacy issues are emerged with the proliferation of the using the IoT-enabled systems because maintaining the integrity of data and protecting the data from unauthorized access is the great concern. The purpose of this work is to design, build and create a high efficiency 1kW solar charge controller with an accurate and efficient MPPT algorithm. The system will be developed on an Arduino board which will perform the MPPT algorithm and will be also responsible for controlling the overall system. Moreover, to allow the users having access to the system for remote control with the ability to control heating/cooling and make adjustments in real time, further components include the ESP32 microcontroller for Wi-Fi connection. This will enable a user to monitor various systems performance indicators such as voltage, current and temperature, to guarantee that the system performs at optimum conditions in every weather condition. However there are other issues of security and system integration which the project aims to go further than merely monitoring. Security measures should also be tightened so as to ensure that no data is tampered with or accessed by unauthorized personnel -- hence enhancing the reliability of remote management to the users. Consequently, the project will deliver a cost-effective and easily reproducible model that appeals to DIY fans, homeowners and any operator of a small-scale solar power system to enhance energy efficiency.

II. CONTRIBUTION

1. This project will afford innovative solutions to the problem and thus make a substantial impact in the fields of renewable energy, electronics, and IoT. The key contributions of this project include: The key contributions of this project include: 2. MPPT- Based Efficiency Optimization: Now it is proposed that through incorporating an Arduino-driven MPPT algorithm, the utilization of the extracted solar energy by the solar charge controller will be optimized constantly by reaching the point of maximum power transfer irrespective of varying conditions. 3. Remote Monitoring and Control: The integration of ESP32 microcontroller will facilitate wireless connection and means that clients can control and monitor the entire system through web or a mobile application. This feature particularly contributes to the functionality of the system as it brings about up-to-date information on power production, system status, and conditions of the environment: thus enabling quick changes for proper functioning. 4. Enhanced Security Protocols: In addition, the system will use modern security measures to guard the data that is to be transferred over the network from being accessed by undesirable persons. This is especially so since the number of devices connected to the Internet of Things (IoT) continues to grow with others being vulnerable to cyber miscreants. Organization's focus on security in managing the information reinforces dependability and soundness of systemic surveillance and command. 5. Scalability and Future Potential: This should be good design since it will be scalable; users can add more components to the system for increased powers at any one time in the future. Also, by SIP the foundation is to be created to integrate the machine learning algorithms that can predict and program the behavior of the system within the changing environment conditions and increase the level of the

automation of the solar energy system. Open-Source Accessibility: This work -- using components that are easily accessible like Arduino, ESP32 among others – is going to offer a DIY solution to renewable energy systems that is cheap to implement. It is relatively flexible and can be modified which makes it possible for the community to give it further enhancements and customization. Promoting Sustainability: In the regard of the global trend for renewable energy this project corresponds to the worldwide tendencies and supports the main principles of sustainable development for providing people with more effective and less expensive solar systems. The efficiency of energy usage and the practical display of the systems' characteristics assures that energy is utilized better to decrease dependency on unbounded resources. In conclusion, it is proposed that this project will transform those small-scale solar energy systems and ensure that they become as efficacious as possible, easy to use, and, in addition, will be equipped with a remote monitoring system. With the use of MPPT technology, IoT, and advanced security, which have been incorporated into this work, this project will be a reference point for future development in renewable energy. In general, the project will help to expand access to solar power systems and improve the efficiency and overall management of them to help increase the availability and use of clean energy among individuals and organizations across the world.

2.1 Systematic Literature Review:

Arduino in Solar Systems- Different solar energy systems are now using Arduino microcontrollers due to their cheap, diverse and easy to install nature. Patel and Mehta (2019) show the case of an Arduino MPPT controller for a small-scale PV system to indicate their efficacy in running algorithms and affordable platform. From their study they pointed out that Arduino based systems are capable of achieving efficiency in the range of commercial MPPT controllers at a much lower cost.In addition, the Arduino plays more than the role of the MPPT control as will be discussed. Seng et al. (2021) demonstrate a tracking method using Arduino to adjust the position of the panels during the day or night for maximum efficiency which is 30% more productive than the fixed tilt systems. The authors pay much attention to Arduino's input and output interfaces, highlighting the acceptability of Arduino board for small to medium-size solar application and prototype development due to its flexibility in accommodating numerous sensors and actuators. However, Ramirez et al. (2020) state that Arduino may serve as an excellent platform for educational use and for prototype systems; however, proper industrial applications would necessitate more dependable and exclusive hardware to withstand high-standard real-time applications.

IoT/ESP32 in Renewable Energy- Through the IoT technologies and more specifically by using ESP32 microcontrollers, the potential of monitoring, controlling, and optimizing renewable energy systems has been a possibility. The authors well illustrate ways and means through which IoT integration can bring down the operational costs by a large measure as well as enhance the resilience and efficiency of the system by preventing early detection of the fault.More so, ESP32 contains integrated WI- FI and Bluetooth thus enabling the development of connected renewable energy systems. In their research, date Chen et al. (2023) designed and developed ESP32-based smart grid that includes solar PV system, wind system and energy storage system. Their system incorporates prediction of energy forecasts thus creating an efficient load balancer and energy control system. In addition, Gupta and Sharma (2021) demonstrate an ESP32- based DAQ system for a solar-wind hybrid system, which presents the real-time performance parameters of the installed system; in addition, the mobile application is utilized for the remote control of the system.However, any business venture instantiating IoT in renewable energy systems exposes itself to a number of challenges. Some critical and emerging problems have been identified by Lopez et al. (2023) in the research on IoT application in smart Grid that includes cybersecurity risk and the demand for steady communication platform.

2.2 System Design and Methodology

System Architecture-The solar MPPT system architecture consists of five main components: the solar panel, the MPPT controller which regulates the power from the solar panel that feeds the battery, ESP32 microcontroller for controlling all the operations of the system and the load which is the electrical appliance that draws power from the battery. The solar panel comprises solar cells which convert solar energy to electrical energy that is then regulated by the MPPT controller. This controller is used to ensure that the solar panels are working at their full power and this is in spite of fluctuations in the environmental factors.The optimized power is used to charge the battery which is an energy storage system as depicted in Fig1 above. The major component of the system is the ESP32 microcontroller which oversees the operation of the MPPT controller and the general management of the total system. For instance, it measures voltage, current, and power and output can all be done locally though Wi-Fi can be used to transmit data to a central point.The load consists of the electrical appliances or systems which are powered by this solar installation. It also controls the connection and disconnection of the load depending on battery charged level and power supply.This architecture enables power acquisition, conversion, and storage, besides permitting a monitoring and controlling facility principally based on the IoT systems.

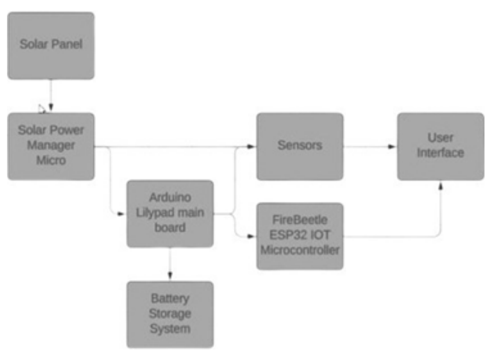

Figure.1: shows the architecture diagram of the project

MPPT Algorithm-The control of the available power is possible by using the Maximum Power Point Tracking (MPPT) algorithm. As for the system used for the control, we select the simplest and most effective one, namely the Perturb and Observe (P&O) algorithm.P&O algorithm is based on the oscillation of the operating voltage of the solar panel and measuring the change in the power produced. The algorithm follows these steps:The algorithm follows these steps:

1. The values of the voltage and the current for the solar panel should be measured.
2. Use the formula for power calculation (Power = Voltage*Current).
3. Apply small distortion (an increase or a decrease) to the voltage.
4. Record the new voltage and new current that has been in use to determine the new power.
5. Compare the new power with the previous power: Compare the newpower with the previous power:

A. If power is raised then keep on perturbing in a similar manner.
B. If power has reduced, then reverse the perturbation in the concerned direction.
C. Repeat steps 3-5 continuously.

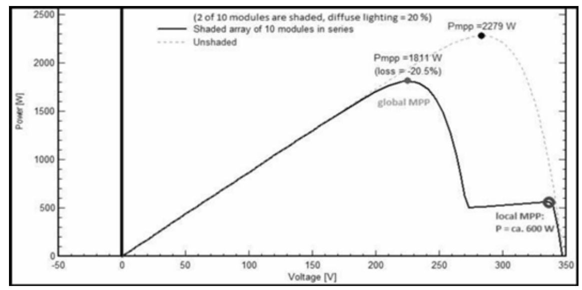

Figure.2- Shows the working principle of the MPPT Algorithm.

MPPT Algorithm:
The P&O algorithm is implemented as a function that runs at regular intervals. Here's a simplified version of the core MPPT function:
'C++'

```
void runMPPT() {
float voltage = readVoltage();
float current = readCurrent();
float power = voltage * current;

if (power > lastPower) {
if (voltage > last_Voltage) {
dutyCycle += stepSize;
}
else {
dutyCycle -= stepSize;
}
}
else {
if (voltage > last_Voltage) {
dutyCycle -= stepSize;
}
else {
dutyCycle += stepSize;
}
}

lastPower = power;
last_Voltage = voltage;
dutyCycle = constrain(dutyCycle, 0, 255);
analogWrite(PWM_PIN, dutyCycle);
}
```

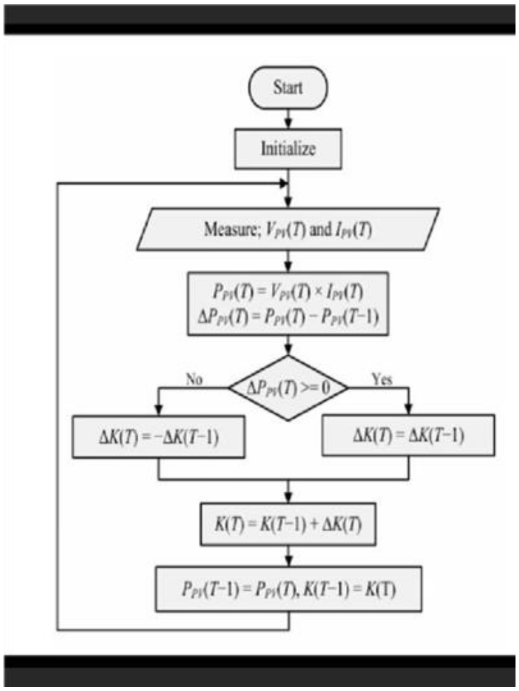

Figure.3: shows the working of MPPT algorithm

3. Major Hardware Components:

1) The LilyPad Arduino Main Board, designed by Leah Buechley together with SparkFun Electronics, uses the low- power ATmega168V or ATmega328V microcontroller. The LilyPad series (LilyPad Arduino Simple and also Simple Snap) does not program easily onto the normal Arduino boards, but rather it requires a USB to Serial interface. The use of the Arduino USB 2 Serial interface is preferred, although any FTDI-compatible interface can be employed. A USB 2 Serial interface operates in the same way as the Arduino UNO and supports the same drivers.

Specification	Details
Microcontroller	ATmega168 or ATmega328V
Operating Voltage	2.7-5.5 V
Input Voltage	2.7-5.5 V
Digital I/O Pins	14
Analog Input Channels	6
DC Current per I/O Pin	40 mA
Flash Memory	16 KB
SRAM	1 KB
EEPROM	512 bytes
Clock Speed	8 MHz

Table1.1

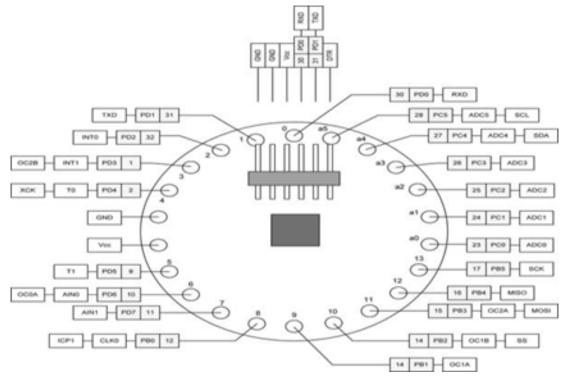

Figure.4: shows the connection diagram of Arduino LilyPad.

2) FireBeetle ESP32 IoT Microcontroller- The DFRobot FireBeetle series offers optimized low-power microcontrollers designed specifically for IoT projects. In this series, the FireBeetle ESP32 stands out as a formidable IoT controller. This ESP32 development board integrates the dual-core ESP- WROOM-32 module, supporting dual-mode communication for microcontroller, Wi-Fi, and Bluetooth. As a result, ESP32 microcontroller to find wider applications in low-power IoT projects, encompassing a broader range of possibilities.

Specification	Details
Working voltage	3.3V
Input voltage	3.3V~5V
Maximum discharge current	600mA
Maximum charge current	500mA
Frequency	240MHz
SRAM	520 KB
Flash	16 MB
Wi-Fi protocol	802.11 b/g/n/d/e/I/k/r
Frequency range	2.4~2.5 GHz

Table1.2

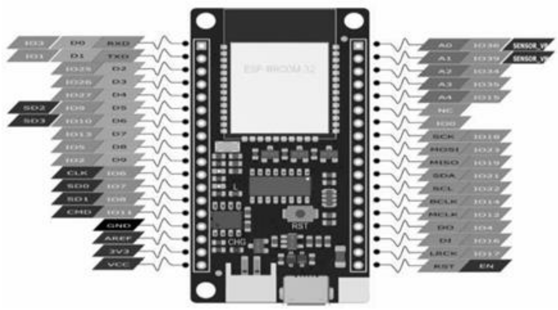

Figure.5 : shows the connections diagram of the ESP32 board

3) Solar Power Manager Solar Power Manager Micro is a compact, high-performance module designed to manage solar power on IoT-based low-power wireless sensors or controllers using small solar panels with voltages from 1V to 3V with power consumption fewer functions use , with built-in MPPT (Maximum Power Point Tracking) function, efficiently harnessing solar energy even in low light conditions This feature enables wireless devices to operate without the need for replacement battery or usually charged. The module uses a constant voltage ratio MPPT algorithm to optimize the power of the solar panel and can charge a 3.7V LiPo battery via solar or USB, delivering charging currents of up to 70mA and 100mA

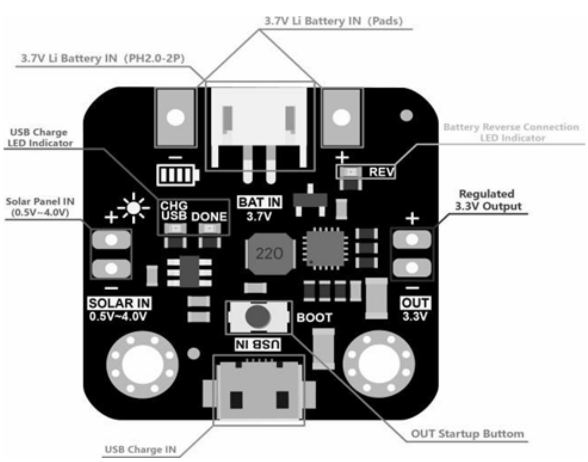

Figure – 6: shows the Connections diagram of the Solar Power Manager.

Specification	Details
Solar Power Management IC	SPV1050
Solar Input Voltage (SOLAR IN)	0.5 V~4 V
Battery Input (BAT IN)	3.7 V Lithium Battery
Charge Current	37 mA @USB IN; 70 mA @SOLAR IN
Overcharge Protection Threshold	4.2 V
Over-discharge Protection Threshold	3.1 V
Regulated Power Supply	3.3 V 90 mA @ BAT IN 3.7 V
Operating Current	<3 uA
Operation Temperature	-40℃ ~ 85℃
Dimension	30.0mm*30.0mm

Table1.3

CONCLUSION

The Arduino MPPT Solar Charge Controller project, 1kW, with ESP32 and Wi-Fi, cares about making the most of available components to efficiently harvest solar energy. The MPPT technology will have the ability to extract maximum possible power from solar panels by continuously readjusting the electrical operating point of the modules. This feature becomes crucial since it enhances general efficiency, especially under variable weather conditions like sunlight and shading. One of the key things in this project is the use of an Arduino microcontroller for handling the MPPT algorithm. Arduino applies in the maker community due to its flexibility, low cost, and ease of use. It easily controls functions on a solar charge controller ranging from battery management, voltage regulation, all the way to power conversion. This then makes it excellent to be used in some DIY solar energy systems, including educational projects.

This project, besides Arduino, also includes the microcontroller ESP32. The ESP32 is a very highly integrated, low-power system-on-chip that includes Wi-Fi and Bluetooth. The incorporation of ESP32 in the design of a charge controller allows intelligence in the system for real-time wireless monitoring. It makes it possible to allow users to monitor solar panel performance, battery status, and system health remotely using a web interface or a mobile application. The adding of Wi- Fi connectivity greatly enhances the user experience of the system, making it scalable for a wide array of applications ranging from off-grid solar systems to hybrid energy set-ups. The project presented is an inexpensive yet powerful solution for solar energy management applicable to small-scale renewable energy installations. MPPT is applied in the system for high efficiency energy conversion; it allows a system to work at an optimum point irrespective of the environmental conditions. Also, remote system monitoring via Wi-Fi capability with ESP 32 offers massive advantages concerning troubleshooting maintenance and performance optimization. It normally consists of the following key components: a solar panel, an energy storage facility that is normally a battery, a load that could be a light or any household appliance, and the charge controller itself. The mechanism of action or operation involved in a charge controller is the regulation of power flow from solar panels coming into a battery for appropriate and safe charging. It avoids overcharge and undercharge conditions in addition to battery damage, which are considered the most important features in the reliability and longevity of the energy storage system. But equally important, aside from this hardware, is the software side. Programming on the Arduino consists of an MPPT algorithm that keeps updating the operating point in pursuit of maximum power output from the solar panels. ESP32 handles the communication by transmitting voltage, current, and temperature values to a web server or a cloud platform for real- time monitoring. The combination of software and hardware makes the system powerful as well as user-friendly.

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