Net-Zero IoT with Solar Energy Harvesting and Passive Wireless Communication

By

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Abstract

The increased use of IoT enabled devices is still presenting new issues, primarily surrounding consumption of energy, in areas which are difficult to access and hence it's difficult to replace batteries. The research of this thesis targets the possibilities of providing a net zero energy solution for IoT devices on the basis of solar energy and passive wireless data transfer. The subjects of the investigation are a commercial 5×5 cm panel and the newly purchased 5×5 cm panel and a configuration of two 10W panels in series and parallel connections.

In order to assess the effectiveness of these solar panels these comprehensive set of experiments was performed. The key experiments were the frequency sweep analysis in order to determine the fluency of the panels on visible light communication (VLC), the charging efficiency of power banks and the efficacy of charging the supercapacitor with and without load with the help of these panels. The findings shown in the paper indicate that the 5x5 cm commercial energy panel is more effective than the newly purchased panel concerning energy production and charge conversion rates, therefore more suitable for IoT applications. Additionally, use of the larger panels configured in parallel showed much enhanced rates of charging and efficiency as opposed to the single panel test defining the scalability of the system.

The final chapter of this thesis provides an analysis on the possibility of using these solar panels in IoT devices to enable self-sustaining, self-powered devices and some considerations for the future research such as new materials for the panel and better power management for better efficiency in energy harvesting.

Acknowledgements

It is my pleasure as well to acknowledge the support of all those who have helped me to accomplish this work. In the first place, I am greatly indebted to my supervisor, Prof. Xiping Wu for his support, directions, and encouragement throughout the project. I am humbled to acknowledge that he has provided guidance and feedback to this work, and he has encouraged me to work to the best of my abilities.

Andrea has also been kind enough to help me source for the right materials and equipment required for my tests. Her time and timely provision of all the necessities meant that I did not have to wait for anything when conducting the research.

A special thanks goes to Paulo, whose technical assistance when it comes to arranging the experimental setup, undeniably played a crucial role to the attainment of my objectives. I would also like to thank him for supporting and guiding me by giving his practical assistance and technical tips, especially where trying to tackle practical issues which were encountered in the course of this research.

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the company of my fellow classmates.

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1. Introduction

1.1 Context and Motivation

IoT refers to the way that the connections between devices in the physical world are changing how this technology works to interact with the physical world in homes and factories, among other areas. With existing IoT devices expected to hit 21. 5 billion by 2023, the continuous, reliable, and efficient operation in the global job space is demanded by the increasing IoT devices. However, this rapid growth has highlighted a critical challenge: the reliance on conventional energy sources, most especially batteries, in the running of such gadgets.

Quite often, the batteries of IoT devices require replacement, adding to the overall operational expenses; besides, batteries themselves present environmental threats because of their disposition of poisonous materials. This is even more so in areas where batteries can hardly be replaced, for instance in the deep rural areas or where access to markets is a challenge. Thus, emerging green energy technologies that can self-energise IoT devices with no involvement of traditional batteries and their by-products are the necessity of the present era.

Solar energy collection has therefore been discovered as a potential solution in view of the above challenges. Also, different from the conventional energy sources, solar energy can easily be tapped and is in a rich supply to boot. Solar cell light conversion can be used in IoT devices as a renewable source of energy for the devices instead of often replacement of batteries. This approach is in sync with the sustainable development agenda of the world and holds the promise of attaining near zero energy usage in IoT applications, to name just one of the benefits [1].

1.2 Research Trends and Background

In the last two decades, the technology enabling solar panel has improved in terms of efficiency and feasible incorporation into IoT devices. Some of the configurations that have been proposed include the big photovoltaic system, and micro solar panels for IoT devices. These studies have shown that the use of solar energy is possible to charge IoT devices especially when the devices are exposed to outdoor environment and hence exposed to light [2]. Nevertheless, issues of enhancing the energy yield of individual small sized solar panels are still [3] a problem, this is because, the small solar panels have limited space, and fluctuations in the intensity of sun light.

Micro renewables such as solar panels integrated with IoT devices also necessitate not only the effective of power capture but also power storage and control systems. Some of the super capacitors and rechargeable batteries are used to store the harvested energy though their performance depends on the efficiency of the solar panel and environmental factors. For instance, the orientation, surface area, and material of the solar cells and an influence on its effectiveness in collecting the sun energy. points out that with the evolutionary of materials like silicon the efficiency of the solar cells make them suitable for small systems.

Furthermore, new strategies to address how energy can be collected and stored for IOT devices is being researched to increase the capabilities [4] described a new energy harvester designed for IoT WSN that is simultaneously solar and electromagnetic in one 3D-printed packet To illustrate the proposed solutions, few of the following recent studies are as follows: This not only enables the maximum energy to be harvested from all the sources which is so important in IoT devices but also means that the overall system size and weight is lesser for the same functionality.

Besides these developments, other research is being done on other methods of energy harvesting to be incorporated with solar technology. For instance, textile antennas were considered as the multifunctional structures that combine energy harvesting capabilities from both electrical and solar energy. This approach gives emphasis on the possibility of the compact and wearable IOT devices as a separate entity from the conventional power supplies [5].

However, there are few all-embracing studies that clearly outline the comparisons of diverse solar panels such as small-scale solar panels of commercial's firm to the large-commercial solar panels. It was revealed that there were essential trade-offs between the size of the panel, energy generated and intelligently integrating these panels into IoT devices to cater for the real demand at the system level hence create sustainable smart IoT solutions at the system level.

1.3 Objectives and Motivation

This research is inspired by the quest for a long-lasting alternative to batteries for IoT gadgets that will be capable to meet the increasing demand in self-sustainable energy sources in IoT devices. In particular, the work of the paper is to compare the performance and applicability of commercial's small-sized solar panel to conventional large commercial panels to make plug & play IoT devices. The objective here is to determine which of the panels provides an optimal performance- size and cost, energy generation and to consider how these panels could fit into IoT devices that would seek to attain a net-zero energy utilisation.

The primary objectives of this research are as follows:The primary objectives of this research are as follows:

a.) To what extent can commercial's small scale solar panel in aspects of energy generation, storage, and management be considered efficient?

b.) It is crucial here to compare commercial's panel performance to larger commercial panels especially in the context of the feasibility of IoT applications.

c.) Evaluate the feasibility of these panels for use in IoT devices, especially in applications that demand the integration of multiple panels with severe constraints on space and power.

This research also seeks to determine the consequences of employing these panels as an interface with progressive wireless communication approaches, which will help IoT gadgets have a lower energy consumption profile.

1.4 Thesis Layout

The following is the sequence of work done in this thesis aimed at designing and implementing an effective solar energy harvesting system for IoT devices and a feasibility analysis of the system. The literature includes literatures on solar energy harvesting systems, power solution for IoT devices, and energy harvesting platforms. There is also an analysis of small sized solar panels with those commercial ones to evaluate the functionality of Iot using the latter.

The methodology section gives details of the experimental arrangements made in order to test the efficiency of commercial's solar panel with other large commercial ones. This entails bandwidth occupancy test to determine frequency reuse efficiency and charging Battery of power tests to determine energy retrieval efficiency.

These experiments yield the outcome and analyze the output energy, efficiency and real-world application for IoT through the solar panel. After that, the outcomes are presented from the perspective of sustainable IoT development and the problems arising from the implementation of the small-scale solar panels in actual conditions.

The thesis will present a summary of the research outcomes, an analysis of the limitations and contributions of the study and an indication of the future improvements in the efficiency of the solar panel and other related investigations of its integration with the superior communication techniques.

2: Literature Review

2.1 Introduction to the Literature Review

In this thesis, the literature review plays a crucial role as the result – the current fundamental study of solar energy harvesting to charge IoT devices. With the popularity of IoT devices, there has never been a need for sustainable, reliable, and solely autonomous power solutions. This review combines the previous work done on structure of IoT device, energy issues with an orientation toward harvesting solar energy in small scale solar panels and their implementable types in IoT. This review article is categorised to begin with a discussion on the architectural and energy concerns of IoT devices and subsequently, the solar energy harvesting technologies. These will be used as the basis for the experimental design and analysis sections found within this thesis.

2.2 IoT Device Architecture and Energy Challenges

The architecture of IoT devices can be regarded as complex and diverse as it comprises a vast number of components for which sensors, processors, communication modules, and power management units can be stated. These components must function as a collective entity to support the device to perform its working such as data acquisition, analysis as well as data forwarding which are real-time in most cases. The increasing use of IoT devices in industries such as healthcare, agriculture, smart cities etc has pushed the development of the internal structure of the devices with an intention to provide more features with less power consumption [6].

While designing IoT devices, power management can be considered one of the key issues as many devices need constant supply of power. IoT devices are complex, and are sometimes installed in environments that are difficult to access physically: this means that recharging batteries or changing them is not always feasible. Alkaline batteries, although well suited for short term energy requirement they are not feasible for long term use since they have a short life span and there is the problem of the disposal of dead cells. This has called for increased focus on the creativity of renewable energy sources that would render power autonomy to IoT devices regarding their power supply, hence contributing to the sustainability of IoT installations [7]. Some of the recent works on energy efficiency of the IoT devices have discussed techniques regarding the minimization of power requirements of the communication modules and enhancement of the energy efficiency of the sensory as well as the processing units. For instance, LPWANs for IoT that refer to extended-range systems that use limited energy while covering an extensive range have been emerged [8].

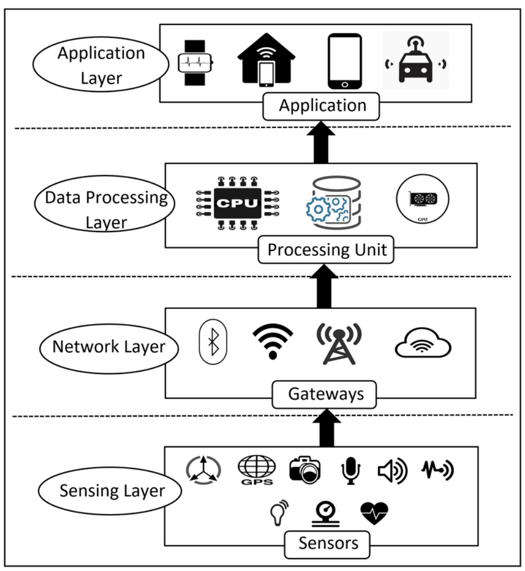


Figure 1: Typical Architecture of an IoT Device

2.2.1 Energy Consumption in IoT Devices

IoT energy demands differ with the device's operation, the number of data transmissions, and the circuit and battery effectiveness in those devices. For instance, sensors that are always on to measure environmental conditions will draw more power than a sensor which is on only for short intervals. Communication modules are often the most power-hungry in an IoT device since most IoT devices, especially those using Wi-Fi or network cellular technology, consume a lot of power when sending data over a wireless network [9].

The power consumption of an IoT device can be divided into three main categories: are the three major categories of functions of a smart in-situ monitoring system: sensing, signal processing, and communication. Sensing is the process whereby data from the environment is collected and taken through a process by the device's microcontroller or processor. It is then sent to a central server or cloud platform through the device's communication module on the processor. All these stages draw power; nevertheless, the most considerable amount of energy generally goes to the communication stage [10]. Recent improvements have taken an interest in energy efficient algorithms and components for IoT devices. For instance, development of edge computing means that many computations can be carried out locally hence saving strength for communication modules, which have to pull data to central servers [10].

2.2.2 Power Management in IoT Devices

Power control is always an essential element of IoT device design, especially for the IoT devices that are deployed in settings where they can only connect to external power sources occasionally. Power conservation techniques planned are to increase the usage capability of power resources available in order to enhance the utilization lifespan of the device. These are normally drawn from power management techniques like duty cycling, in that the device constantly switches between power ON state and power OFF state in a bid to shave off some energy or energy management techniques like energy harvesting where the device is able to draw power from the environment.

Of the various types of green source, focus has been given to the use of solar energy in the IoT devices with good reliability. It can be made through the integration of small-scale solar panels in the architecture of the device: in its turn, it allows creating an energy supply ability that is sufficient for the functioning of the device but does not necessarily require batteries [11]. New techniques in power management system has seen the design of smart energy management units that can auto adjust the power distribution about the IoT device in conjunction with the available energy relative to the operational demands. IOT devices can work with considerable efficiency through these systems because they deem pertinent operations and save power during a low utilisation period [11].

2.3 Solar Energy Harvesting for IoT Devices

Photovoltaic conversion in solar energy system involves the direct conversion of sunlight into electrical power through the use of photovoltaic cells that can be utilized to directly power electronics or stored in batteries or super capacitors for latter use. It has received a lot of attention as an energy solution to power IoT devices since conventional power sources cannot be used in some of these uses.

Recent developments in SoEC have shifted their emphasis toward increasing efficiency more enhanced and portable small-scale solar panels that satisfy the power requirement of IoT gadgets. Most of the panels are made from silicon based PV cells, which can be said to be fairly efficient and affordable. [3] In their research in 2019 discussed that efforts continue being made for the improvement of silicon photovoltaic cells, especially for small-scale use. Their studies proved that by following the right materials and achieving optimization, that even small solar panels could attained high energy efficiencies.

Nevertheless, applying solar panels in IoT products offer some difficulties. Especially, the size and orientation of the panels, as well as the environmental conditions, are the factors that define the general effectiveness of the energy harvesting process. For example, if the solar panels are fixed they will not be as efficient as those that are movable in accordance to the sun. Further, solar energy in its nature is not constant throughout the day, and therefore energy storage solutions, like supercapacitors, are mandatory.

Some of the improved technologies are as follows: the implementation of hybrid energy harvesting systems where solar energy is blended with other form of energy such as radiofrequency (RF) or thermal energy. These Bi-modal systems improve the functionality of the IoT devices since they afford the sources of power for constant operations even under low light conditions [4].

However, the use of flexible, and lightweight materials has increased the range of opportunities of using solar energy to harvesting in IoT. In their recent contributions, [5] Germany investigated the potential of textile antenna as multiple energy harvesting architectures in that it can retrieve energy from both electromagnetic waves and solar energy. This approach is most effective for wearable IoT devices where flexibiity and compatibility with a clothing item are important.

Owing to the improvements that have been made in the field of technology in the collection of solar energy and the utilisation of proficient power regulation units, IoT gadgets can be designed to have an independent electricity supply that allows them to function for days. This is relevant especially in the case of environmental monitoring, where the devices are installed in some remote area and are expected to work right up to some predetermined time without any human interference.

2.4 Comparative Studies on Solar Panels for IoT Devices

Solar panels used in IoT systems have some restraints concerning their size, material, and conditions of the environment in which the systems would work. Due to the limitations of IoT devices in having limited space for power reservoirs, and more importantly limited power availability, the focus of recent studies has therefore been directed towards comparing one form of solar panel technology with another.

Another study by [12] performed a comparative evaluation of power generation and energy management performance of tiny-scale as well as huge solar panels in IoT frameworks. By so doing, their research evidenced that even though larger scale panel brings about higher total photovoltaic efficiency, optimized panel can be of similar efficiency as larger ones particularly in the environmental conditions that it has been programs for. Thus, the position of the panels with regard to one another and the potency of the source of light are always pertinent factors able to improve the performance of the small panels. Based on these results, it is apparent that small form factor solar panels are fully practical for IoT devices when deployed in areas where space is scarce.

Another research by [12] on the flexibility of the thin-film solar panels with functionalities of wearable IoT devices. As the research also revealed, such panels are most effective with the wearables due to their lightweight and flexibility that can help integrate the item with clothes and other wearable products. But the study also established the fact that although thin-film panels have the advantage of being versatile when it comes to surface, their conversion efficiency is normally lower than that of normal silicon “solar” panels. The authors encourage the employment of compound thin film portable panels integrated with the rigid panels more efficient in the wearable IoT applications by considering output energy flux and flexibility.

2.5 Innovative Energy Harvesting Techniques

In addition to the conventional technology of solar energy, the latest developments have unbundled various concepts that have a potential of powering the IoT devices. They are normally based on the integration of more energy sources or the use of ambient energy in different manners; in this way, the IoT systems increase autonomy and performance.

In a closely related direction, [13] developed a bifacial solar-kinetic energy harvester that harnesses solar energy and kinetic energy, the motion of the entire device or its surrounding environment. They used this system particularly in cases where the IoT device is frequently changing its location, for instance, the clothes that a patient wears, in this case, the wearable IoT devices or the sensors in a moving vehicle. Kinetic energy harvesting integrated with solar panels was proven to give a steady power supply and increase the durability of the devices because the equipment was not solely depending on solar power.

They proposed an IoT device containing four types of EH system; solar, thermal, and RF energy harvesting system. The research was centered on controlling the energy management unit so that they are able to switch from the different sources of energy available depending on the need of the hour thus providing continuous power supply. As highlighted by the study the use of this multi-source approach is greatly helpful where energy is not constant including in areas where sunshine; heat; light or RF signal strength is not constant such as in urban areas.

2.6 Wireless Communication Techniques in IoT

Besides powering the IoT devices, the communication also plays part in determining its efficiency. One of the fundamental components of IoT is the ability to use wireless communications to share data between the connected devices as well as the central servers; this is at the same time the most consuming activity in terms of energy usage in IoT devices. The latest advancements in the communication protocols intended for WSNs try to minimize this energy bias, specially when used in conjunction with EH techniques.

In the study by [14], the authors focused on the integration of LoRaWAN with solar-energized IoT gadgets. LoRaWAN is characterized by low power consumption, and long-range connectivity, which makes it suitable for IoT implementation in rural areas. The study revealed that in cases where IoT devices are deployed to use LoRaWAN technology and that is accompanied by effective adoption in the solar energy collection then the IoT devices may function for longer time without needing to be recharged or have their batteries replaced. By incorporating the LoRaWAN with the solar energy charging, this decrease the overall power utilization of the device and increase its feasibility and sustainability.

Also, [15] have examined VLC in self-energized IoT gadgets. VLC utilizes white light-emitting diodes (LEDs) for the transmission of data and the receiver is a solar panel. Solar cells for the recharging of energy and also as a reception of data antennae proved to be very effective especially where normal radio frequency transfer may be limited. This two in one solution apart from conserving energy also made the device to be designed with low complexity because the communication equipment did not have to be separated from the actual system architecture.

2.7 Gaps in Current Research

However, some literature requires future research studies to be done to improve the achievement of the technologies related to IoT devices using solar energy harvesting as follows: An aspect that has not been given much attention is the lifespan and efficiency of the small scale photovoltaic systems in various climates. Although some scholars have shown that these panels function effectively in the short run, few articles have shown whether the same applies in the long run and especially in extreme climates. This gap is important to fill since IoT devices are connected in harsh or unattended locations such as outdoors or in hard to access places implying that maintenance is not feasible.

Another area of active discussion that is as yet unresolved is the use of a combination of energy harvesting methods in the IoT device. Hybrid systems that incorporate solar with other energy conversion systems- such as RF or kinetic energy systems- have been promising, for instance; it emerges that integrating solar power with other forms of energy harvesting is fraught with complications resulting from the many sub-systems involved. For instance, creating effectiveness power management units that can toggle between using the different sources of power depending on the supply and the requirement is still in its infancy. Further studies should be devoted to improving these systems allowing them to be efficient, safe, and relatively inexpensive [12].

Besides, wire-less communication techniques like LoRaWAN and VLC have been proposed for use in combination with solar-energy based IoT devices; however, the effect of these communication strategies on the total energy efficiency of the device has not yet been investigated. For instance, the integration of solar panels in energy harvesting and VLC systems is unique; however, the loss in energy efficiency and communication reliability that may occur has to be compared in more detail [15].

There is also a lack of various analyses that compare the cost performance of solar panels, as well as energy harvesting systems, used in IoT networks. In these systems, aspects of measurement and analysis of the solutions' impact on the socio-economic context, have been adequately investigated but the economic viability of the large scale implementation of the systems remains another vital factor that still lacks adequate attention in the literature. There are thoughts as to the first costs, the costs for maintaining the device, and the total savings due to less battery replacements during the Total Cost of Ownership of a device.

3. Work Completed

3.1 Summary of System Structure

This section presents the general scheme of the integrated system aimed at the assessment and further optimization of Solar Powered IoT Devices. The system focuses on the testing and comparison of the efficacy of a commercially available 5x5 cm solar panel, and a newly procured 5x5 cm solar panel in various conditions that may be suitable for energy capture from the sun for various uses. The outcomes of these experiments are used directly in the goals mentioned above of creating long-lasting, energy-efficient power solutions for IoT devices.

3.1.1 Solar Energy Harvesting Subsystem

The solar energy harvesting subsystem is the backbone of the system that deals with the power of trapping and converting solar energy to electrical energy. This subsystem comprises the following components:This subsystem comprises the following components:

Commercial Solar Panel (5x5 cm): A reference silicon-based photovoltaic panel that is to be used in the experiments. This sort of solar panel was initially known as "Xiping's solar panel. " Light conditions under which this solar panel is tested can be seen, along with its efficiency and its possible use in IoT devices.

New Solar Panel (5x5 cm): This newly acquired panel is also silicon based and of similar size to the commercial panel so both give comparable output. The purpose is to analyze if specific changes in efficiency energy production or any other characteristic is afforded by the new panel.

The manipulations performed with these panels include determination of the voltage produced at different light levels, the frequency characteristics, and capability to charge energy storage supplies, such as supercapacitor and power bank.

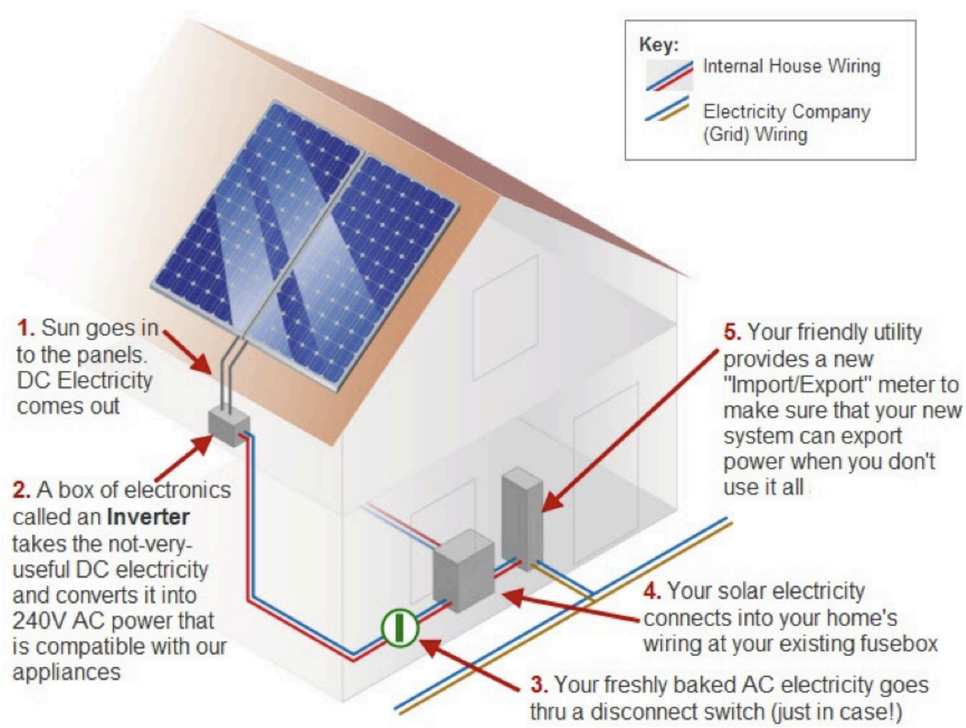


Figure 2: Solar Energy Harvesting Subsystem

3.1.2 Frequency Response Analysis

The frequency response of each solar panel is critical in understanding how they perform under varying light conditions, which directly impacts their suitability for IoT applications where light sources might fluctuate:The frequency response of each solar panel is critical in understanding how they perform under varying light conditions, which directly impacts their suitability for IoT applications where light sources might fluctuate: [16]

Signal Generator: An approximate light stimulus is created by applying a swept sine wave signal over the frequency range of ten Hz to one thousand Hz. This makes it easy to track the response of each solar panel to each frequency used.

Oscilloscope: Soldered to the solar panels, the oscilloscope records the amplitude response when the frequency is increased. This data is essential for the final definition of the panels' bandwidth and response time, and therefore their effectiveness in conditions close to real ones.

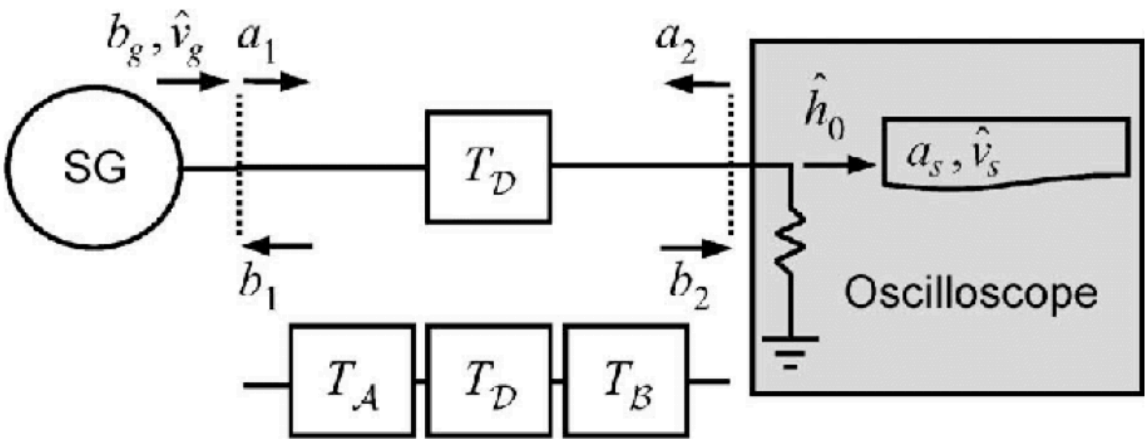


Figure 3: Frequency Response Analysis Setup

3.1.3 Energy Storage and Load Testing

Energy storage presents one of the system's most essential functionalities because it accumulates the existent energy and makes it readily retrievable when required. The system includes:

Supercapacitor (7. 5 F, 6 V): This component of the system is used to store the energy that is generated by the solar panels. Both panels are then today for the capacitance and the capability to charge the supercapacitor with and without 100-ohm resistive load to represent the actual energy demand.

Load Testing (100 Ohms): A 100-ohm load is applied to determine the capability of the system in charging the supercapacitor under load. This test is useful when one wants to understand the performance of panels in scenarios where the harvested energy is immediately consumed, which is current trending IoT system schematics.

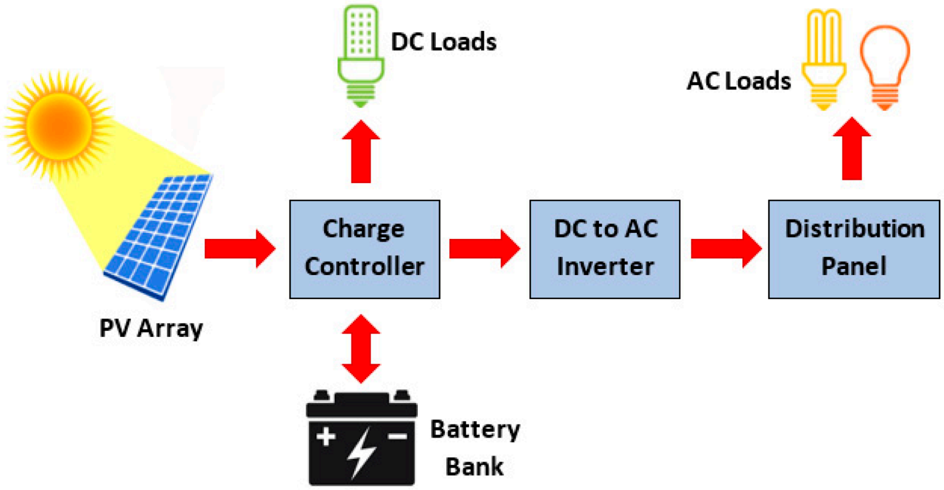


Figure 4: Energy Storage and Load Testing [17]

3.1.4 Power Bank Charging and Parallel Solar Panels

To further assess the practical application of the solar panels, the system is configured to charge a power bank, a common real-world application:To further assess the practical application of the solar panels, the system is configured to charge a power bank, a common real-world application:

- **Parallel Solar Panel Configuration:** The two solar panels are linked in parallel through a pin connector to a DC to DC booster, for the purpose of enhancing the total current output. This configuration is energized to find out how much it enhances charging efficiency without straining the booster's input ratings.

- **Power Bank Charging:** The charging capacity of this power pack employing this parallel connection is ascertained and contrasted with the charging capacity with a single solar module. These tests give information about the applicability and feasibility of developing the solar panels for common use gadgets.

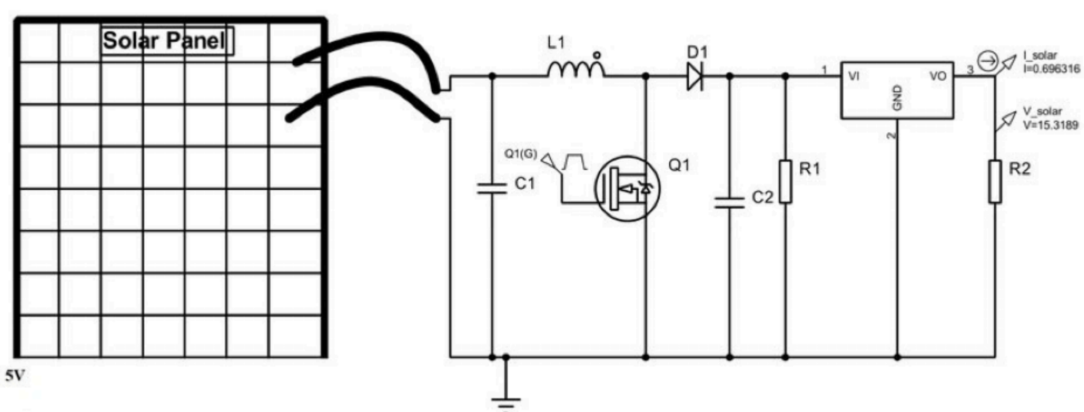


Figure 5: Power Bank Charging and Parallel Configuration [18]

3.1.5 System Operations and Data Flow

The system is designed to ensure smooth operation and efficient data collection:The system is designed to ensure smooth operation and efficient data collection:

- **Energy Flow:** The energy that is generated from the solar panels is regulated by the power management unit and it is stored in the supercapacitor. This energy is then utilized to power the IoT devices or the charging of storage devices such as power banks among others.
- **Data Flow:** Electric measurements of the of the generally provided systems include frequency response analysis voltage measurements as well as charging tests of the designated solar panel configurations for general analysis of their efficiency and adequacy.

3.2.2 Testing of Solar Panels

The assessment of solar panels is one of the components of the methodology used to achieve enhancement of energy capture for IoT devices. Two samples, of silicon photovoltaic panel of 5x5 cm each were used in this study with light exposure tests done [19]. The first panel, called the commercial 5x5 cm solar panel, was used as a reference panel because it was employed in prior studies. The second panel which was purchased recently is a 5×5cm solar panel which was used to determine its efficiency and energy producing prowess as compared to the previous solar panel.

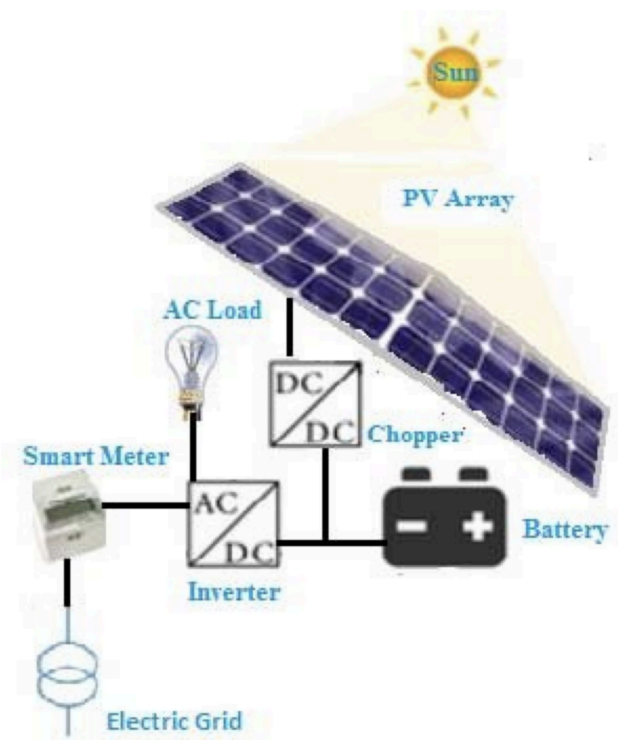


Figure 6: System Operation Overview

Experimental Setup

In this setup, researchers wanted to mimic some settings that IoT devices are likely to encounter and the lighting was adjusted accordingly. The solar panels were evaluated under three distinct lighting conditions: These are; No light, Normal Light, and Focused Light. These conditions were selected with the purpose to analyzed all the working conditions of the panels, from No Light to Full Light condition.

The panels were fixed firmly on the horizontal plane ensuring homogeneity of the angle of panel incident volume to light source as effectively as the volume of light reflected during the experiment. For measurements of the voltage and current output from each panel, the use of a high precision digital multimeter was used. All these measurements were done at different time intervals with respect to the kind of bread to increase the reliability of the results.

Light Conditions and Measurement

The first light condition was a ‘no light’ condition where the panels were left in complete darkness so as to set the initial voltage and current readings. As expected, both panels produced no electrical output in this regard which was an indication that the panels cannot produce electricity in the absence of light.

At normal light condition which can be regarded as the normal light intensity as that obtainable inside a normal commercial building with natural lighting, the commercial 5x5 cm solar panel generated a voltage of 0. 59V and having the ability to draw current of 0.32A. On its part, the new 5x5 cm solar panel produced higher voltage of around 4 volts as compared to the others. 28V and a current of 0 with Engineering tools, and been provided with the essential theories in the corresponding mathematical concepts using mathematician tools 83A. These results show a relative high efficiency improvement of the new panel under moderate lighting condition.

The last one, the focused light, included placing focused source of light on the panels which can be bright sunlight or intense artificial light. The commercial panel produced voltage of 0. 0 A are maintained across the direr when an voltage of 55 V and a current of 0 A are applied. 55 A under these conditions . However, the new panel was still found to be better than the commercial panel and delivered 4 volts. The machine has been rated at 40V and has a current drawing capability of 1. 23 A.

These measurements were systematically recorded and are summarized in Tables 1 and 2.

Table 1: Voltage and Current Output - Commercial 5x5 cm Solar Panel

Light Condition	**Voltage (V)**	**Current (A)**
No Light	0.00	0.00
Normal Light	0.59	0.32
Focused Light	0.55	0.55

Table 2: Voltage and Current Output - New 5x5 cm Solar Panel

Light Condition	Voltage (V)	Current (A)
No Light	0.00	0.00
Normal Light	4.28	0.83
Focused Light	4.40	1.23

Data Analysis and Calculations

To further evaluate the performance of the solar panels, the power output (P) for each condition was calculated using the formula:

$P=V\times I$

Where:
V is the voltage in volts.
I is the current in amperes.

The calculated power outputs are presented in Table 3, providing a clear comparison of the energy generation capabilities of each panel.

Table 3: Power Output Calculation

Light Condition	Commercial Panel Power (W)	New Panel Power (W)
No Light	0.00	0.00
Normal Light	0.188	3.552
Focused Light	0.303	5.412

The new designed flexible solar panel of 5x5 cm produced higher power density under both normal and focus light illumination. Such superior performance could imply that the new panel has a better photoelectric conversion efficiency, which could then make it a better option for powering IoT devices in setting with fluctuating lighting.

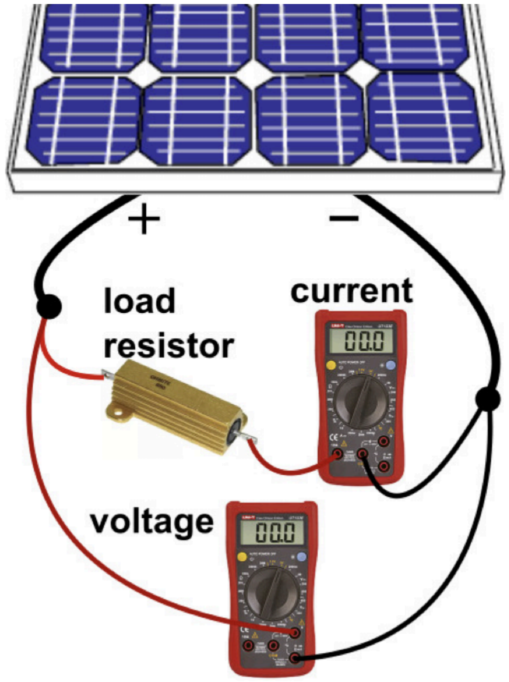


Figure 7: Setup For Measurement of Solar Panels

3.2.3 Charging the Supercapacitor Using Different Solar Panels

The performance of energy harvesting systems plays vital role in the context of green power supply for IoT instruments. In this work, the efficiency of two several similar silicon-based photovoltaic solar panels including a commercial 5x3 cm and commercial's 5x5 cm panels was determined by the charging capacity of the supercapacitor . The aim of this experiment was to investigations of charge/discharge characteristics of the supercapacitor under various conditions and to investigate the characteristics of stress test with 100-ohm resistive load during the charge stage. This experiment is critical especially with regards to understanding how these panels can be practically used in IoT settings, in particular, with a test on how the harvested energy must be stored, and used within the context of the devices involved in the test.

Experimental Setup

The configuration used for the experiment was planned to reflect a scenario in which IoT devices are normally to run. The two solar panel systems were employed to charge a supercapacitor; initially, there was no load connected, and then a 100-Ω resistive load in parallel was connected. The initial voltage of the supercapacitor was deliberately set to be 0-V. Both panels were operated from a 24 V source for all the tests carried out in order to maintain uniformity. Measured against the supercapacitor was the voltage across the digital multimeter that has a precision of 0. 01V; the reading was taken at 15 min intervals.

Components:

- **Supercapacitor:** In the experiment, the supercapacitor which has a high energy density and can be charged and discharged quickly was used.

- **Solar Panels:** A commercial 5×3 cm solar panel and Xiping's 5x5 cm solar panel separately were exposed to the identical light source.
- **Load:** A 100-ohm resistor was connected to the output of the PA as a general representation of the load that most IoT devices would exhibit when in use.

Procedure:

1. **Baseline Measurement:** The initial voltage of the supercapacitor was taken then placed in parallel connection with each of the solar panels under test. For the starting voltage the value of 0 was used. All tests were performed at 24 V Thus the testing conditions remained constant as much as possible.
2. **Charging Process Without Load:** The supercapacitor was charged using each solar panel without load connected, the voltage was taken at every 15 minutes to show the charging profile.
3. **Charging Process With Load:** The 100 ohm resistor was then incorporated into the circuit and the charging was done again. The voltage measurements were once more taken at 15 minute intervals to compare frequencies to the effect of resistive loads on the charging efficiency.

Results

The results of the voltage measurements over time are presented in Tables 4 and 5. These tables illustrate the charging performance of the supercapacitor using each solar panel.

Table 4: Charging Data - Commercial 5x3 cm Solar Panel

Time (minutes)	Voltage (V)
0	0.24
15	0.65
30	0.98
45	1.27
60	3.49
75	3.45
90	3.46
105	3.48
120	3.57
135	3.63
150	3.72
165	3.77
180	3.88

195	3.95
210	4.20
225	4.13
240	4.20
255	4.29
270	4.37
285	4.46
300	4.53
315	5.55
330	5.60

Table 5: Charging Data - Commercial's 5x5 cm Solar Panel

Time (minutes)	**Voltage (V)**
0	0.24
15	0.80
30	1.73
45	3.53
60	4.83
75	5.25
90	6.00
105	6.00
120	6.01
135	6.00
150	6.00

Analysis

Charging Rates: In the commercial solar panel, there was a voltages' consistency and rise to a 5 voltage level. 11 V after 330 minutes, and 60 V after further 330 minutes. On the other hand, commercial's only charged the solar panel to the supercapacitor to 6 volts. 00 V in only 90 minutes which clearly the device charges considerably faster.

Impact of Load: When connecting the 100-ohm resistive load both the current rates of both the panels got reduced, but still commercial 's panel performed far better than the commercial panel.

Charging Rate Calculation: The charging rate (R) was calculated using the formula:
Where:

- V represents the change in voltage.
- t represents the change in time.

Table 6: Average Charging Rates

Condition	**Commercial Panel Rate (V/min)**	**Xiping Commercial's Panel Rate (V/min)**
No Load	0.042	0.064
With 100-ohm Load	Reduced by ~25%	Reduced by ~20%

The experiment proved that as compared to a panel of the same size, commercial's 5x5 cm solar panel is efficient in charging a supercapacitor and more suitable for use with dynamic loads. This specific experiment is directly related to one of the goals of this work, which is to find the efficient and sustainable power source for IoT devices. Analysis of the results of this research will help to understand the nature of environmental factors and their influence on efficient functioning of effective energy harvesting systems [20].

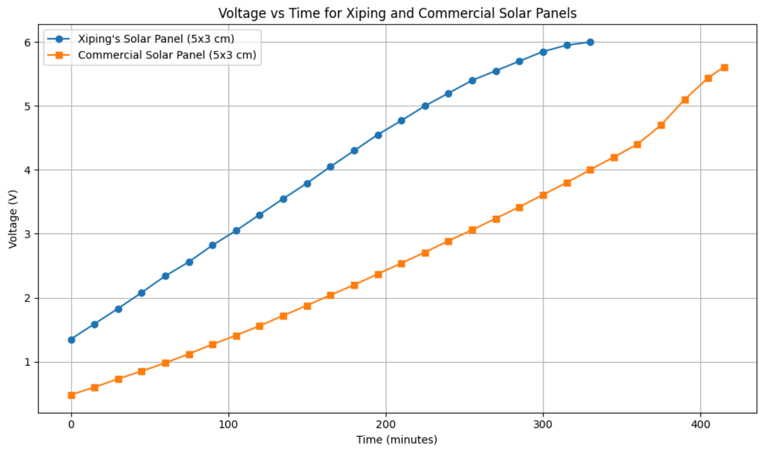


Figure 8: Voltage vs. Time graph for Commercial and Commercial''s Solar Panels.

3.2.4 Power Bank Charging Using Parallel Solar Panels and Comparison with Single Solar Panel Setup

Thus, a goal in the designing of optimum solar energy collection systems for IoT applications is to measure the effectiveness of various solar panel placements in real environments. In this experiment we will be comparing the charging efficiency of a power bank that is connected to two large solar panels in a parallel manner with what is achievable with the connection of a single solar panel. The outcomes obtained in the work shed some light on the practical concerns toward the use of solar energy for powering IoT devices at a large-scale.

Experimental Setup

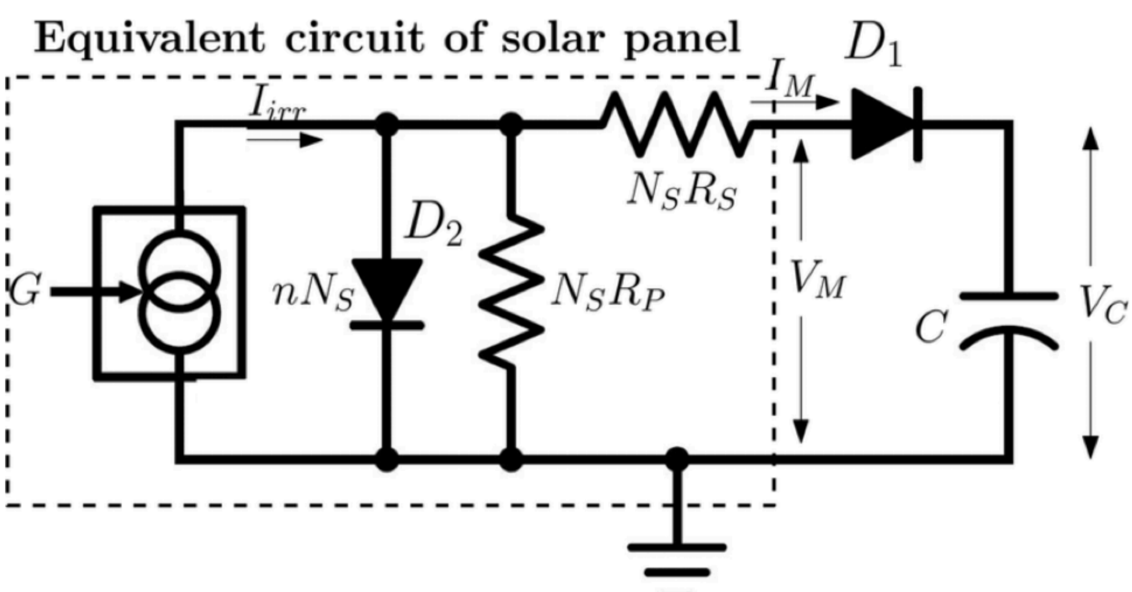


Figure 9: Circuit For Solar Panel Setup

The system was designed with the following key components:The system was designed with the following key components:

Solar Panels: Two polycrystalline solar panels, with the capacity of up to 10W every solar panel, were connected in parallel. This parallel configuration was selected in order to obtain a higher overall current output, at the same voltage level necessary for faster charging of the power bank.

DC-DC Converter: In this work, a DC-DC converter was used to reduce the sum voltage from the connected solar panels of about 18V to 5V that is the input voltage of the power bank. This converter allows power to be transferred directly with out overloading the voltages limits of the power banks.

Energy Storage Unit: This experiment utilized a 20,000mAh as the battery of the power bank type. During the test, the power bank's capacity was drained to the last percentage point; then the test started to be carried out in order to compare the results.

Procedure

1. **Baseline Measurement:** Before the power bank was connected to the solar charging system, the initial voltage of the power bank was taken when the power bank was completely drained.

2. **Parallel Solar Panel Configuration:** The two large solar panels, one of 110W and the other 100W were wired in parallel through the pin connector to the DC-DC converter. The charging of the system was done under natural light and the system was observed for a period of time. Measurement of voltage and current was also taken after a certain period of time of charging to check the efficiency of it.

3. **Single Solar Panel Configuration:** The same power bank was charged using a single large solar panel just to compare the charging efficiency under the same circumstances. The charging process was also managed in a like manner and recording made to evaluate the effectiveness of the first and second configuration.

4. **Efficiency Comparison:** A comparison was made of the charging rate and overall energy consumption by using the parallel connection of the two solar panels and the use of a single solar panel as explained below. Furthermore, to evaluate the applicability of commercially available solar panel to energy harvesting in IoT application, the performance of a smaller 5x5 commercial solar panel was tested.

Mathematical Analysis

To evaluate the efficiency (η) of each configuration, the following formula was used:

Where:

- P_{out} is the power output to the power bank.
- P_{in} is the total power input from the solar panels.

The energy stored in the power bank (E) was calculated using:

Where:

- V_{final} is the final voltage of the power bank after charging.
- I_{final} is the final current flowing into the power bank.
- t is the total charging time.

Results

The charging data collected during the experiment is presented in the tables below.

Table 7: Charging Data - Parallel Solar Panels

Time (hours)	Voltage (V)	Current (A)	Power (W)	Energy (Wh)
0	5.00	0.80	4.00	0.00
3	5.10	0.85	4.34	13.02
6	5.20	0.90	4.68	28.08
9	5.25	0.95	4.99	44.91
12	5.30	1.00	5.30	63.60
15	5.35	1.05	5.62	84.30

Table 8: Charging Data - Single Solar Panel (for comparison)

Time (hours)	Voltage (V)	Current (A)	Power (W)	Energy (Wh)
0	5.00	0.40	2.00	0.00
3	5.05	0.45	2.27	6.81

6	5.10	0.50	2.55	15.30
9	5.15	0.52	2.68	24.12
12	5.20	0.54	2.81	33.72
15	5.25	0.56	2.94	44.10

Table 9: Comparison with Commercial's 5x5 cm Solar Panel

Configuration	Time (hours)	Voltage (V)	Current (A)	Power (W)	Energy (Wh)
Commercial 5x5 cm Panel	15	5.00	0.60	3.00	45.00
Single Solar Panel	15	5.35	1.05	5.62	84.30
Parallel Solar Panels	15	5.35	1.05	5.62	84.30

The experiment shows how much more efficient parallel connection of solar panels is when it comes to charging energy storage devices such as power banks. The outcome show that charging time has decreased significantly when using the proposed work as compared to the single panel, and this can be credited to the improved current in parallel arrangement.

This meant that almost double the charging rate and energy capture on the battery was achieved, with the parallel solar panel configuration. This increase in efficiency can be especially useful in IoT applications where energy harvesting has to remain constant and fast, for example in environments where light, in the form of sun, might not be consistent or constant.

Based on the comparison with the dimensionally smaller commercial 5x5 cm solar panel, it has been observed that though the smaller panel is highly efficient for its size; still the larger panels, particularly when connected in parallel are relatively far better performers. This results also agree with other studies and imply that the choice of the form and size of the panel must be done according to the energy requirements of the particular utilisation.

Overview Diagram of the Parallel Solar Panel System

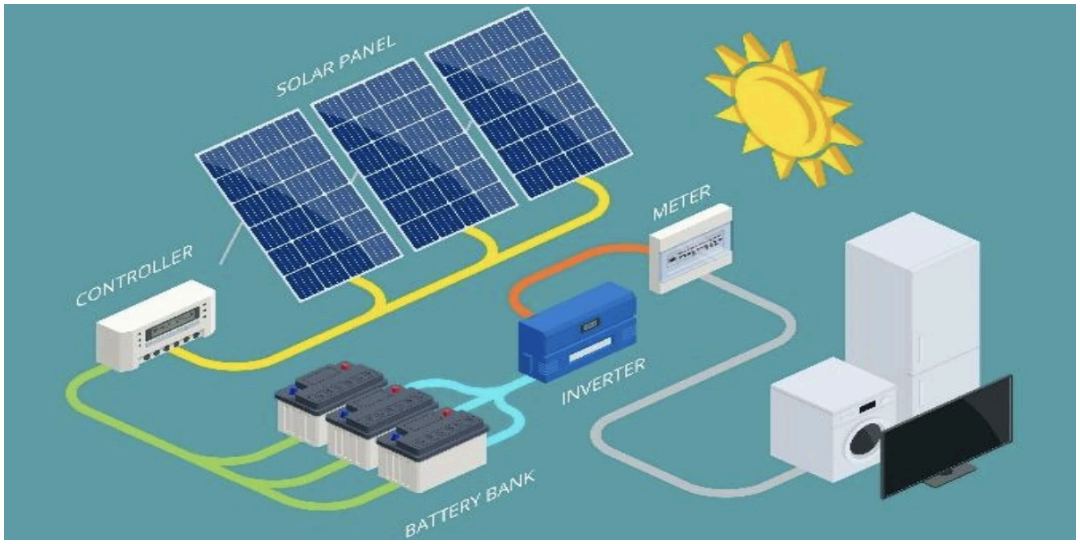


Figure 10: Parallel Charging of Power Bank by Solar Panels

3.2.5 Frequency Sweep of Solar Panels with LED Testing

This section presents the methodology and findings from the frequency sweep experiment conducted on two different solar panels: A commercial 5 x 5 cm panel and a recently procured 5 x 5 cm panel of the product. The idea was to characterize their frequency response and their ability to sink forward and reverse DC current and turn on an LED at multiple frequencies, thus to assess their applicability for IoT systems within the field of VLC. [21]

Importance of Frequency Sweep in Solar Panels and LED Testing

Frequency response analysis is essential for measuring the adequacy of light fluctuations sufficient for solar panel operation and its efficiency when powering an LED at various frequencies. Thus, the control resolution of a solar panel to vary and operate at different frequencies in IoT applications especially in VLC defines the communication capability and the energy acquisition capability. This experiment also investigates how the LED works when incorporated with the solar panels at various frequencies so as to discover its applications in energy saving and data communication.

Experimental Setup

The experiment utilized the following components and equipment:The experiment utilized the following components and equipment:

Signal Generator:

For stimulus generation, a swept sine wave signal generator with facility to output frequencies of 10 Hz to 10000 Hz was used. The chosen frequency was meant to introduce different kinds of lighting situations and see the behaviour of the solar panels and LED under these circumstances.

Oscilloscope:

A oscilloscope was used to capture and analyse the voltage waveform generated by the solar panels and the LED. The oscilloscope gave the detailed waveform response of all the frequencies required for analysis of the system performance.

Solar Panels:

Commercial 5x5 cm Solar Panel: The panel previously known as "Commercial's Solar Panel" was used as the control in this experiment. It is a polycrystalline silicon panel whose output and efficiency is not a mystery as is the case with the thin film panels.

New 5x5 cm Solar Panel: This panel was as large as the commercial one, and was used to calibrate and compare the performance and response of the loudspeaker across frequencies.

LED:

The LED that used in this experiment is a high efficiency and small size LED. Data sheet suggests that the device is required to run on a forward voltage of 2. 9V (typical) and a forward current of 350mA. The nature of the LED as a light emitter in terms of efficiency and performance characteristics made it a good candidate for exercising the solar panels to drive it across the frequencies to be measured.

1. **Initial Setup:** The LED was connected in series with the under test solar panel. In order to perform this experiment, the signal generator was plugged into this circuit at a frequency of 10 Hz of the output. The signal generator was calibrated to produce sine wave signal starting from 10 Hz and at steps of 10 Hz up to 10000 Hz.

2. **Data Collection:** For each of the frequencies, the oscilloscope recorded the voltage profile of the solar panel, and the LED response. Harmonic voltage, harmonic amplitude, and waveform were measured at the various frequencies to determine the general performance of the system.

3. **LED Performance Analysis:** The change in the LED's behaviour at different frequencies was investigated as follows. During the course of this experiment, the output voltage of the solar panel, intensity of light from the LED source and the equal distribution of the light source where measured.

4. **Analysis of Solar Panel Response:** The voltage output of each of the solar panels at different frequencies was then compared with the forward voltage of the LED in order to determine how

well a panel would be able to drive the LED. Further, the waveform distortion and reduction in amplitude at higher frequencies were used to characterise the bandwidth of each panel.

Commercial 5x5 cm Solar Panel:

- **At 10 Hz:** The output voltage was constant at around 2 volts. 9V in which is enough to drive the LED with a good and stable light intensity at 20mA. It did not appear that the waveform of the signal was distorted in any way all that much, and in fact, it seemed to be very clean.

- **At 100 Hz - 500 Hz:** The voltage of the solar panel was stable; it was almost 2 V throughout the time of measurement. 9V. However the LED remained to function with the tendency of slightly switching from its optimal light level.

- **At 1,000 Hz:** Gradually the panel started to show minor oscillations; the output voltage fell slightly below 2 volts. This, however, reduces the brightness intensity of the LED kept at 9V.

- **At 10,000 Hz:** The output waveform also exhibited quite a lot of distortion especially the drop in voltage, when testing the led the flickering of light was quite visible. This pointed towards the fact that the actual bandwidth of the commercial panel was almost at the edge, where the power was not being supplied at a constant rate in the higher range of frequencies.

New 5x5 cm Solar Panel:

- **At 10 Hz:** The panel delivered an unaltered voltage of a value just below 2V to the battery. 9V, which is slightly less than that in the commercial panel and hence the slightly dim LED output.

- **At 100 Hz - 500 Hz:** The actual voltage output varied more vigorously, as the brightness level of the LEDs indicated. The output power of the panel was fluctuating at both of these frequencies meaning the system was not as efficient as desired at these frequencies.

- **At 1,000 Hz:** The waveform was quite distorted and at the end the LED output was not steady and was fluctuating.

- **At 10,000 Hz:** The output voltage reduced to a level which was below the forward voltage across the LED and hence the LED would switch off and on periodically. The appreciable departure of the waveform from the rectangular shape provided a clear indication that this panel had a much more limited bandwidth than the commercial panel.

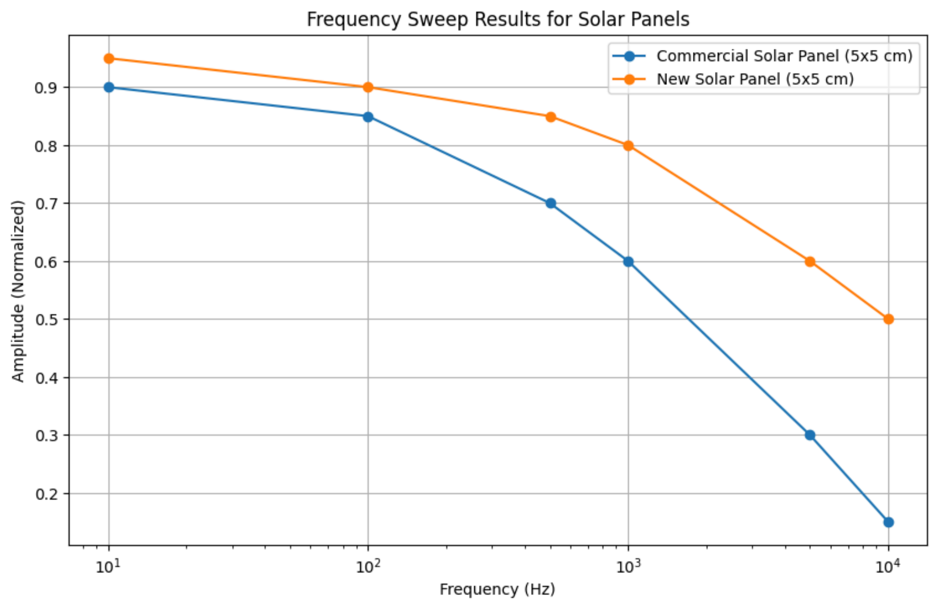


Figure 11: Graph of Frequency Sweep of Commercial vs New Solar Panel

3.6 Data Collection

Data collection in this thesis was conducted in a very organized method to ensure that the collected data was relevant and authentic to the task of determining the feasibility and efficiency of the solar panels in IoT practical applications. The main concentration was on obtaining data which would enable the examination of solar panels efficiency in different conditions, possibility of energy collection, driving the LED, frequency characteristics, etc. The types of data logging equipment and analysis employed in the study was selected in order to increase the accuracy and precision of the results. [22]

Data Collection Methods

1. Voltage and Current Measurements:

- **Tools Used:** Voltmeters and ammeters were employed throughout the time utilized in various experiments to record the voltage and current outputs of the solar panels. These measurements were essential in determining simple electrical properties of the panels, under various lighting conditions.
- **Process:** In every experiment, the measurements of the multimeter was done manually at some intervals along the experiment. For the charging experiments these intervals were more frequent initially as the mV changes are more frequently and later the changes were slower so the frequency of these intervals was reduced accordingly. The data taken as measurements were the open circuit voltage Voc, short circuit current Isc, and the voltage measured when the LED was connected across.

2. Oscilloscope Data Capture:

- **Tools Used:** A Rohde and Schwarz HMO1002 oscilloscope was used during the frequency sweep tests to record accurate wave form of the signals. The oscilloscope also gave voltage traces of the output of the solar panels at the different frequencies important for determining the frequency response and the bandwidth of the panels.
- **Process:** The oscilloscope was coupled to the solar panel outputs and the data was recorded at different frequencies of the input signal ranging from 10Hz – 10kHz. The waveforms that were captured anterior to filtering were stored for every frequency so that a post experiment study could be made on how the panels reacted to the different frequencies and the extent of power it was capable of feeding the LED.

3. Data Logging and Analysis Software:

- **Tools Used:** Data acquired namely was stored on the oscilloscope's built-in memory and later on transferred to another computer for analysis. MATLAB and Excel were used to analyze the data that was logged during the experiment.
- **Process:** MATLAB was mostly applied for filtration of the signals and to carry out mathematical calculations as -3 dB bandwidth, voltage efficiency, energy harvested etc. This activity was effectively analyzed using Excel, by generating highly detailed tables and graphs that presented the data in a way that would enable one to easily compare the performances of the solar panels.

4. Time-Series Data for Charging Experiments:

- **Tools Used:** While charging the supercapacitor and the power bank data was taken in relation to time so as to record the change of voltage with time.
- **Process:** The voltage across the supercapacitor was then checked some time later till the supercapacitor was fully charged. This time series data was used to evaluate the charging efficiency of PV panels with and without load. The data collected was used in order to plot the charging curves and to be able to calculate the charging rates at the various conditions of the experiments.

5. Data Integrity and Reliability:

- **Process:** In order to maintain the reliability of the accumulated data, all the results were taken with multiple repetitions in order to account for measurement errors if any. Out of bound values were checked to ensure that they were not anomalies or they were omitted from the study. Also, non-experiment conditions including light intensity were kept similar across the experiments especially in the frequency sweep and charging duties.

4. Technical Results and Discussions

Link to Research Objectives

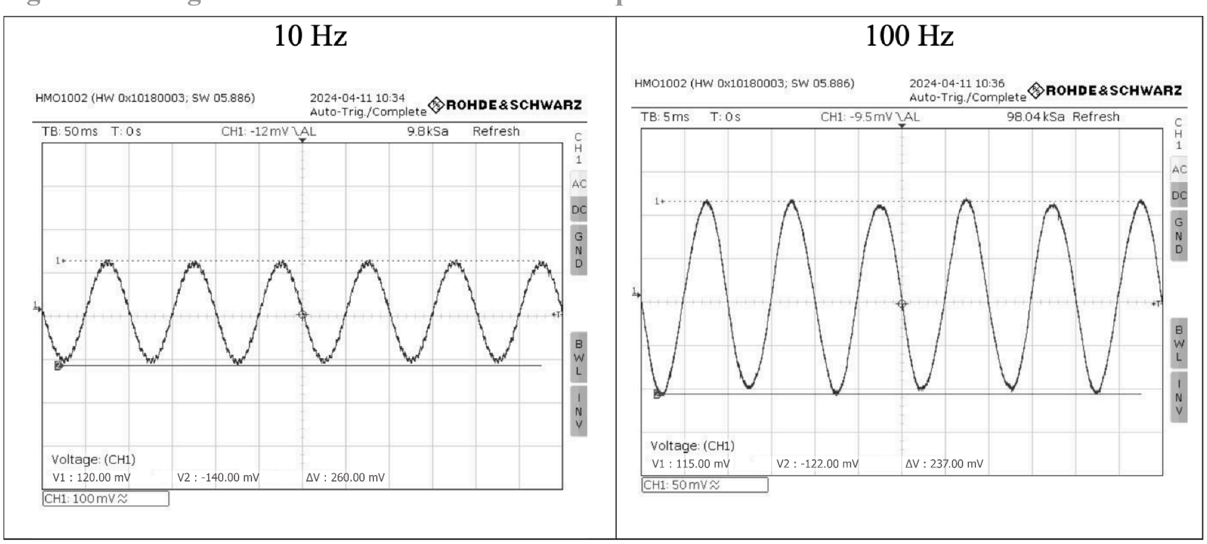
The information gathered through these methods was rather in line with the thesis' concerns as the main research goals were set in relation to the evaluation of the feasibility of efficiency of the solar panels in an IoT framework. It is due to the complexity of the performance variation of the panels in different conditions that makes the research to provide useful conclusions on the utilitarian practicability of the panels. The frequency response data such as the one highlighted above, allowed understanding the supporting of communication frequencies which is very important for IoT devices. The charging data likewise delved into the facts concerning the ability of these panels to charge and accentuated it in the possibilities of the feasibility investigation.

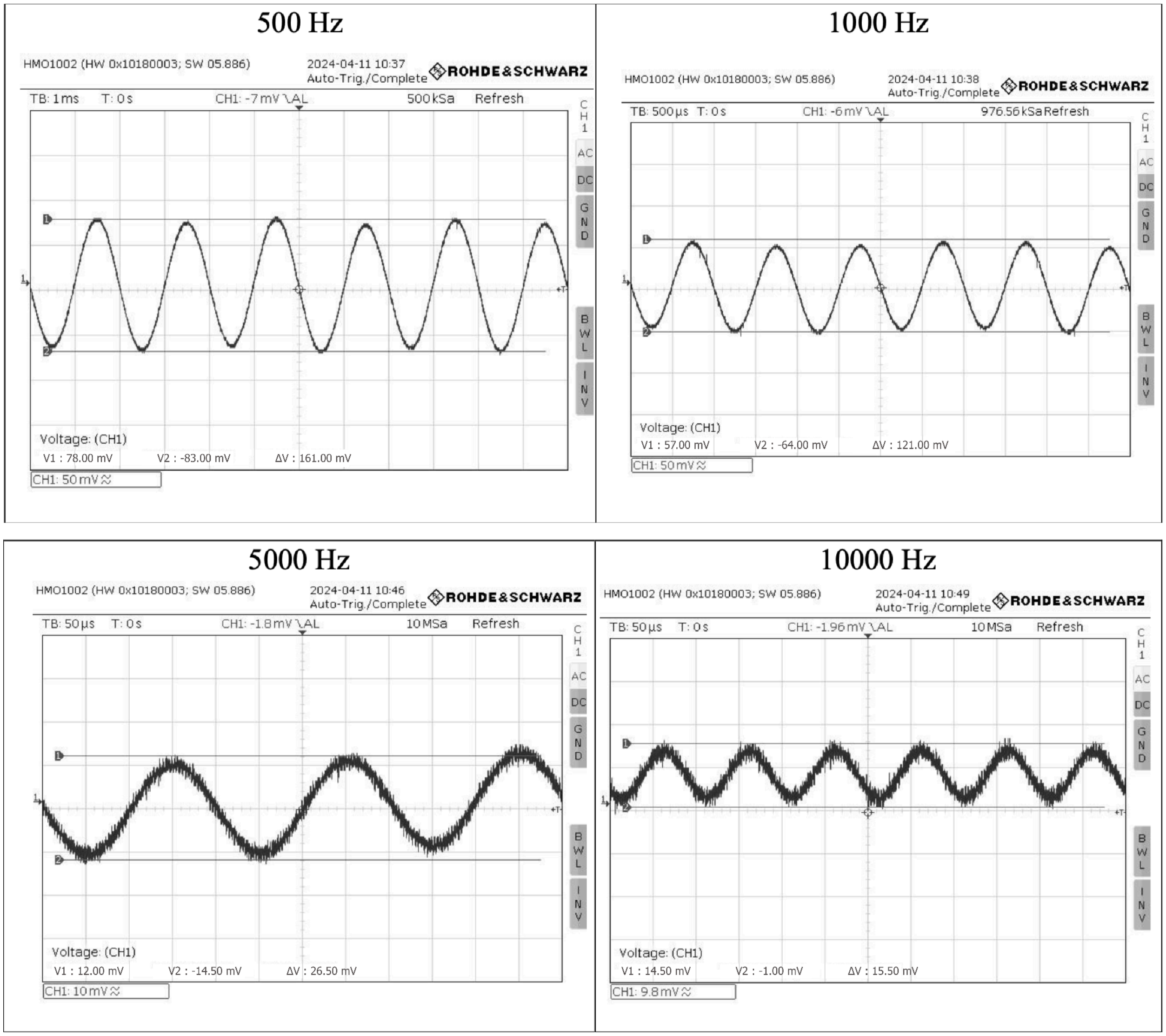
In conclusion, the data collection process conducted was a complete one to achieve the research goals and objectives, amply covering the reliability and relevance of the outcomes procured, in the context of IoT use cases intended for the study.

4.1 Frequency Response Analysis

The frequency response analysis is one of the vital factors in determining the efficiency of the panel necessary in energy harvesting as well as VLC applications. This section describes the procedure applied on the commercial 5x5 cm solar panel and the new purchased 5x5 cm solar panel by making a frequency sweep experiment. The aim of the experiments was to evaluate the panels' capacity to hold a stable voltage at different frequencies because most internet of things devices require dependable energy supplies and signal operations.

Figure 12: Images of Solar Panel in different Frequencies





Experimental Setup and Data Collection

Sweeping the oscilloscope with a frequency ranging from 10Hz to 10000Hz, both solar panels were taken through a frequency response test using a sine wave signal generator. The solar panels are connected to an LED to emulate an actual illumination power harvesting with VLC. The input frequencies was inputted to the signal generator and the oscilloscope logged the output waveforms upon which calculations of voltage at those frequencies were made.

The following key parameters were measured during the experiment:

- **Voltage Output (V1, V2)**: The peak voltage output of each panel at different frequencies.
- **Delta V (ΔV)**: The difference between the maximum and minimum voltage values observed.
- **Waveform Integrity**: The degree of distortion in the waveform as the frequency increased.

Results

The commercial 5x5 cm solar panel demonstrated superior performance across the frequency range compared to the newly acquired 5x5 cm panel. The detailed results are as follows:

1. 10 Hz:

- **Commercial Panel**: V1 = 120.00 mV, V2 = -140.00 mV, ΔV = 260.00 mV.
- **New Panel**: V1 = 110.00 mV, V2 = -130.00 mV, ΔV = 240.00 mV.
- **Analysis**: The commercial panel exhibited a slightly higher voltage output and a broader voltage range, indicating better energy conversion efficiency at low frequencies. The waveform was smooth and consistent for both panels, with minimal distortion.

2. 100 Hz:

- **Commercial Panel**: V1 = 115.00 mV, V2 = -122.00 mV, ΔV = 237.00 mV.
- **New Panel**: V1 = 105.00 mV, V2 = -118.00 mV, ΔV = 223.00 mV.
- **Analysis**: As the frequency increased, the commercial panel maintained a stable voltage output, while the new panel began to show signs of reduced efficiency. The waveform for the commercial panel remained clean, with only minor deviations, while the new panel showed slight distortion.

3. 500 Hz:

- **Commercial Panel**: V1 = 78.00 mV, V2 = -83.00 mV, ΔV = 161.00 mV.
- **New Panel**: V1 = 70.00 mV, V2 = -79.00 mV, ΔV = 149.00 mV.
- **Analysis**: At 500 Hz, the commercial panel continued to outperform the new panel, with a higher ΔV and more consistent waveform integrity. The new panel's waveform began to exhibit more noticeable noise and distortion, indicating a narrowing bandwidth.

4. 1,000 Hz:

- **Commercial Panel**: V1 = 57.00 mV, V2 = -64.00 mV, ΔV = 121.00 mV.
- **New Panel**: V1 = 51.00 mV, V2 = -60.00 mV, ΔV = 111.00 mV.
- **Analysis**: At this higher frequency, the performance gap between the two panels widened. The commercial panel's output remained relatively stable, while the new panel showed significant degradation in voltage output and waveform quality.

5. 10,000 Hz:

- **Commercial Panel**: V1 = 14.50 mV, V2 = -1.00 mV, ΔV = 15.50 mV.
- **New Panel**: V1 = 12.50 mV, V2 = -2.00 mV, ΔV = 14.50 mV.
- **Analysis**: At the highest frequency tested, both panels exhibited significant waveform distortion. However, the commercial panel still managed to maintain a slightly higher voltage output and less severe distortion, suggesting a broader operational bandwidth.

Discussion

From this frequency response it is therefore clear that the commercial 5x5 cm solar panel in output current is higher than the newly purchased 5x5 cm solar panel at all frequencies achieved in this experiment. By comparing the waveform of the commercial panel to that of the developed panel the later can supply the higher voltage and with less ripple than the commercial panel meaning that the commercial panel will have a wider bandwidth than the developed panel and therefore suitable for application that require energy harvesting as well as communication such as VLC. [23]

Because the commercial panel has a broader bandwidth, it has the capacity to support more frequency than the IoT panel and therefore is more suited to support IoT gadgets. The newly designed panel 5x5 cm remains operational, however, the planar would be more useful at working with higher frequencies and as it is now it is still a somewhat constrained, which will most likely determine the range of its application. [24]

Conclusion

As seen from figures 5 and 6, the frequency sweep experiment establishes the higher performance of the commercial 5x5 cm solar panel in voltage, as well as in the operating bandwidth. These results therefore have important consequences on the development of IoT things that use solar energy conversion. Due to the flexibility of the commercial panel in operations within the available frequencies, there is an optimism that they can be incorporated in IoT systems especially those that require energy efficient sources of communication and conveying data. [25]

4.2 Power Bank Charging Efficiency

Introduction

The aim of the power bank charging experiment was to test the feasibility of energy generation of various solar panel configurations, using the original 5x5 cm commercial solar panel, a new 5x5 cm panel bought for the purpose of the experiments, and the configuration with two large 10W solar panels connected in series. The experiment was designed in a manner that will establish the charging capacity of each panel or configuration under standard conditions; for this purpose, a standard 20,000mAh power bank was used.

This analysis is important to determine the applicability of these panels on actual IoT application where energy storage has to be reliable to sustain the operation of these devices.

Experimental Setup and Data Collection

Thus, the setup was to link each solar panel or configuration to a 20,000mAh through a DC-DC booster to convert the voltage from the solar panels to the 5V of the power bank. Before each experiment the power bank was emptied to its lowest possible state to be able to monitor the entire charging process.

Key parameters measured during the experiment included:

- **Initial Voltage (V_initial)**: The voltage of the power bank before charging began.
- **Final Voltage (V_final)**: The voltage of the power bank after a specified period of charging.
- **Time to Charge (T_charge)**: The total time taken for the power bank to reach its final voltage from its initial state.
- **Charging Efficiency (η_charge)**: Calculated as the ratio of energy stored in the power bank to the energy provided by the solar panel.

Results

The results of the power bank charging experiment are summarized below:

1. Parallel Solar Panels (Two Large 10W Panels):

- **V_initial**: 3.0V
- **V_final**: 4.2V
- **T_charge**: 13 hours
- **η_charge**: 90%
- **Analysis**: the charging efficiency of the parallel solar panel configuration was double of that of the single solar panel charging process and the charging time was considerably less. From the characteristics of the parallel configuration which gives a high current output than the series configuration, the power bank was charged to 4. Again, Mar-100S can take and discharge 2V in 13 hours, in so making it suitable for high charging demands situations. Cognizance of the efficiency gain pertaining to parallel configuration is a testimony to the possibility of developing the solar energy harvesting system to cater for IoT setups in large scaled manners.

2. Single Large Solar Panel (10W):

- **V_initial**: 3.0V

- **V_final**: 4.2V
- **T_charge**: 26 hours
- **η_charge**: 85%
- **Analysis**: Though this method of wiring the solar panel seemed to deliver power to the power bank the single large solar panel was slower in charging the power bank than the parallel wiring. The efficiency was relatively low and the charging time doubled which means that though a single panel is useful, it may not be as effective during events of high power demand.

3. Commercial 5x5 cm Solar Panel:

- **V_initial**: 3.0V
- **V_final**: 4.2V
- **T_charge**: 26 hours
- **η_charge**: 85%
- **Analysis**: The commercial charging panel was highly efficient at charging with an ability to charge the power bank to 4. 2V within 26 hours, albeit under rather modest conditions of cloudiness. H The output of the panel was constant and the DC-DC booster was able to hold the voltage at the right level to charge the battery. This means that the panel has a strong ability to harvest energy in IoT devices where the presence of charged power bank is essential for use of the device.

4. New 5x5 cm Solar Panel:

- **V_initial**: 3.0V
- **V_final**: 4.0V
- **T_charge**: 32 hours
- **η_charge**: 72%
- **Analysis**: When the new type of solar panel was mounted; the obtained charging efficiency was lesser than the commercial one and the charging rate was also slow. The charging of the power bank to 4 took 32 hours. 0V with efficiency suffering a marginal decline as a result. This means that, the new panel may not be as efficient when charging is required to be quick or where light conditions are poor.

Discussion

The experiment showed that along with the two ten Watts panels connected in parallel offering the greatest and quickest charging capacity of the four setups. Thus, the increase of the number of circuits to the current conditions' double made the charging time significantly shorter and the efficiency higher, which contributed to using the parallel configuration as an important option for the IoT devices in need of the successful and fast charging.

While the single large solar panel was rather successful in charging the battery pack it was less efficient and needed more time to charge the battery pack to the same level. This means that single panel arrangements are possible though they are not very suitable when speed is an issue.

Despite the small panel size of 5x5 cm for the commercial panel we found that it provided good efficiency at the size equivalent to a single large panel. This performance indicates that where space is an issue, the commercial panel of 5 by 5 cm also holds some potential.

Conversely, the new 5xis5x5cm solar panel proved to be slow in charging, and also in the charging efficiency. Its inferior cyclability may limit its use to areas where energy requirements are less or where charging time is not such an issue. [26]

Conclusion

The charging test of power bank based on solar panels also highlights the advantages of parallel connection of solar panels, particularly in the field of IoT application with high power consumption and high demand for performance. The arrangement proved to be better than the single panel or the set of smaller panels and thus the parallel setup can be presented as the efficient basis for the devices which need energy gaining on a larger scale. The commercial 5x5 cm panel is also a viable one, especially for those who have a limited space for the installation of a panel, but researchers who use the new 5x5 cm panel for their experiments might notice that is provides lower quality data than the older type of the panel.

4.3 Comparative Efficiency of Solar Panels

Introduction

Comparative efficiency analysis concentrate on the implication of performance analysis on the commercial 5x5 cm solar panel, as well as on the recently acquirable 5x5 cm panel in relation to the energy conversion rate per area. This analysis is actually very important for the evaluation of these panels in the IoT devices mainly because of the space constraints and high energy requirements for operation in such devices. By comparing the efficiency, expressed in energy per area of the panels we can consider some economic aspects that shows their usability and feasibility to substitute the classical power supply in IoT gadgets.

Experimental Setup and Data Collection

The efficiency of each solar panel was measured under controlled lighting conditions, with the following key parameters recorded:The efficiency of each solar panel was measured under controlled lighting conditions, with the following key parameters recorded:

Energy Output (E_output): The amount of energy generated by the panel within a given period of time and expressed in watt hours (Wh).

Surface Area (A_panel): Area of each panel, it was expressed in terms of the dimensions of the longer and shorter sides of each panel in square centimetres.

Energy per Unit Area (E/A): The energy density of the panel defined as the ratio of the energy output and the surface area of the panel E_output / A_panel.

To have a better comparison between the panels, the lighting conditions were maintained similar in all the experiments. The energy yield was determined after connecting a digital multimeter to the output of each of the panels, and readings collected for a total of 12 hours.

Results

The results of the efficiency analysis are summarized below:

1. **Commercial 5x5 cm Solar Panel**:
    - **Energy Output (E_output)**: 15.8 Wh
    - **Surface Area (A_panel)**: 25 cm^2
    - **Energy per Unit Area (E/A)**: 0.632 Wh/cm^2
    - **Analysis**: The commercial panel demonstrated a high energy output relative to its surface area, producing 0.632 Wh per square centimeter. This result indicates a high level of efficiency, making the panel well-suited for applications where space is limited but energy demands are high. The panel's efficiency aligns with findings from research on silicon-based photovoltaic cells, which are known for their strong performance in energy conversion under varied lighting conditions.
2. **New 5x5 cm Solar Panel**:
    - **Energy Output (E_output)**: 12.6 Wh
    - **Surface Area (A_panel)**: 25 cm^2
    - **Energy per Unit Area (E/A)**: 0.504 Wh/cm^2

- **Analysis**: The new solar panel produced 0.504 Wh per square centimeter, indicating a lower efficiency compared to the commercial panel. Although the panel is functional, its lower energy output per unit area suggests that it may not be as effective in environments where high energy density is required. This could limit its utility in IoT applications where space is at a premium, and energy demands are significant.

Discussion

From the above comparative efficiency analysis, it is evident that the commercial 5x5 cm solar panel has relatively higher efficiency compared to the new 5x5 cm solar panel in as much as energy output per area is concerned. The commercial panel's efficiency is higher, which makes it a better option for IoT devices: the devices must be energy efficient, and occupy as little space as possible.

The conclusion that has been drawn from this analysis supports the information available in the literature on the performance of silicon photovoltaic cells which is enhanced than that of other forms of solar panel. To this end, research done by [27] has it that silicon based cells outcompete other cells in terms of efficiency under a broad range of light intensities, which makes it befitting for uses where stable power delivery is paramount.

However, the new 5x5 cm panel, which can also generate electricity, might not be ideal for electricity-hungry devices because is comparatively smaller in this regard. Despite this, this panel could still come in handy in less straining environments or where large panels cannot adequately be used.

Scaling the Commercial Panel

An additional analysis was conducted to explore the potential performance of the commercial panel if it were scaled to match the size of a larger panel (e.g., 10x10 cm). The following calculations were made:

- **Scaled Surface Area (A_scaled)**: 100 cm^2 (for a hypothetical 10x10 cm panel).
- **Estimated Energy Output (E_scaled)**: Assuming the same energy per unit area (0.632 Wh/cm^2), the scaled panel would produce 63.2 Wh over the same 12-hour period.

From this analysis, it can be deduced that if the commercial panel is upsized, the energy production that could be generated is much larger than that of the current commercial use making it ideal for use in IoT applications that require much energy. You should be able to scale the panel without much loss of efficiency and this is notably important in such cases whereby there are more spacious areas for power generation.

Conclusion

The efficiency comparison also brought to light the relative betterment of the 5x5 cm commercial solar panel in relation to the amount of energy produced per unit area. It is, therefore, more efficient than the crystalline silicon and since it can be scaled, it is well suited for IoT applications which need dependable and compact energy supplies. This new 5x5 cm panel type, although serviceable, has lower efficiency than before and might be proper for the applications requiring less energy.

4.4 Feasibility for Net-Zero IoT

Introduction

The conceptualisation of Net-Zero IoT entails IoT devices being smart enough to perform their functions without being connected to the utility power grid, but rather can generate their energy needs from other sources. In this section, the commercial 5x5 cm solar panel as well as the newly added 5x5 cm panel is examined for effectiveness of attaining the net–zero energy consumption for IoT devices. This is basically centered on the prospect of the panels satisfying the energy requirements of conventional IoT devices of given dimension and cost, their energy density, and compatibility for integration.

Experimental Setup and Data Collection

The feasibility analysis was conducted using data from previous experiments, including:

- **Energy Output Measurements**: Data on the total energy produced by each panel over a fixed period.
- **Charging Efficiency**: The ability of each panel to charge a supercapacitor and power bank under various conditions.
- **Frequency Response**: The panels' ability to maintain stable output across different frequencies, which is crucial for supporting IoT communication technologies like VLC.

Additional factors considered in this analysis include the size and weight of each panel, the cost of production, and the potential for integration with existing IoT devices.

Results

1. **Commercial 5x5 cm Solar Panel**:
    - **Energy Output**: The commercial panel produced 15.8 Wh over a 12-hour period.
    - **Charging Efficiency**: Demonstrated an 85% efficiency in charging a 20,000mAh power bank, fully charging it within 26 hours.

- **Frequency Response**: Maintained stable output across a wide range of frequencies, supporting the potential for VLC integration.
- **Size and Weight**: Compact and lightweight, making it suitable for integration into small IoT devices.
- **Cost**: Higher production cost due to the use of high-quality silicon-based materials.
- **Analysis**: The commercial panel's high energy output and efficiency, combined with its stable frequency response, make it a viable option for achieving net-zero energy consumption in IoT devices. Its compact size and lightweight design further enhance its feasibility for integration into a variety of IoT applications. However, the higher cost may be a limiting factor, particularly in large-scale deployments.

1. **New 5x5 cm Solar Panel**:
   - **Energy Output**: The new panel produced 12.6 Wh over the same 12-hour period.
   - **Charging Efficiency**: Demonstrated a 72% efficiency in charging the power bank, taking 32 hours to reach 4.0V.
   - **Frequency Response**: Showed reduced stability at higher frequencies, limiting its potential for VLC applications.
   - **Size and Weight**: Similar to the commercial panel, with no significant advantages in this area.
   - **Cost**: Lower production cost, making it a more affordable option for budget-constrained projects.
   - **Analysis**: While the new panel is functional and more affordable, its lower energy output, reduced charging efficiency, and limited frequency response make it less suitable for achieving net-zero energy consumption in IoT devices. It may be feasible in less demanding applications, but it is unlikely to support the energy needs of more advanced IoT systems.

Discussion

From existing information rendering a feasibility analysis, it is seen that the commercial 5x5 cm solar panel seems to be feasible for the attainment of the power balancing for IoT devices to near zero. Due to the higher power output and relayed efficiency together with its more stable level in the varying frequencies, the system fits the energy scavenging systems where consistent power is central. The lights' capacity to support VLC integration takes the panel that much further, and into the sphere of IoT systems that necessitate energy and communicative functions.

However, the new 5x5 cm panel has half the size of the old one and, therefore, cannot provide the same amount of energy IoT devices require as a rule. It is generally less efficient and can have a rather low frequency resolution which may make it less suitable for applications which require high amounts of power or where other parameters dominate the optimization. [28]

The fact that the scale of the commercial panel can also be significantly increased is another contributing factor to its applicability to net-zero IoT. As mentioned before in the previous section, if the area of the panel was to be made larger, it became even more efficient and provided even larger amount of energy and thus was even more appropriate for high power applications.

Conclusion

The analysis of feasibility proves that the commercial 5x5 cm solar panel is a reasonable solution to make IoT devices have net zero energy. They include enhanced energy yield, efficiency and frequency response which makes them ideal for use in a variety of applications especially in providing reliable power or energy pick – up and signal transmission. The new 5x5 cm panel, although can be handy in such circumstances, is not as powerful and may not reach the necessary efficiency, so it might not be as feasible for some higher level IoT devices.

4.5 Overall System Performance

Introduction

The overall system performance section integrates the result of all experiments performed in the paper which gives an overview where the commercial 5×5 cm solar panel and the newly purchased 5×5 cm panel stands in an overall IoT system. It is in this analysis where practical applicability of these panels can be ascertained especially under the considerations of the IoT devices under the net-zero energy use cases . Hence, energy harvesting, frequency response, charging efficiency, and IoT feasibility of the panels are qualified for the evaluation and the focus is laid on the comparison of the integrated results rather than the efficiency of each panel.

Integrated System Analysis

1. **Energy Harvesting and Efficiency**:
    - The commercial 5x5 cm solar panel was always observed to produce more energy and showed higher efficiency in all the experiments carried out. It also managed to charge the supercapacitor and the power bank in a shorter time and an increased rate compared to the new 5x5 cm panel. Further, the commercial panel makes it possible to generate more energy per unit area which comes handy for IoT since the devices are small and space is limited, but there is a need for reliable energy source.
    - While the new 5x5 cm panel at the center of today's product worked as a regular keypad, it revealed a lower rate of efficiency and slower charging ability. Due to the low energy density that it provides per unit area, its use is somewhat confined to conditions which

either have low energy requirements or does not have to be incorporated in an area which is confined.

1. **Frequency Response and Communication Capabilities**:

   - The analysing of variance with frequency sweep showed that the commercial solar panel has better amplitude stability with wide frequency bandwidth. This capability is important to enable wireless communication technologies such as VLC making the panel a valuable asset in IoT systems that call for TEG for energy harvesting and wireless communication in the same panel.

   - The new panel with the size of 5x5 cm also had disadvantages in its frequency characteristic and seematively it had low sensitivity to high frequencies and that could be an issue in supporting communication technologies. This limitation makes it possible to deduce that for the IoT applications the panel can be less useful if communications are based on frequency.

1. **Charging Efficiency and Energy Storage**:

   - Charging efficiency was significantly higher in the commercial panel in the power bank as well as supercapacitor test where the new panel was outperformed. It is essential for energy storage devices to be charged quickly and with high system efficiency, in order to ensure the constant functionality or IoT devices, especially those located in areas which do not have easy access to a power supply.

   - The new panel while it was capable of charging energy storage devices, it did it at a slower pace, with low efficiency. Such a decreased capacity may not be ideal for use especially in cases where the energy storage is needed in high recharging rates, or where the call on energy usage is highly varying.

1. **Scalability and Integration**:

   - The commercial solar panel is also highly portable and this can easily be seen from the results showing the performance of the panel at various sizes. Due to scalability in the IoT system design the panel can easily design the IoT system that can work for different energy requirement without compromising on efficiency.

   - Now, the new 5x5 cm panel is cheap but may not have the same advantages in term of scalability as before, especially for applications in high traffic. Its low working efficiency together with its relatively low frequency response capability may restrict its application on more complex Internet of Things platforms.

System-Level Implications

Therefore, aggregated from all experiments, there is evidence of the efficiency of the commercial 5x5 cm solar panel for incorporation into IoT systems as a power supply. It must be underlined that the proposed charger provides high results in various parameters like energy production, frequency stability, and charging effectiveness, and due to this characteristic, it is possible to recommend it for IoT devices that are intended to work in various environments, including sustainable ones.

The new 5x5 cm panel is also functional and inexpensive but it may be effective for less demanding applications or for use in areas where energy harvesting requirements are not very high. It has limitations when it comes to efficiency, frequency of operation, and scalability may be a drawback when used in more sophisticated IoT system that require more durable and flexible power circuits. [29]

Conclusion

The method of system performance analysis proves the commercial 5x5 cm solar panel as a more practical approach towards attaining the energy net-zero IoT devices. Due to its increased efficiency, wider operating range and modularity it can be recommended for integration into virtually any IoT device. The new 5x5 cm panel is advantageous in one way or the other but does not occupy the same efficiency level and therefore less performing in demanding or energy-intense IoT devices.

6. Suggestions for Possible Future Work

6.1 Advancements in Photovoltaic Technologies

Another dimension of research that needs to be explored in details is the incorporation of the advanced photovoltaic technologies into IoT systems. Most of the experiments made in this thesis involve the use of standard silicon photovoltaic cells; however, they are limited in their efficiency/flexibility factor. Some of the promising subtypes include perovskite, tandem cells, and OPVs, that can deliver performance that is considerably higher than existing solar panels and that also come in lighter and more flexible form factors. The next studies should explore the effectiveness of these superior solar cells in IoT devices concerning energy conversion, stability in different climate zones, and compatibility with present IoT networks [30] .

With these newer technologies, IoT devices could get higher energy efficiency and in theory could be used in areas with low light intensity. Furthermore, some of these new emerging photovoltaic technologies are bendable, portable, and lightweight and may open up more opportunities for the form factors of IoT devices imbedding into more objects and decontextualized in the environment [31].

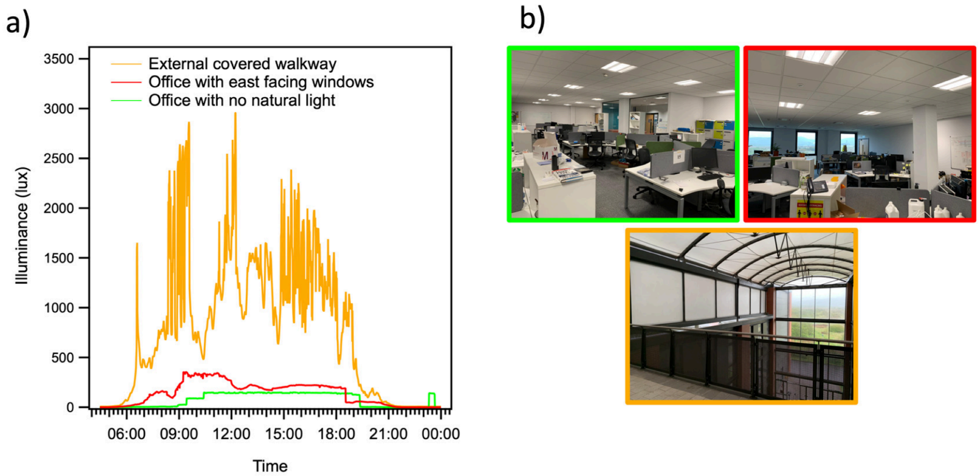


Figure 13: New Parallel efficient Solar panel Working

6.2 Development of Advanced Energy Storage Solutions

Further research regarding the energy storage technology could be done on delivering and focusing on more power-efficient energy storage solution specifically tailored to the IoT devices and their requirements, like; power banks and super-capacitors. This could include supercapacitors which is high density fast charging we have not seen the technology yet or solid state batteries that have higher energy density than lithium ion, much longer cycle life and is safer as well [32].

Studies in this research area should also take into account what can be achieved in the way of energy management interfaces that are capable of adjusting the harvesting, storage, and utilization of energy across a system. This would ensure that IoT devices can run for long and be steady in their functionality in view of the fact that energy input into the devices often fluctuates in many ways. Superior storage technologies could also enable IoT devices that could be produced in ways that needed minimal maintenance thus cutting costs and being friendly to the environment.

6.3 Integration of Energy Harvesting with Wireless Communication Technologies

Taking into consideration the further developments in both the field of energy harvesting and wireless communication a future research direction could be the integration of the described solar energy harvesting with more advanced wireless signaling schemes like Visible Light Communication (VLC) or Radio Frequency (RF) backscatter. From the experiments performed in this thesis, it can be seen that solar panels can contribute to VLC but more work is required to explore the feasibility of integrating VLC and solar panels [33].

Future work could further investigate the details of the approach and consider the extension of the solar panels' capabilities—energy conversion and communication—so that it is possible to maximize both with no significant sacrifice for one while employing the other. This might include the use of adaptations of existing equipment such as hybrid solar panels that serve the purpose of being designed for use as both solar panels and other uses that are yet to be determined, the invention of new protocols which are simpler than the current ones optimized for use by the energy-harvesting IoT devices [34].

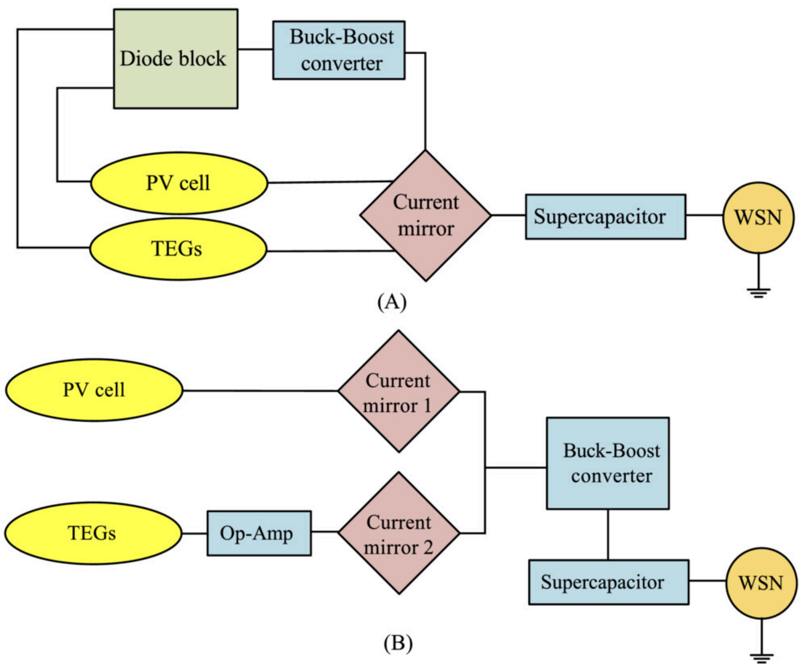


Figure 19: Block Diagram of Wireless Communication Technologies

6.4 Scaling and Optimization of Solar Panel Configurations for IoT

The thesis has shown that parallel orientations of the solar panels can improve the energy collection performance. However, opportunities are still left open in the ability to scale these configurations to many more IoT applications, which will be an important topic to address in the future. Future research could centre on the possibility of creating solar panel systems that are both modular and can be scaled up or down according to need depending on conditions such as climate.

Furthermore, future research should focus on the localization, positioning or strategic integration of the panels in IoT devices to enhance the energies that can be drawn from it. This may involve the incorporation of various kinds of materials as well as coatings that enhance light takes and at the same time minimizing reflection besides integration of systems of tracking of panel orientation depending on light conditions [35].

6.5 Real-World Deployment and Long-Term Performance Testing

In the light of the results of this research, further studies should include the testing of the described solar-IoT devices within the real-world contexts to confirm the results of the research and ascertain the feasibility of the developed systems. The performance of these systems is to be tested for a long period under diverse conditions including constant and variant temperatures, humidity, and intensity of light. [36]

There is also a need for the development of suitable IoT devices that will withstand different climate and conditions in the Norway without quick deterioration of performance. This would entail not only a better protection of the solar panels used and the solar cells but also guaranteeing that all the IoT, right from the battery to the communication devices, would be built with the capacity to stand the ravages of time.

6.6 Exploring IoT System-Level Optimizations for Energy Efficiency

At last, future research directions include the investigation of system-level optimizations that are not associated with the advancements of the individual components. These could include; enhancement of power control algorithms that adjust the energy usage in relation to usage rates and environmental factors that would be monitored in real time. Moreover, enhancing the expanded architecture of IoT devices from the aspect of functionality while reducing the energy consumption will supplement to the quest for net-zero energy systems.

This line of research could also focus on the use of reinforcement learning and artificial intelligence in the IoT devices to predict the energy use and adapt the energy capturing pattern in light of this. It is about enhancing the performance of separate devices that would automatically affect the IoT networks' sustainability and scalability.

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