ABSTRACT

("A Novel IOT-based Monitoring and Feedback System for use with Off-Grid Photovoltaic Modules")

The advance in the use of photovoltaics in the field of energy generation is well-documented and offers great promise as an effective candidate for a viable energy solution, particularly for consumers in rural or underdeveloped areas. Consumers in these areas require an effective off-grid solution to this problem in order to ensure sufficient energy is produced to meet the demand of the household. Of course, the major problem with photovoltaics and most other renewable energy generation methods is their intermittent nature. Their varying levels of energy production create a huge mismatch between production and demand over the course of a day. To attempt to combat this problem, previous work created an algorithmic power diversion system combined with a Maximum Power Point Tracking (MPPT) system using the Arduino microcontroller platform. However, the scope of this system was limited and had a minimal user interface.

Given the increased digitization of the energy sector, and the growth of IOT (Internet of Things) based devices, a new system was developed to maximize the feasibility of a long range monitoring system that is able to respond to external conditions and user input in real time, while simultaneously relaying production information to the user. This project uses the Blynk development platform and the previously utilized Arduino system, coupled with the W5100 Ethernet shield to accomplish this. Specifically, the project allows for power production and panel conditions (temperature etc.) to be sent to the user in real time, requiring only a connection to a local network. Furthermore, the user is able to adjust their energy goals based on production or vice versa (algorithmic parameters are adjusted based on the preset goals). The effectiveness of the system arises from the ability of the system to function like the previously utilized system (mean energy availability of 12% more than on-grid system), as well as the ability to accurately provide a functional monitoring interface to the user at different ranges. The meeting of both of these benchmarks will greatly improve the practicality of an off-grid solar panel system for use in the aforementioned areas, while demonstrating that effective real-time monitoring and feedback is possible for many renewable energy production methods.

Novel IOT-based Monitoring and Feedback System for Off-Grid Photovoltaic Modules

ABSTRACT

The advance in the use of photovoltaics in the field of energy generation is well-documented and offers great promise as an effective candidate for a viable energy solution, particularly for consumers in rural or underdeveloped areas. Consumers in these areas require an effective off-grid solution to this problem in order to ensure sufficient energy is produced to meet the demand of the household. Of course, the major problem with photovoltaics and most other renewable energy generation methods is their intermittent nature. Their varying levels of energy production create a huge mismatch between production and demand over the course of a day. To attempt to combat this problem, previous work created an algorithmic power diversion system combined with a Maximum Power Point Tracking (MPPT) system using the Arduino microcontroller platform. However, the scope of this system was limited and had a minimal user interface. Given the increased digitization of the energy sector, and the growth of IOT (Internet of Things) based devices, a new system was developed to maximize the feasibility of a long range monitoring system that is able to respond to external conditions and user input in real time, while simultaneously relaying production information to the user. This project uses the Blynk development platform and the previously utilized Arduino system, coupled with the W5100 Ethernet shield to accomplish this. Specifically, the project allows for power production and panel conditions (temperature etc.) to be sent to the user in real time, requiring only a connection to a local network. Furthermore, the user is able to adjust their energy goals based on production or vice versa (algorithmic parameters are adjusted based on the preset goals). The effectiveness of the system arises from the ability of the system to function like the previously utilized system (mean energy availability of 12% more than on-grid system), as well as the ability to accurately provide a functional monitoring interface to the user at different ranges. Meeting both of these benchmarks will greatly improve the practicality of an off-grid solar panel system for use in the aforementioned areas, while also showing that effective real-time monitoring and feedback is possible for all renewable energy production methods.

PURPOSE/HYPOTHESIS

Purpose:
The purpose of this research is to develop a remote, IOT-based mechanism to improve the user interface and long range functionality of the algorithmic power diversion system constructed before by:
Utilizing the Blynk development platform to transmit information to and from the user in real time by coupling the micro-controller with a cloud-based home network
Adjust the production of the system based on the previously used parameters and others (temperature, user goals) with functionality being equally as effective as before, except for the inclusion of some minimal lag time.
Thus, the developed system should produce at least a 10% increase in total power availability over the course of a day compared to a unmodified, grid-connected panel while being equally as functional as the previous system with the user at least 1 km from the system.

Hypothesis:
It is hypothesized that through the completion of this research, a novel, IOT-based remote monitoring and feedback mechanism will be developed that will be able to increase the total power availability/production capability of a typical photovoltaic system by 11-13 percent* [when compared to an unmodified, "grid-connected" solar system], and being able to effectively relay information to and from the user (adjusting the algorithm in real time as necessary)

**Generated based on analysis of existing data regarding solar panel power production.*

BACKGROUND/METHODS

1. Fundamentals of Photovoltaic Cells and Intermittent Energy Problem
Solar cells are essentially p-n junction diodes that carefully utilize the photoelectric effect in order to produce an electric current. By using a semiconducting material, like crystalline silicon or a Group III-V alloy (here on, just silicon), electrons can be ejected from the material upon acceptance of photons with the required band gap energy -- the energy required to excite a valence electron into the conduction band (for C-Si, this value is around 1.14 eV). This energy corresponds to a maximum wavelength of around 1100 nm. Silicon has a peak efficiency wavelength at close to 680 nm, which is calculated using the Shockley-Queisser function (curve plotting efficiency of semiconductor against photon energy). Solar cells are formed by forming a junction between two oppositely doped (p-type and n-type) semiconductor surfaces in order to produce an electrical imbalance (hole-electron recombination theory) that can be manipulated to produce a current.

Solar panel power production may be impacted by a variety of factors, most notably including temperature, tilt angle, cloud cover and location. High temperatures (band gap decreases, electrons have lower kinetic energy) and extreme tilt angles (photons strike surface at non-perpendicular angles) result in substantial losses to solar panel production. However, the most important determinant of solar panel production is the presence of sunlight with the required excitation energy(appropriate wavelengths). Accounting for all these factors puts a standard solar panel's efficiency close to 18 percent (solar irradiance factor- ~1000W/m^2) Therefore, it is crucial to maximize power collected, and manage power appropriately to minimize wastage. Maximal solar energy production occurs during midday, and demand is at a maximum in the mornings and evenings, when production is minimal.

2. Summary of Previous Work
The previous solution to the intermittent energy problem sought to do three things: 1) keep power coming out of a standard 20W solar panel at a relative maximum, 2) divert power to a battery based on operating condition for later usage, and 3) discharge battery at controlled rate when production is less than predicted demand. This was be done by incorporating two subsystems that were monitored and managed by 2 8-bit microcontrollers.

1. MPPT (Maximum power point tracking): The power production of the system was calculated by periodically measuring the voltage (analog input on Arduino) and the current (indirect measurement using a Hall Effect sensor). The power produced by the solar panel was controlled using PWM/SPI signals sent from the microcontroller to an MCP4131 10Ω digital potentiometer (7-bit, 128 steps; step size ≅ 39 ohms). The power produced was compared to the previous value and adjusted accordingly.
2. Algorithmic Power Diversion: This subsystem will distribute the power going to the battery from the solar panel based on the situation (current production/demand, battery charge level, time of day etc.). Additionally, the discharge rate of the battery will be controlled based on the same factors listed above. These two things are done primarily using 2 IRF510 N-Channel MOSFETs. The interface between the source and drain pins is managed by PWM signals sent to the gate. Various signal values (range 0-255) allow the amount of current flowing into/out of the battery to be regulated based on the situation. The MOSFETs working in tandem minimize the possibility of the solar system operating under a surplus or deficit, resulting in minimal wastage of produced power, while also ensuring that the battery's life is prolonged and charging is regulated at a safe rate.

3. Proposed Solution
This year's work sought to build upon previous work that focused purely on the functional aspect of an off-grid solar panel solution. This was done by developing a functional user interface through the Blynk development platform, which allows for the construction of an easy-to-use digital dashboard that creates an effective connection between the user and the microcontroller systems. Later, the project will be exported into a standalone app that will be available on the Google Play and App Stores. Concerning the hardware utilized in conjunction with the previously developed system, an additional W5100 Ethernet shield is attached to the power diversion microcontroller (the MPPT mechanism doesn't require any user input, however the effectiveness of the MPPT subsystem is provided through the data sent from the power diversion controller → master-slave I2C protocol). The ethernet shield is connected via LAN to the home router, and the router broadcasts the signals sent/picked up by the microcontroller to the cloud, which is then relayed directly to the user's device (a smartphone with the project open. The following parameters are displayed on the user's device: instantaneous solar panel current, voltage, and power conditions; instantaneous battery current and voltage conditions; panel temperature (updated in 20 minute intervals using LM35 temperature sensor); historical power and energy chart over any of the following periods (with the user able to choose period length) -- 1d, 1w, 1m, 3m. Of course, all of these parameters are directly involved in the diversion algorithm described earlier, the sensor is also utilized to control a water cooling system that will allow the solar panel to remain at or near the peak operating temperature ** (implementation not complete).

On the user's end, the user is able to modify expected weekly energy consumption in (on a scale from 60% to 120% of "typical" consumption). Depending on this primary setting, the charge and discharge rate of the battery under different conditions is modified to best meet this expectation. Additionally, the device is optimized to work for any standard solar panel (the panel used in this project is a 20W panel, with Voc = V and Isc = A). Furthermore, update speed is also adjustable → higher speeds require more power diversion to the microcontroller over time. Finally, optimal operating temperature can be adjusted based on user's panel peak operating temperature (the panel used has T_{peak} = 25°C).

4. Existing Solutions
Many commercial panel systems and companies offer remote monitoring methods, however their usage is extremely limited in the current market for photovoltaic technology. The primary reasons include their expensive nature and limited scope. More recently, work by Gusa et al. at Bangka University, Indonesia attempts to offer a smartphone-based remote monitoring solution. Though the system is able to relay data from the panel to the user, the communication is one-directional and not as extensive in the parameters considered as the ones used in this work. Work is continually being done to investigate the ability to incorporate effective remote monitoring alongside photovoltaic and other renewable energy generation methods, but most of these investigations still look at working in conjunction with grid-tied systems, that are limited in their accessibility as mentioned before. Furthermore, many of these systems require a substantial amount of accessory equipment and additional installation.

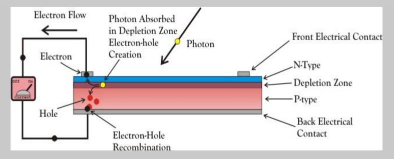


Fig. 1 Cross-Sectional View of Solar Cell upon Illumination

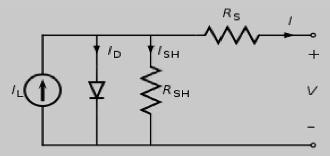


Fig. 2 Simple Equivalent Circuit of a Solar Cell

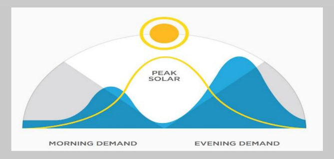
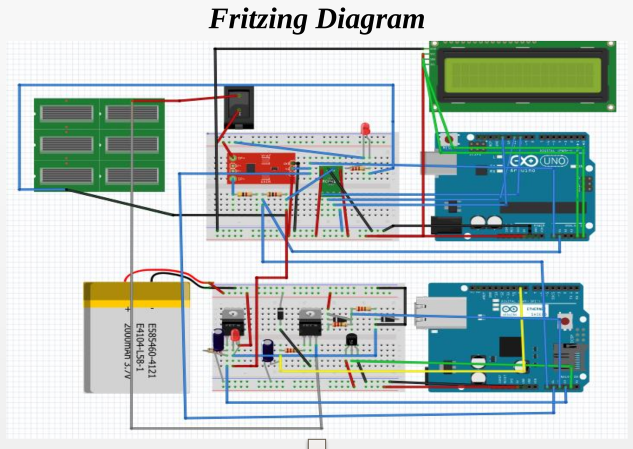
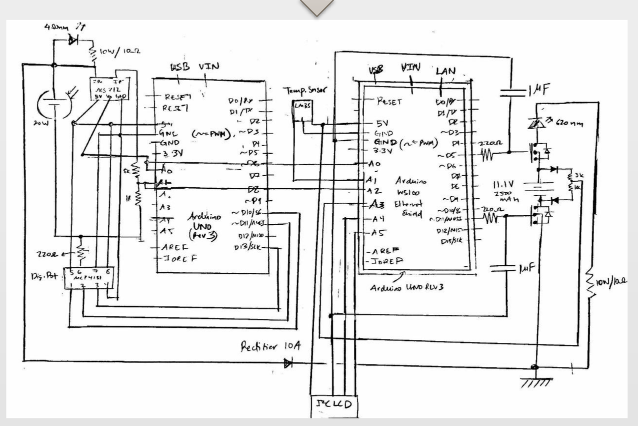


Fig. 3 Energy Demand vs. Production Throughout Day

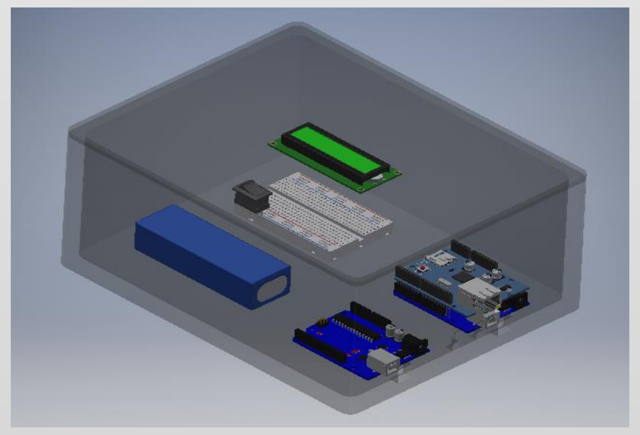
MECHANICAL, ELECTRICAL, AND SOFTWARE IMPLEMENTATION

Fritzing Diagram



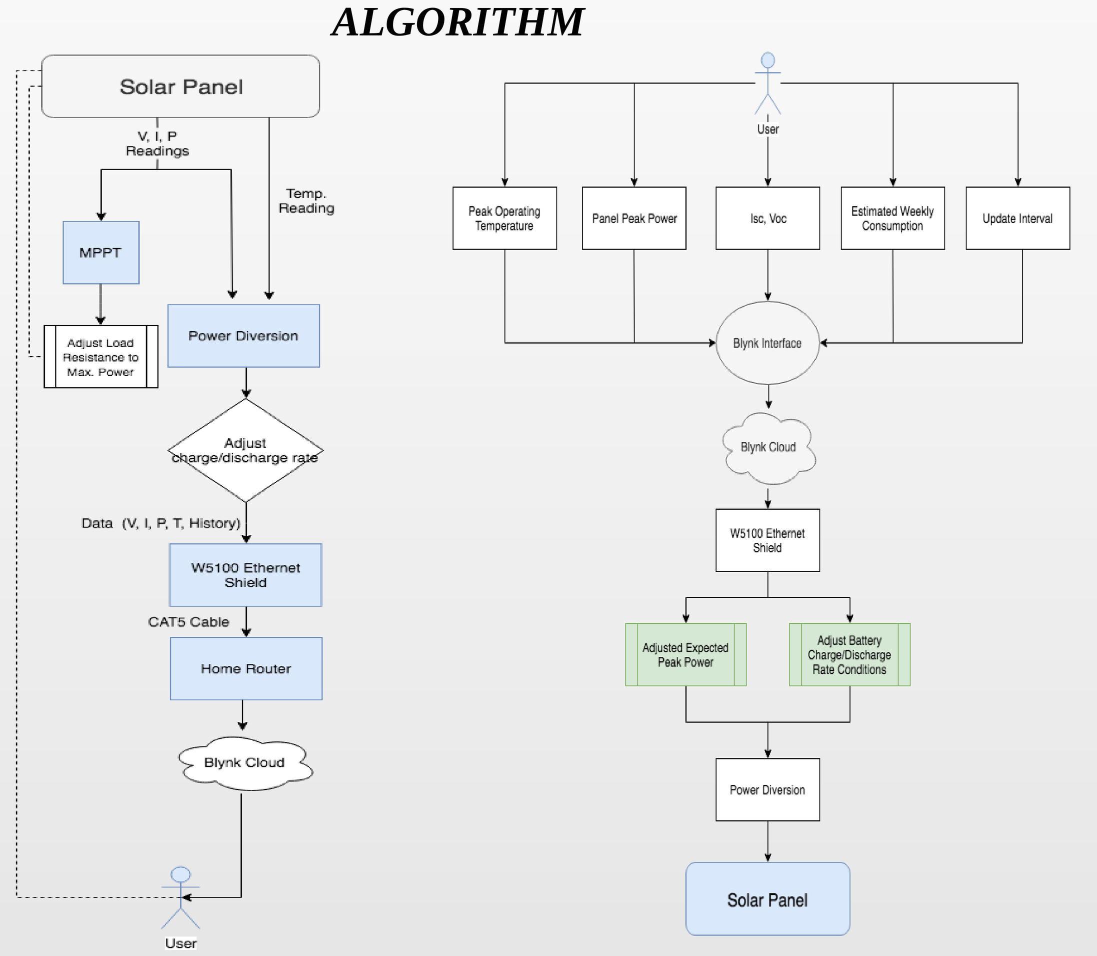


Circuit Schematic

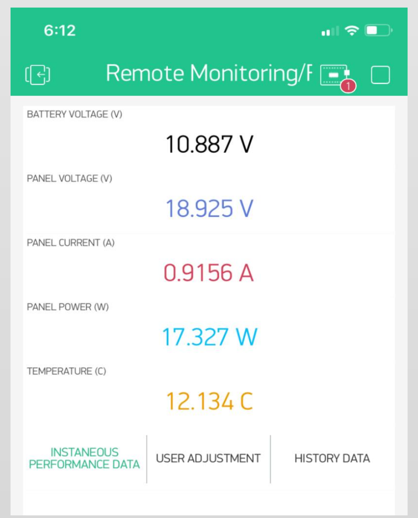


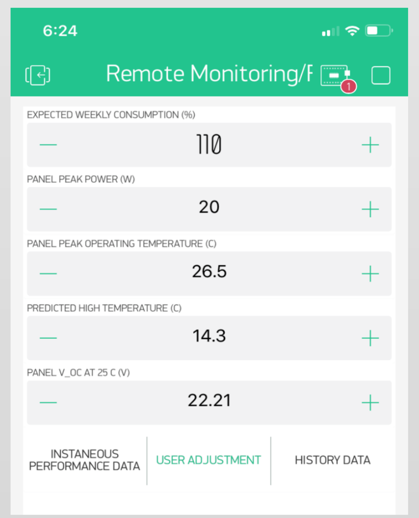
CAD Model of Device Housing

ALGORITHM



Panel → User ***User → Panel***





User Interface Through Blynk App

TESTING

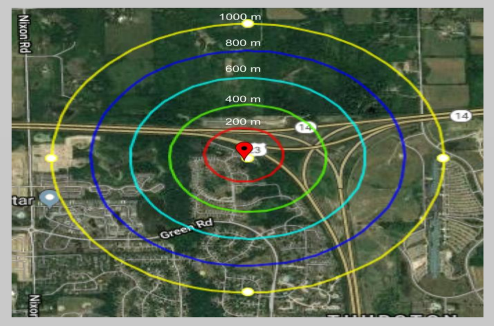
PROCEDURE

Testing the developed system occurs as follows:

- The system functionality is tested using a standard, unmodified, 20W solar panel (Voc = 22.18 V, Isc =1.27 A, Vpp =18.02 V, Ipp = 1.11 A; specifications given for peak solar conditions at 25°C → algorithm adjusts for these expectations under different conditions)
- The novel system is evaluated both against an unmodified panel (analogous to being "grid-connected") and against the local system from last year under different scenarios (described below).
- Of course, the effectiveness of this system is dependent on its performance in being able to ensure that the mean power availability 1) meets the load demand 2) exceeds the mean power availability of the unmodified, grid connected panel by at least 10 percent at any point in the day.
- The developed system's fundamental algorithm is essentially very similar to the prior system, save for the fact that is more dynamic and flexible to other constraints like temperature and panel-specific conditions. Thus, to compare the effectiveness of the two systems against each other, the system must be tested in these dynamic conditions.
- To do this, the power production of the panel under 4 operating temperatures is simulated (don't have to actually get the panel to a certain temperature, instead can simply cap the power production of the panel by including a few dissipating resistors that dampen the power being sent to the loads).
- Change "panel-specific" properties (Voc, Isc, PP) using a similar method and evaluate the two systems against each other with regard to the type of panel being used.
- Modify the load to assess the adjustability of the algorithm to user-specific energy consumption (60% of expected → 120% of expected)
- Lastly, we test the range of the newly developed system by collecting data at the following distances from the panel (measured in meters) : 0, 200, 400, 600, 800, 1000, 1200.
- All of the above criteria are quantitatively measured by evaluating the fractional difference between the panel power production between the 3 systems under each of the various scenarios (a selection of which are included in the upper right).

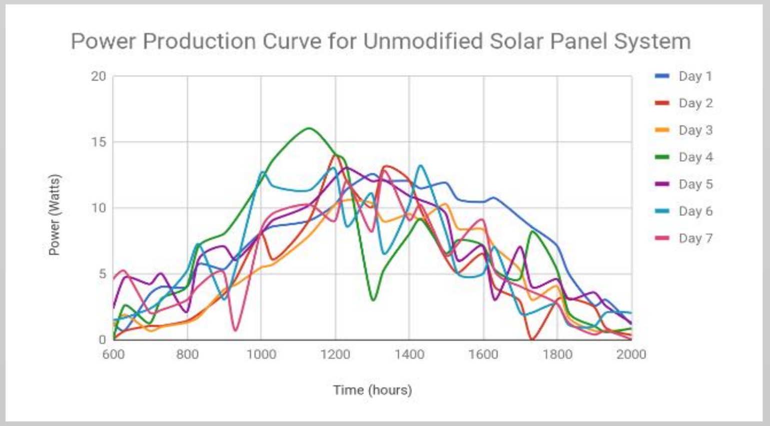
SETUP

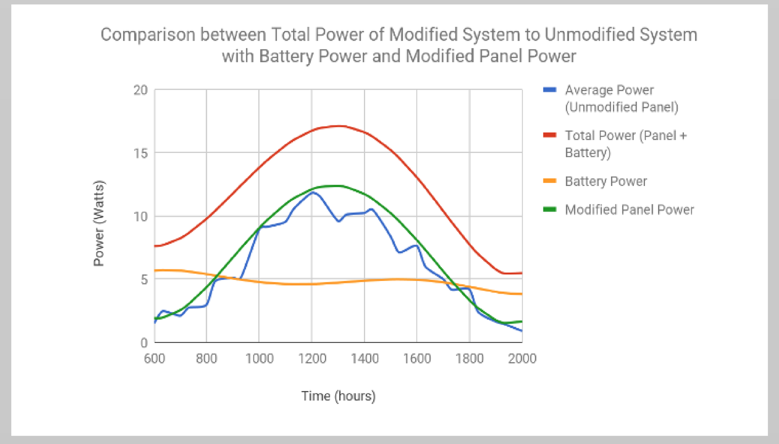
Device Testing



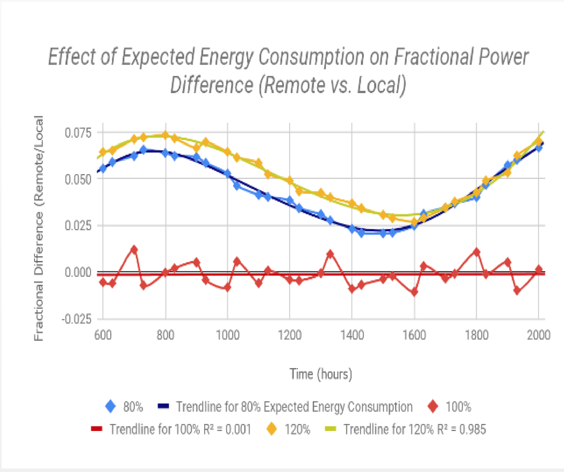
Range Testing

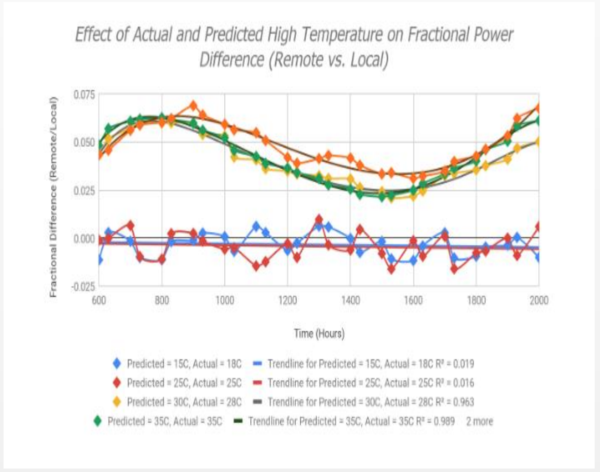
PRIOR RESULTS

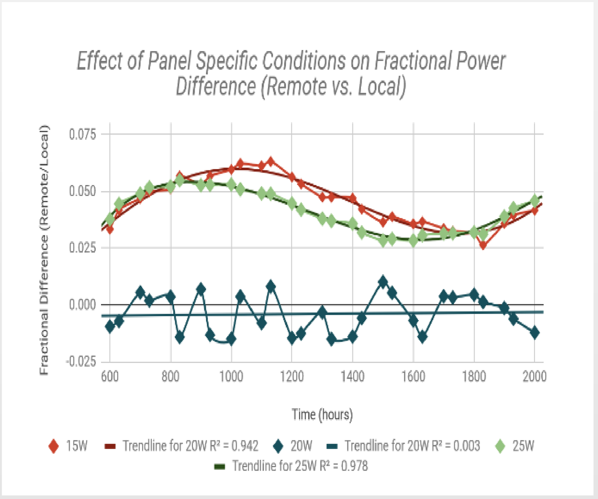




RESULTS







DISCUSSION

Through the completion of this research, a novel method of remotely monitoring and implementing user feedback to a photovoltaic module using IOT-based technology was developed. Such a solution helps to further improve the feasibility of a off-grid solar solution, as well as potential implementation alongside other renewable energy generation technique. The solution improves upon prior work that used maximum power point tracking (MPPT) mechanism (regularly adjusts the circuit load in order to keep the power coming out of the solar panel at a relative maximum) and an algorithmic power diversion mechanism is implemented (periodically divert power to and from a battery based on the current status of the system).

In this system, the Blynk development platform is used to implement a smooth and functional user interface that expands the applicability of the prior solution. The following factors are incorporated to improve the scope of the local solution used before: panel specific conditions (peak operating temperature, peak power, Isc, Voc), expected weekly energy consumption, and predicted daily high temperature. Furthermore, relevant operational parameters are relayed back to the user in real time via Ethernet connection to a local router (microcontroller coupled with W5100 Ethernet Shield), along with 1d, 1w, 1m, 3m history data of panel power production The system is tested against an unmodified panel system with a similar method used to last year, but most importantly, the novel remote monitoring/feedback mechanism is evaluated against the local monitoring mechanism, and the fractional power production difference between the remote mechanism and local mechanism is computed for a set of different user inputs (a set of 3-vectors that describe a certain configuration of the panel system). The systems are tested by modulating the load to simulate the effect of each variation in the input parameter.

From the results of this testing process, the effectiveness of the novel system can be readily observed. In the above graphs, we can see that the novel system, which adjusts the charge/discharge rate of the battery in the power diversion algorithm, yields fractional power differences up to approximately +7 percent in comparison to the local monitoring system for any deviation away from the "standard" panel conditions (20W, 25°C, 100% expected consumption). However, it is observable that for these "standard" conditions, the local mechanism does perform marginally better over the (0600, 2000) time interval (fractional difference between remote and local system is approximately -1.5 percent). Regardless, the overall comparison between the two systems, and the likely real applications of this system in non-standard conditions would imply that this newly developed solution offers a substantial improvement in the effectiveness in carrying out the desired task, and the overarching goal of this extended work. Still, the solution has the potential to be improved with a few key changes proposed for the near future, particularly to minimize the fractional difference between the local and remote power production for standard conditions. These changes are described in detail in the section below. In conclusion, we see that the IOT-based remote monitoring and feedback system offers a substantial improvement in applicability, efficacy, and user interaction compared to the previous locally bound MPPT/power diversion solution; the applications of this system include: 1) use alongside solar panel systems in rural/underdeveloped areas where grid connectivity is difficult or impossible (and for urban households who find remote monitoring too expensive) 2) use alongside other renewable energy generation methods for monitoring/feedback purposes.

FUTURE WORK

The following changes/additions/investigations are proposed for the near future:

1. Investigate negative fractional power differences produced for standard conditions, attempt to achieve ~0 percent fractional power difference between remote and local mechanisms.

2. Implement additional parameters into the modification of algorithm: tilt angle, latitude, season.

3. Couple the temperature-dependent part of monitoring mechanism with autonomous water/ liquid cooling subsystem.

4. Investigate effect of inverter inclusion and AC component utilization on effectiveness of algorithm (allows to evaluate under realistic usage conditions).

5. Research into more controlled current regulation devices to handle commercially used panels (all components currently used are suitable for low current/low voltage devices).

6. Investigate the possibility of developing a more compatible battery that matches standard panel production (novel electrolytes etc.).