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LIGHT ENERGY HARVERSTING FOR INTERNET OF THINGS DEVICES

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ELECTRICAL & ELECTRONICS ENGINEERING

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Light Energy Harvesting for Sustainable Internet of Things Devices

by

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Dissertation submitted in partial fulfilment of
the requirements of the
Bachelors of Engineering with Honours
(Electrical and Electronics Engineering)

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CERTIFICATION OF APPROVAL

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A progress report/ project dissertation submitted to the
Electrical & Electronics Engineering Programme
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Approved by,

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(Dr. Michael Drieberg)

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JANUARY 2022

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ELYAS JOHARY BIN AMRAN

ABSTRACT

There is an upward trend of using Internet of Things (IoT) devices in recent years, such as Wireless Sensor Network (WSN) for environmental monitoring applications. The sensors nodes in WSN systems are deployed wirelessly in a dispersed manner, calling for disposable batteries as the main source of energy for these devices.

In this paper, a light harvester prototype is designed to power up a sensor node in a WSN; fulling the concept of a sustainable IoT system. The sensor node features sustained operation over a prolonged time. The prototype will be using Photovoltaic (PV) cells to generate energy to power up the sensor node. Any excess energy will be stored in a Lithium-Ion battery, which will act as the power source during the absence of light. The sensor node includes a humidity and temperature sensor for environmental monitoring, where the data will be sent to a sink node through a Zigbee wireless communication module. The sensor uses low power consuming devices; where the system power is 22.76mW. The data gathered shows that the energy generated by a 3W PV cell in 3.5 hours is enough to sustain the sensor node's operation for more than 3 days.

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The completion of this project could not have been possible without the assistance of people whose names may not all be enumerated. Their contributions are sincerely appreciated. I would like to express my gratitude to my supervisor, Dr. Micheal Drieberg for providing guidance and counsel throughout the project. My gratitude expands to Universiti Teknologi PETRONAS and their Electrical & Electronics Engineering department for providing the resources that I needed to complete my Final Year Project.

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LIST OF ABBREVIATIONS

FYP	Final Year Project
IoT	Internet of Things
PV	Photovoltaics
DC	Direct Current
BLE	Bluetooth Low Energy
WSN	Wireless Sensor Network
IDE	Integrated Development Environment
Li-on	Lithium Ion
USB	Universal Serial Bus
API	Application Programming Interface
V	Volts
A	Amps
W	Watts
J	Joules

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The Internet of Things (IoT) refers to the countless physical devices globally that are currently connected to the internet, all compiling and sharing data. Since the arrival of low-cost computer chips and the omnipresence of wireless networks, there is now high potential to turn anything, from something as small as a coin, to something as big as a car, into part of IoT. Linking up all these separate devices and adding sensors to them adds a layer of digital intelligence to the devices that otherwise dumb, allowing them to broadcast information in real time without the involvement of a human worker.

Energy harvesting is the practice by which energy is extracted from external sources such as light energy or any other ambient energies. This energy is trapped and stored for tiny, wireless autonomous physical devise such as wearable electronics and/or IoT devices. Energy harvesting can only give a small amount of power for low energy electronics as the process harvest only ambient energies.

Light energy harvesting is the concept of capturing ambient light energy, either from sunlight or indoor artificial light. The process of converting light energy into electricity is called the photovoltaic effect. Using special semi-conductor material, a PV cell can generate Direct Current (DC) from any light sources. The energy generated can be used for low power devices and sensors.

IoT has enabled applications that require low cost, low power, remote monitoring and ease of deployment. IoT devices are typically powered by small batteries, that have a limited lifespan. Nevertheless, energy harvesting especially based on light offers a promising solution to the energy supply issue for IoT devices.

1.2 PROBLEM STATEMENT

IoT encompasses a myriad of devices connected over the internet. This includes remote sensors that monitor an environments' parameters. As most IoT devices uses small batteries, the battery source of the current IoT devices will eventually be depleted. The current measure is to regularly change the batteries to ensure constant device operation. With IoT applications required to operate for several years, replacing batteries is a time-consuming and cost prohibitive exercise.

1.3 OBJECTIVES

The objectives of this project are:

- To develop a Light Energy Harvester for IoT devices
- To test the devices to ensure their sustained operation over a prolonged time

1.4 SCOPE OF STUDY

This study is done mainly on adopting light harvesting concept for the sensor node in IoT. To ensure the energy sustainability, it is crucial to ensure that the PV cells generate enough energy to not only power up the sensor node, but to also store enough energy to maintain the operation through moments where the light source is not available. Therefore, the project is designed using low powered devices, i.e., Arduino Pro Mini, DHT22, and Xbee Pro Series 1 module. This is to ensure that the device can operate in a self-sustaining manner, where the ultimate goal is to have lifelong operations with minimal need for maintenance. A prototype is to be built to ensure the working operation of all the functions mentioned as well as gain additional data for any further improvements.

CHAPTER 2

LITERATURE REVIEW

2.1 INTERNET OF THINGS

In the most general sense, the term IoT contain everything that connected to the internet, such as a phone, computer, sensors, actuators, etc. IoT is the progression of Information Technology which aspire to create a digital infrastructure that integrates and connect all electronics devices globally. As stated by Irmak and Bozdal [1], the emergence of IoT suggests a potential of unlimited integration of devices which subsequently call for an unlimited power supply. IoT. With the unlimited integration of electronics devices, there will be IoT devices that is used in environments where charging is not accessible. As seen in Figure 1, there are 3 fundamental layers in IoT; application layer, network layer and perception layer. The perception layer includes sensors and actuators. Wireless sensors that monitor an environment's humidity and temperature are operated using batteries. Therefore, their energy to perform the determined functionality is constrained.

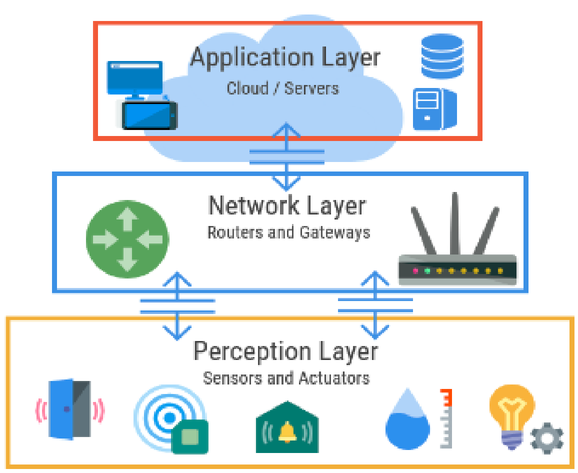


Figure 1: Fundamental Three Layer IoT Architecture *[2]*

2.2 SUSTAINABLE INTERNET OF THINGS DEVICES

IoT enables efficient observation and management in a building, a small town, or even a large city. This however, call for the deployment of countless wireless devices. As specified by Akan et al. [3], to accomplish prolonged monitoring and control, an additional or even a completely new power source should be integrated to the sensors. This can improve the overall functionality, reliability and efficiency of the system. Therefore, energy harvesting methods became an excellent solution to deter energy problems by harnessing ambient energy. According to Yun et al. [4], harvesting untapped ambient energies, such as light energy, kinetic energy and microbe energy, and transforming them into a practical form is a great technique to satisfy the long-term energy needs and environmental sustainability.

Furthermore, the United Nation [5] enforced 17 Sustainable Development Goals (SDGs) that aims to increase global sustainability. Figure 2 shows the relevant goals that are associated with this project.

Figure 2: Relevant SDGs *[5]*

2.3 ENERGY HARVESTING

Energy harvesting is the practice of extracting ambient energies to energize a sensor network for its endless operation. Figure 3 shows the example of energies that are being harvesting for various applications. Over the decade, energy harvesting technologies has developed to have higher efficiencies, which enables stable power output from various energy sources. In addition to that, recent Wireless Sensor Network (WSN) devices are engineered to be highly energy efficient. This creates the opportunity to for WSN devices to function with minimal harvested energy for an extended period of time without stopping due to insufficient energy. In line with Harb [6], the power consumption of the IoT devices must be lower than the average harvested power in order for the electronics device to function continuously.

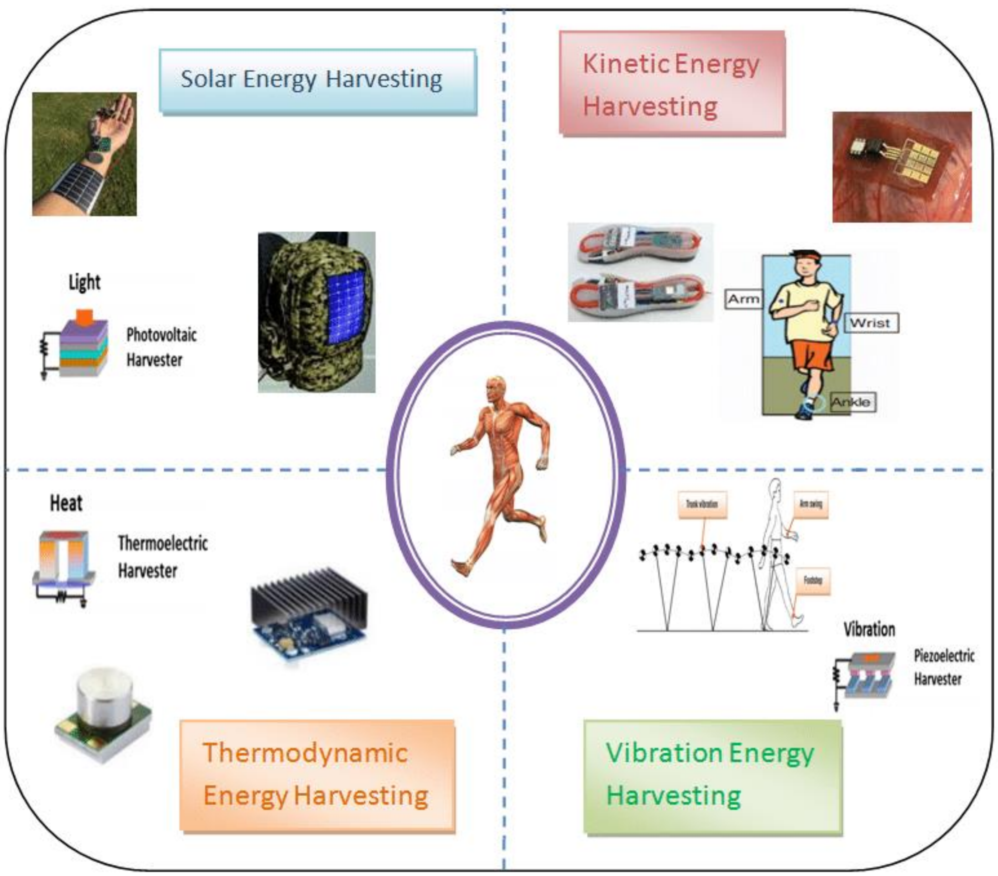


Figure 3: Energy Harvesting *[7]*

2.4 LIGHT ENERGY HARVESTING

In accordance to Ma and Bader [8], light energy harvesting has proved to be a feasible solution for energy-autonomous WSN devices. Light energy harvester includes the use of PV cells to convert light energy into usable electricity. In order to design the system, there needs to be a good estimate of the light intensity in the site where the WSN devices are to be deployed. By characterizing ambient light conditions, the data can be used calculate the dimensions as well as the reliability of the components in the system. There is no ideal method for predicting output power for harvesting energy from ambient light. One of the common ways of doing so is by using the PV cells and measuring the power directly. This however is only viable for the specific tested PV cell, and is not applicable to other types of PV cells. Therefore, primary source research is paramount to determining the sizing of the system to ensure lifelong operation. As mentioned before, the generated energy must be higher than the power consumption of the IoT device. As a result, it is crucial to incorporate low power consuming devices, a highly efficient PV cell as well as an efficient storage unit.

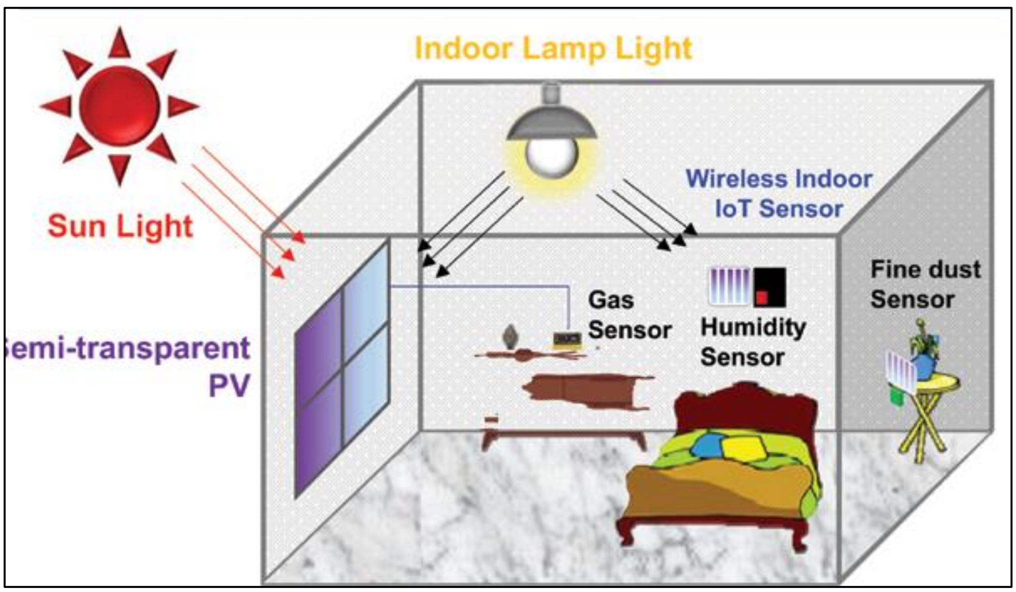


Figure 4: Low-Power Generation by Photovoltaics *[9]*

2.5 RELATED WORK

There are a few researches done on similar works to narrow down the scope of the project. This section highlights the key findings to the related works that was published in journal articles. All the related works encompass the title of this project, i.e., building a prototype for a light energy harvester for IoT devices.

In [10], the prototype that was designed to test a light energy harvester using constant indoor lighting. The articles include testing the prototype using 2 different PV materials, monocrystalline silicon (c-Si), as well as gallium-indium-phosphide (GaInP). Using a constant lighting source of 1000 lux, the prototype was able to supply power for a wireless sensor mote with power consumption of 0.22mW, as well as to charge a 40mA lithium-ion battery. The GaInP photovoltaic cells have overall higher efficiency.

In [11], a light harvester prototype is built for outdoor agricultural application. The system is powered using a 3.7W monocrystalline solar module to power up 320mA worth of loads. Using a 6600mAh lithium-ion battery, the system is not sufficient to have a lifelong operation. The light energy harvester aids in prolonging the lifetime of the system, but does not prevent the battery from depleting. The light source used is outdoor light which has higher irradiance, but inconsistent lighting. Furthermore, the loads of the system also include a Wi-Fi module, which draws the most amount of current (190mA) out of all the other components.

The article in [12] is protype for implementing Bluetooth Low Energy (BLE) devices for indoor localization applications. The prototype uses light energy harvesting with intermittent lighting with both indoor and outdoor test conditions. The test conditions include low light conditions as low as 40lux, which the prototype was still generating energy for the system. Using a small 3mW photovoltaic cell, it was able to generate enough power to power up the BLE (15mA peak) as well as to charge a 1.5F super capacitor. It is important to note that current consumption of communication device is based on how often a signal is sent, which impact the overall power consumption.

In [13], the protype includes a 3.65W PV module, an Arduino uno, a power converter, a 6600mAh lithium-ion battery, 2 sensors as well as well as an XBee module. Using outdoor intermittent lighting, the system was able generate power to energize the loads as well as to charge the battery. The sensors successfully monitor environmental parameters and the XBee module successfully transmit the data to the sink node. However, the system only has a lifetime of roughly 1 week. This is due to the intermittent lighting conditions. The system was able to generate enough energy to energize the loads and charge the battery during daytime. However, at night, the battery was used as the only source for the loads. The charging rate is not enough to charge the battery to full; therefore, the battery level decreases periodically over the span of a week.

Lastly, [14] is a light energy harvester prototype with supercapacitor as a storage element. Using a 0.36W PV cell, the prototype was able to power up the sensor node using indoor lighting condition. The solar panel was able to sustain the whole system, energizing the load and charging the storage unit at the same time. The prototype has a long operation lifetime. However, the lighting is constant. To improve upon the system, intermittent lighting test condition is needed to verify the system's energy sustenance in the case where light may not be present at certain time of the day (i.e., at night).

Based on the 5 articles that were mentioned above, important features were extracted and complied into a table. Table 1 shows the comparison between the related works, where the columns show the notable features from each article. The purpose of the table is to integrate all of the different features of different works into the prototype. The features include testing the prototype using intermittent lighting source, where the light source will not be constantly available throughout the 24 hours in a day. The next feature is to incorporate low power consumption devices to ensure lifelong operation. Finally, the prototype will include sensors as the prototype is mainly targeting to rectify the problems of battery usage in WSN's sensor nodes. As none of the related works have all the features, this project aims to incorporate all of the features in the prototype.

Table 1: Summarized Comparison of Related Works

Title	Description	Intermittent Lighting	Low Power Consumption	Include Sensors	Long Operation Lifetime
Indoor light energy harvesting for battery-powered sensors using small photovoltaic modules (2021)	A light energy harvesting prototype with constant indoor lighting; a small load attached; and small lithium-ion battery (40mAh)	No	Yes	Yes	Yes
Wireless technologies for smart agricultural monitoring using internet of things devices with energy harvesting capabilities (2020)	A light energy harvesting prototype with intermittent outdoor lighting to power up an Arduino Uno, moisture sensor and a communication unit. It uses a 6600mAh lithium-ion battery.	Yes	No	Yes	No

luXbeacon—A Battery-less Beacon for Green IoT: Design, Modeling, and Field Tests (2019)	A light energy harvester with intermittent indoor lighting to power up BLE beacons for indoor localization applications.	Yes	Yes	No	Yes
Solar-Powered Smart Agricultural Monitoring System Using Internet of Things Devices (2018)	A light energy harvesting prototype with intermittent outdoor lighting to power up an Arduino Uno, moisture senor, humidity sensor and XBee Series 2. It uses a 6600mAh lithium-ion battery.	Yes	No	Yes	No
Self-powered IoT Device based on Energy Harvesting for Remote Applications (2018)	A light energy harvesting prototype with constant indoor lighting to power up the sensor and gateway node. It uses a 120mAh lithium-ion battery.	No	Yes	Yes	Yes

2.6 COMPARATIVE STUDY

A comparative study is done to determine the best components to be selected for the prototype while balancing function, & price. Based on the related works, the main components required for the prototype are the controllers, sensors, photovoltaic cells, wireless communication module and battery. There is a myriad of products available on the market, the products are compared side by side using a table to highlight the important features.

a) Comparative Study between Photovoltaic Cells

Table 2: Comparison between Photovoltaic Cells

Specification	Sanyo AM-1816	CNC 145X145-12	Cytron Polycrystalline
Test Condition	200Lx	120kLx	120kLx
Open Circuit Voltage	4.9V	-	11V
Short Circuit Current	94µA	-	520mA
Operating Voltage	3V	12V	9V
Operating Current	84µA	250mA	467mA
Estimated Price	RM56	RM30	RM39

Table 2 shows the comparison between photovoltaic cells. Out of the photovoltaic cells listed, only Sanyo tested the cells under low lighting conditions. Most photovoltaic cells are tested under sunlight, where 120kLx is the standard test condition. Therefore, multiple cells are to be procured to conduct primary source research to determine the best photovoltaic cell for the prototype.

b) <u>Comparative Study between Controllers</u>

Table 3: Comparison between Controllers

Specification	Arduino Uno	Arduino Pro Mini	Raspberry Pi 3 Model B	Raspberry Pi 4
Processor	ATmega328P	ATmega328	Broadcom BCM2837	Broadcom BCM2711
Clock Speed	16Mhz	8Mhz	1.2GHz	1.5GHz
Current Consumption	50mA	4mA	500mA	700mA
RAM	32kB	2kB	1GB	2GB
Network	Via external module	Via external module	Wi-Fi	Wi-Fi
Programming Language	Arduino IDE	Arduino IDE	Python	Python
Estimated Cost	RM62	RM59	RM155	RM209

Table 3 shows the comparison between common controllers found on the market for prototyping purposes. The Arduino Pro Mini has the lowest current consumption, which makes it ideal for controlling the sensor node. Next, both Raspberry Pi has built in Wi-Fi module, which makes it perfect for the sink node. Therefore, the Arduino Pro Mini is chosen as the controller for the sensor node, due to the low current consumption; while the Raspberry Pi 3 Model B is chosen as the controller for the sink node, as it has a Wi-Fi module and it is cheaper than the Raspberry Pi 4.

c) Comparative Study between Sensor

Table 4: Comparison between Sensors

Specification	DHT11	DHT22	SHT71
Operating Range ➢ Temperature ➢ Humidity	0 to 50 °C 20 – 90%RH	-40 to 80°C 0 – 100%RH	-40 to 120°C -100%RH
Accuracy ➢ Temperature ➢ Humidity	± 2°C ± 5%RH	± 0.5°C ± 2%RH	± 0.9°C ± 3.5%RH
Current Consumption ➢ Active Mode ➢ Sleep Mode	2.5mA 150µA	1.5mA 50µA	0.5mA 0.3µA
Transmission Distance	20m	100m	50m
Estimated Cost	RM10.60	RM26.50	RM124

Table 4 shows the comparison between sensors. The sensors listed includes both humidity and temperature sensors in a single device. Due to the lost cost, low power consumption and popularity in open sources, the DHT series is an excellent choice as the sensors for this project. As observed in the table, the DHT22 has the higher accuracy, higher transmission distance, as well as lower current consumption compared to DHT11. Therefore, DHT22 is chosen as the sensors for the prototype.

d) <u>Comparative Study between Wireless Communication Modules</u>

Table 5: Comparison between Wireless Communication Protocols

Specification	ZigBee	Wi-Fi	Bluetooth	Bluetooth Low Energy
Network Topology	Star, Tree and Mesh	Star	Point-to-Point	Star, Bus
Data Rate	96-250kbps	54-600Mbps	700kbps	1Mbps
Network size	65000	255	7	Unlimited
Transmission Range	10-100m	50m	<30m	50m
Power Consumption	Low	High	High	Low
Security	High	Low	Low	Low

Table 5 shows the comparison between wireless communication protocols. Arduino controllers does not have built in wireless communication modules; therefore, an external module will help relay the information acquired from the sensor node to the sink node. As observed in the table, ZigBee has the overall best fit as a wireless communication protocol due to the large network size, transmission range and security. However, the most important feature is the low power consumption, which enables the sensor node to be energy efficient.

e) Comparative Study between Battery

Table 6: Comparison between Batteries

Specification	Alkaline	Lithium Ion	Lithium Polymer	Nickel-Metal Hydride (NiHM)
Operating Range	0°C - 65°C	-20°C – 60°C	0°C - 60°C	-20°C - 60°C
Cell Voltage	1.5V	3.6V	3.6V	1.25V
Lightweight	Yes	Yes	Yes	No
Self-Discharge Rate	5%	10%	~10%	30%
Charging Time	-	1-3 hours	2-4 hours	10-12 hours
Battery Capacity	2000mAh	1500mAh	5000mAh	2200mAh
Rechargeable	No	Yes	Yes	Yes
Cycle Life	-	500-1000	300-500	300-500
Cost	Low	High	High	Low

Table 6 shows the comparison between different battery types. The typical batteries available on the market are alkaline, lithium ion, lithium polymer and nickel-metal hydride. The most important property is that the battery needs to be rechargeable. Based on the table, lithium ion is chosen as the storage unit for the prototype due to the shortest charging time and high life cycle. This is to ensure that the battery can act as a reliable backup supply.

CHAPTER 3

METHODOLOGY

3.1 SYSTEM METHODOLOGY

The system methodology is based on the structure shown in Figure 5. The structure is used to ensure the most systematically efficient way of organizing the development of the project. The Waterfall model is one of the most common models for engineering project development. It is easy to follow in the sense that the system has a linear structure. Due to the linearity, following the model is intuitive for most individuals regardless of background and experience.

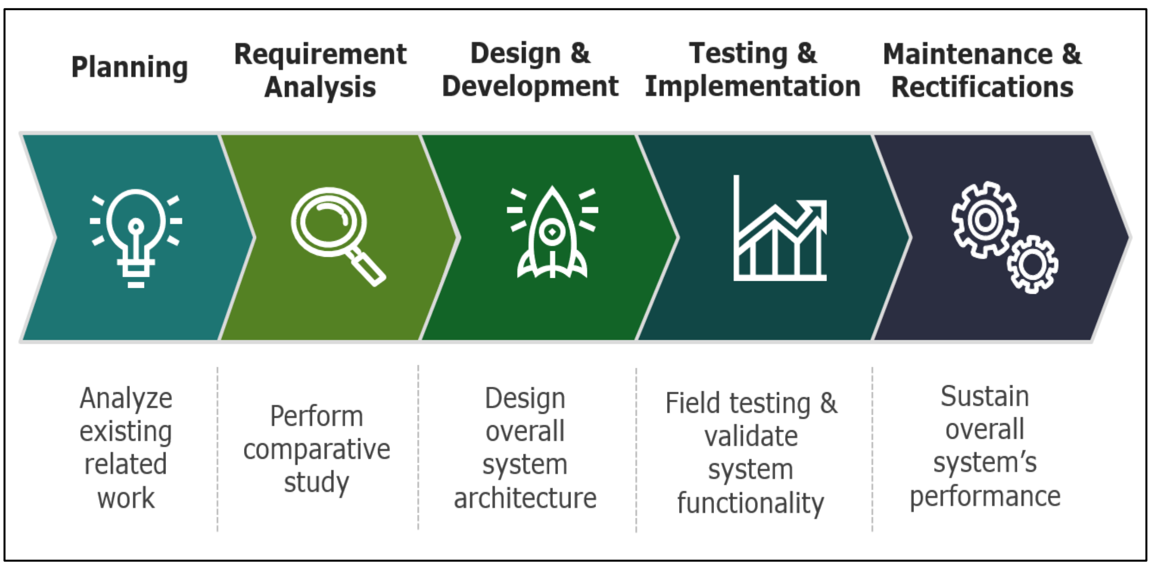


Figure 5: System Methodology

a) Planning

In the project planning phase, the most important parameter to consider is the problem statement as well as the objectives of the project. The objective of this project is to develop a light energy harvester for IoT devices which solves the problem of battery depletion in traditional IoT devices. Therefore, in the planning phase, a feasibility study is done to ensure that the project can be practically implemented. Based on the research (which includes multiple related works from different authors), it is possible to estimate of the scope of work that will adopted for the project. For this project, as there is a need to build a prototype to test the device to ensure their sustained operation over a prolonged time, the research also includes the electronics that are required to achieve the objectives of this project. Furthermore, the planning phase is deemed as the most important phase in project management as it defines all of the activities that needs to be completed as well as the time frame given. The planned key milestones of this project will include all the processes in the project methodology for efficient project execution.

b) Requirement Analysis

The requirement analysis is the process of determining the conditions to meet the product or project. Part of the process is to take account of conflicting variables such as the requirements from the FYP panel, budget, time, as well as logistical parameters. Therefore, the requirement analysis is a continuation of the planning phase as this phase will now clearly define all of the parameters of the project. Based on the research done, the best course of action is to use the DHT22 as the sensors, Arduino Pro Mini as the controller in the sensor node, Xbee Pro Series 1 as the communication module between the sensor node and the sink node, lithium-ion battery as the storage unit, and Raspberry Pi 3 as the controller for the sink node. Furthermore, photovoltaic cells are needed for primary source research to determine total energy generated and its ability to sustain the sensor node’s operation.

c) Design and Development

The design and development stage consists of the designing the technical system architecture for the project. The development of the project will be based on separate subsystems. The subsystem of the project includes, the power subsystem, the control subsystem, as well as the network subsystem. Figure 6 shows the overall system architecture for Wireless Sensor Network application.

The light harvester consists of a PV cell, which will generate DC by harvesting the energy from ambient light sources. The DC will then be fed into the charge controller, which will regulate the voltage being fed into the Arduino Pro Mini and storing access energy into the battery. The battery will act as the power supply in the case where the PV cell is not generating any power. The Arduino will act as the controller for the sensor node, where it will monitor temperature and humidity levels using the DHT22 as an input. Then, the Arduino will send the data to the Raspberry Pi in the sink node via the Zigbee communication protocol (i.e., using Xbee Pro Series 1). The Raspberry Pi will act as a controller for the sink node, which takes data from all available sensor nodes and uploading the data into the cloud thought the internet. Using the built in Wi-Fi module in the Raspberry Pi, data can be transferred to the cloud using UTP's internet, "EnergisingFutures". The cloud is a third-party service provider, "ubidots", where users can access the data from any devices through the internet.

Figure 7 shows the system architecture of the prototype. The prototype is divided into 2 entities, i.e., the sensor node and the sink node. The sensor node contains the photovoltaic cell, charger module, and battery. This will be the main components to have a self-sustaining energy source for the sensor module, which will be deployed in a remote area. The sensor node also includes the Arduino Pro Mini, DHT22 Sensor and Xbee Pro Series 1 to send the data to the sink node. The sink node on the other hand is powered by the grid, as most sink nodes are not deployed in remote areas. The sink node contains the Raspberry Pi 3 and an Xbee Pro Series 1.

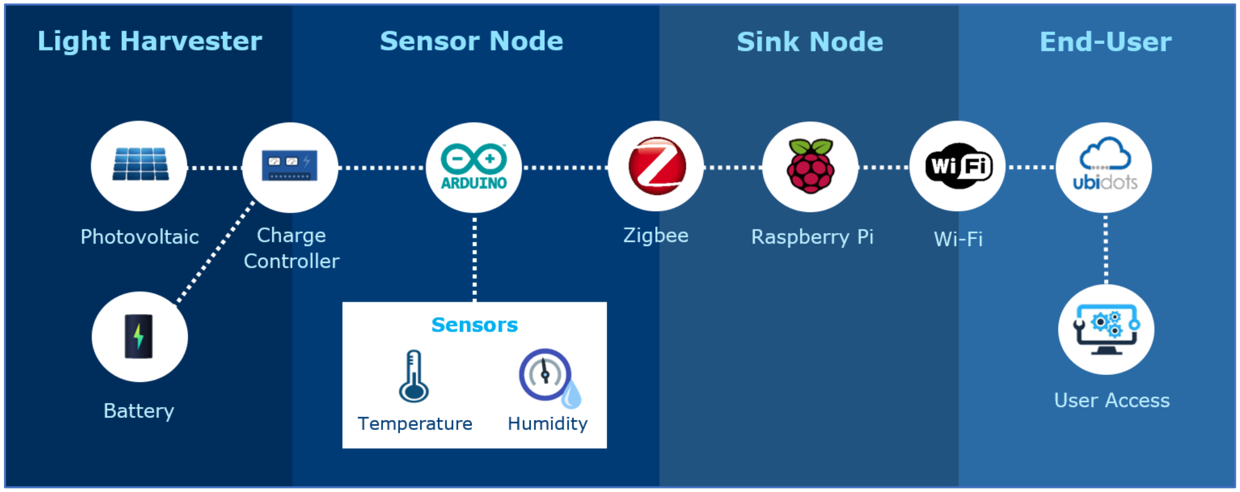


Figure 6: Overall System Architecture

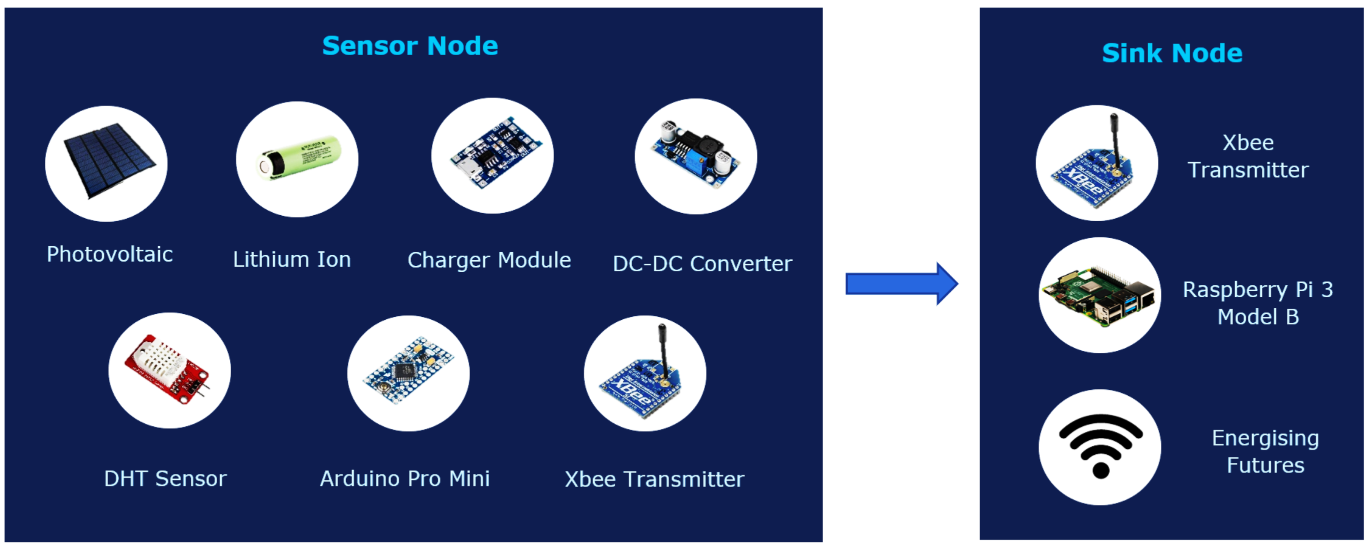


Figure 7: System Architecture

d) Testing and Implementation

The testing and implementation phase is where the designed subsystems are translated into hardware applications. The subsystems will first be tested separately to ensure that each subsystem is working before compiling all subsystems into one product. For the light harvester, the photovoltaic cells would be the priority to ensure sufficient power is generated. The energy generated by the PV cells can be observed using a current sensor. Voltage will be quite consistent while the current is depending on the light intensity. As a contingency plan for the event of insufficient energy generation, PV cells can be connected in parallel or series to satisfy any voltage, current or power requirements. Next, the DHT22 sensor are to be tested for data accuracy and reliability. This data will then be verified at the sink node to ensure that the transmitted data is correct. Additionally, testing include the data transmission to the cloud and it can be verified by comparing the data from the user interface and the data from the sensor node. Furthermore, once the system is functioning properly, there will be a test for power sustainability. This is done by determining the power consumption of the sensor node, and total energy generated by the PV cells in a day. The aim is to ensure that the total energy generated in a day is enough to sustain the sensor node operation throughout the night.

e) Maintenance and Rectifications

The maintenance and rectifications are the process that is carried out after the project is done. Most projects will have problems that are only presented after the project is running, therefore rectification is done to have the most effective system possible. Any rectifications may include resizing the battery, configuring the photovoltaic array or calibrating the sensors for optimal performance.

3.2 PROJECT KEY MILESTONES AND PROJECT TIMELINE

The overall project is in the span of 8 months (2 semesters). The proposal stage is during the September 2021 semester, while the implementation stage is in the January 2022 semester. There are 12 weeks in a semester, which both applies to FYP I (proposal) and FYP II (implementation).

There is a total of 5 key milestones for the entire project. The first 3 milestones are located in FYP 1. The first key milestone is the research on related works. There are multiple similar projects that encapsulates the concept of Light Energy Harvesting for Sustainable Internet of Things Devices. The research on related works narrows down the scope of the project. Next, the second milestone is performing the comparative study. This is to satisfy the requirement analysis, where different components are compared to identify the best solution for the project. Components are chosen based on budget, functionality and reliability. Finally, the third and last milestone of FYP I is finalizing the system design architecture. By completing the third milestone, the project is ready to proceed to the implementation stage.

FYP II commences the fourth milestone of the project, i.e., assembling the prototype. The milestone is achieved after all the physical components of the project is integrated. Finally, the fifth and last milestone is system testing. This milestone is reached when all the subsystems are working, and testing can be done for further optimization. Table 7 shows the FYP I timeline while Table 8 shows the FYP II timeline. The milestones are highlighting in yellow.

Table 7: Final Year Project I Timeline with Key Milestones

Activities	**Week**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Title Selection/ Proposal												
Research on Related Works												
Research on Light Energy Harvesting and Low Power IoT Devices												
Perform Comparative Study												
Equipment Selection												
Finalize System Design Architecture												
Create Budget List for Material Procurement												
Software Development for Arduino & Sensors												
Material Procurement												

Milestones Achieved

1. Completion of Research on Related Works
2. Completion of Comparative Study
3. Completion of System Design Architecture

Table 8: Final Year Project II Timeline with Key Milestones

Activities	**Week**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Design Wiring Diagram for Light Harvester & Sensor Node												
Light Harvester Power Generation Experiment & Tests												
Raspberry Pi Configuration & Setup												
Prototype Assembly												
Sensor Node & Sink Node Communication Configuration												
Integrate Sink Node with Ubidots.com												
Design Web User Interface												
System Testing												
System Rectification & Optimization												

Milestones Achieved

1. Prototype Assembly
2. System Testing

3.3 SENSOR NODE SCHEMATICS DIAGRAM

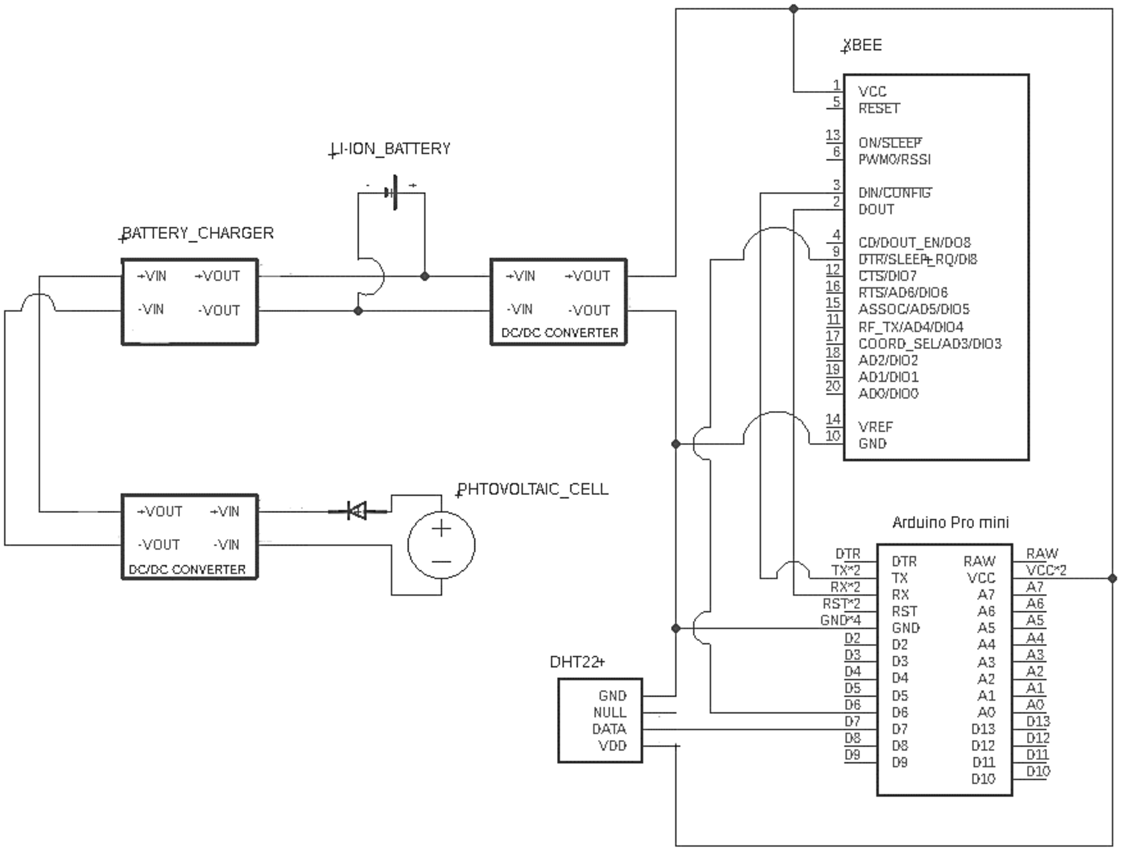


Figure 8: Sensor Node Schematics Diagram

Figure 8 shows the schematics diagram of the sensor node. The PV cell is connected to a buck/boost converter to supply a steady voltage to the battery charger. The battery charger will then charge a 3.7V lithium-ion battery. Parallel to the battery is a buck converter which converts 3.7 V_{DC} to 3.3 V_{DC}. The 3.3V will be supplied to Arduino Pro Mini, DHT22 sensor and Xbee Pro Series 1. The Xbee's DIN and DOUT is connected to the Arduino's Tx and Rx pins. Next, the DHT22 sensor's data pin is connected to the Arduino's digital pin number 7. Lastly, the Arduino's digital pin number 6 is connected to the Xbee's pin number 8 to control the Xbee's sleep mode.

3.4 SINK NODE SCHEMATIC DIAGRAM

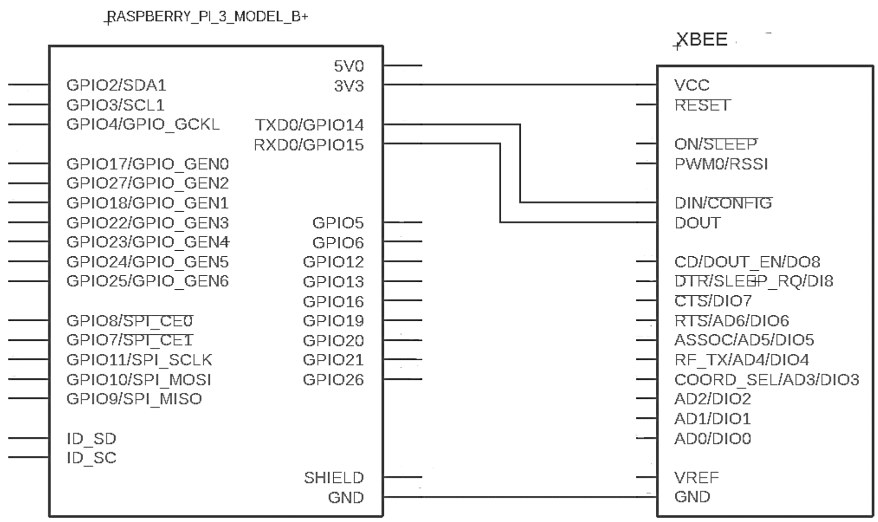


Figure 9: Sink Node Schematic Diagram

Figure 9 shows the schematic diagram of the sink node. A Raspberry Pi 3 Model B is used as the controller for the sink node. An Xbee Pro Series 1 is used as the communication module to receive data from the sink node. The Xbee's V_{CC} is connected to the Raspberry Pi's 3.3V. The ground pins are connected to each other. Next, The Rapsberry Pi's TX pin and RX pin is connected to the Xbee's DIN and DOUT pin, respectively.

3.5 SENSOR NODE FLOWCHART

Figure 10 shows the flowchart of the sensor node. The flowchart represents the coding structure that is implemented in FYP II. The sensor node starts by initializing the sensors and taking temperature and humidity data. Then, the sensor node will transmit the data to the sink node. Next, the Xbee Pro Series 1 will be put to sleep. After 5 seconds, the Xbee will wake up to repeat the whole process again. This cycle will be looped indefinitely.

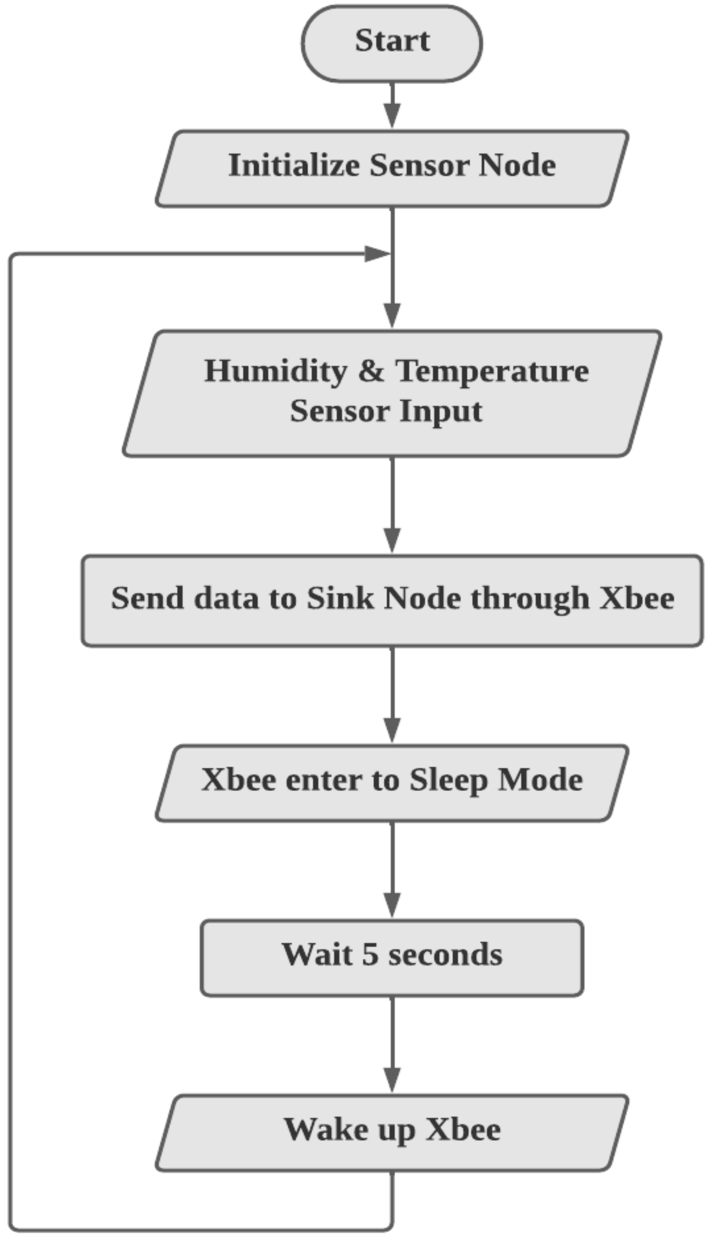


Figure 10: Sensor Node Flowchart

3.6 HARDWARE USED

The prototype makes use of both hardware and software to satisfy the objectives. Both the sensor node and the sink node contain hardware components. The sensor node includes a controller, sensor, wireless communication module, battery, photovoltaic cell, and a charger module. On the other hand, the sink node consists of a controller and a wireless communication module.

a) Arduino Pro Mini

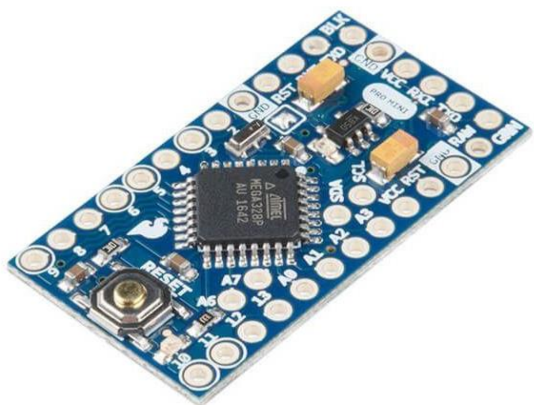


Figure 11: Arduino Pro Mini 3.3V *[15]*

The Arduino Pro Mini is a small microcontroller based on the ATmega328. The Arduino Pro Mini 3.3V is chosen as the controller for the sensor node due to the low power consumption. It draws 4mA during active mode as opposed to the Arduino Uno's 50mA. The Arduino will be used to process the data from the temperature and humidity sensor, as well as sending the data to the sink node though the wireless communication module.

b) Raspberry Pi 3 Model B

Figure 12: Raspberry Pi 3 Model 3 *[16]*

The Raspberry Pi 3 Model B is a microprocessor based on the Broadcom BCM2837. It has a built in Wi-Fi module which allows the device to send data to the internet via Wi-Fi. The Pi will act as the controller for the sink node, which take temperature and humidity data from the sink node and send it over to the cloud.

c) DHT 22

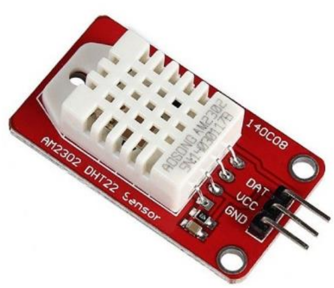


Figure 13: DHT22 *[17]*

The DHT22 is a simple, low-cost digital temperature and humidity sensor. The DHT22 is chosen as the sensors to monitor the environmental parameter around the sensor node. The DHT22 is chosen due to the low current consumption, as well as the wider operating range. The DHT22 consumes 1.5mA during active mode, as opposed to the DHT11 which uses 2.5mA. Furthermore, the DHT22 has a higher transmission distance (100m) compared to the DHT11 (20m).

d) Xbee Series 1 Pro

Figure 14: Xbee Series 1 Pro *[18]*

The Xbee Series 1 Pro is a wireless communication module that uses the Zigbee Protocol which enables the communication between the sensor node and the sink node. The Xbee is chosen due to the low power consumption and high scalability. There will be 2 modules used, one as a transmitter in the sensor node, and one as the receiver in the sink node.

e) Lithium-ion battery

Figure 15: Lithium-ion Battery *[19]*

Lithium-ion battery or also known as Li-ion battery is a rechargeable energy storage unit. Li-ion is chosen as the storage unit for the sensor node due to the low charging time and low self-discharge rate.

f) Photovoltaic Cell

Figure 16: Photovoltaic Cell *[20]*

PV cells are semiconductor devices that converts light energy into electricity. A standard 3W PV cell is chosen as the PV cell for the sensor node. This is because the PV cell is cost efficient and generates enough energy to sustain the sensor node's operation.

g) Charger module

Figure 17: Charger Module *[21]*

The charger module used is the TP4056. The charger module is responsible of regulating the voltage coming from the PV cells and using it to drive the loads as well as charging the Li-on batteries. The module has built in circuit protection and prevents battery over-voltage and reverse polarity connection.

3.7 SOFTWARE USED

The software used are for the controllers, and for transmitting data to the cloud. Both the sensor node and sink node uses software components.

a) Arduino IDE

Figure 18: Arduino IDE *[22]*

The Arduino Integrated Development Environment (IDE) is a software written in functions of C and C++. It is used for writing the code, and uploading the programs to Arduino. This is used to control the sensor node. Therefore, the input and output of the sensor node is configured using this software.

b) Raspberry Pi OS

Figure 19: Raspberry Pi OS *[23]*

Formerly Raspbian, the Raspberry Pi OS is the main operating system for Raspberry Pi devices. The software includes a Python IDE called Thonny. Thonny is used to write the program for the Raspberry Pi 3. This program will be used to control the sink node.

c) Ubidots

Figure 20: Ubidots *[24]*

Ubidots is a 3rd party IoT platform that enables the sink node to transfer information to the cloud. Furthermore, the information can be configured to be displayed through visual tools. Therefore, the temperature and the humidity readings from the sensors can be displayed over the web page on the internet in forms of charts.

d) XCTU

Figure 21: Digi XCTU *[25]*

XCTU is a free, multi-platform application provided by Digi. The software is used to configure and manage the Xbee Pro Series 1 modules. The software includes special features such as graphically representing the Xbee network together with the signal strength of each module’s connection. Furthermore, the mapping function enables wireless reconfiguration of Xbee modules, which is great for optimization.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 TEMPERATURE & HUMIDITY SENSING

The temperature and humidity sensor, DHT22 is connected to the Arduino Pro Mini; where the input supply voltage is connected to V_{CC} and the grounds are connected to each other. The data pin of the DHT22 is connected to the Arduino's digital pin, D7. A USB module is connected to the Arduino's Tx and Rx pin as well. The USB will be used for monitoring the serial port of the Arduino to observe the values of the DHT22 sensor. Figure 22 shows the connection between Arduino Pro Mini and DHT 22.

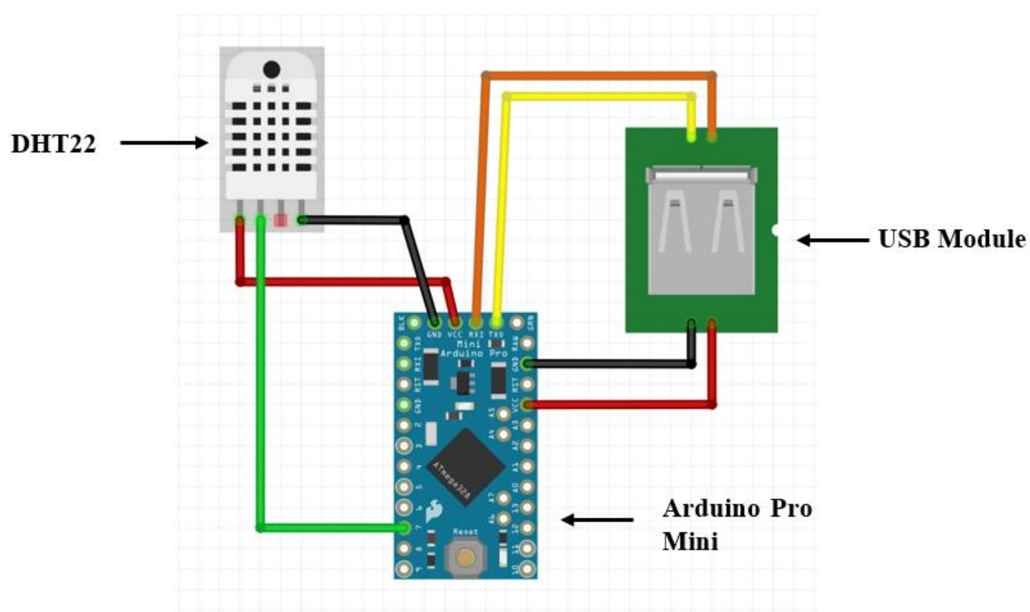


Figure 22: Temperature & Humidity Sensing

Utilizing the connections in Figure 22, a basic program can be written on the Arduino to extract the values of the DHT22. The reading of the temperature and humidity are taken every second. The results of the measured data from the sensor are observed using the serial monitor. Figure 23 shows the results of the DHT22 sensor.

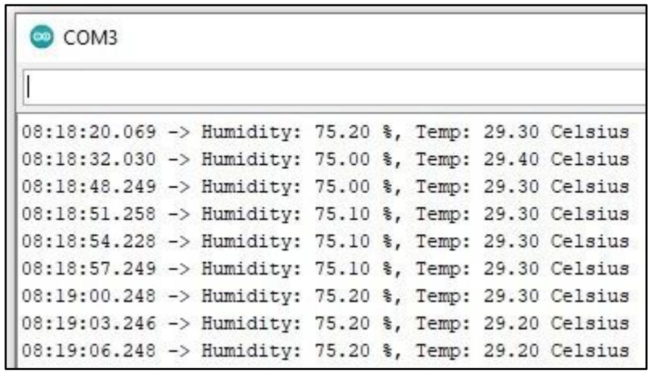


Figure 23: DHT22 Result

Figure 24 shows the average temperature of Seri Iskandar, which is where the experiment is conducted. The figure shows that the temperature of February falls between 24°C to 33°C. Furthermore, according to [26], the average humidity levels in Seri Iskandar in February is around 80%. Therefore, the DHT22 used in this experiment will be integrated into the sensor node as an environmental monitoring sensor.

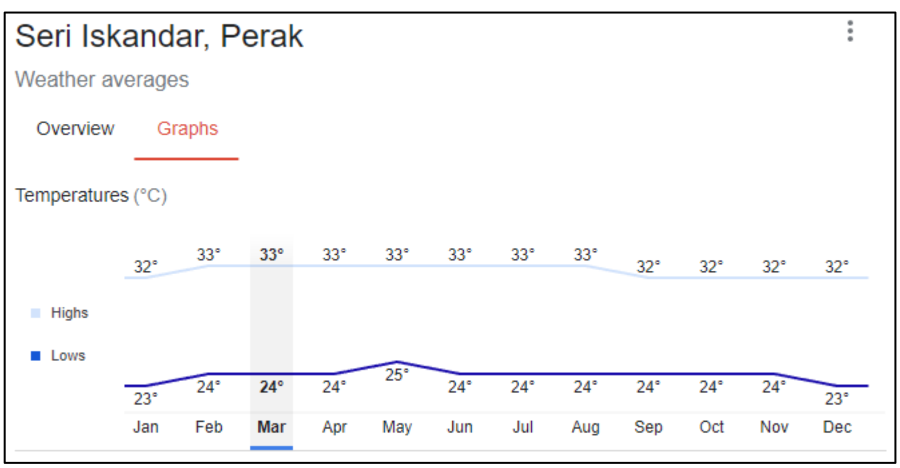


Figure 24: Average Temperature in Seri Iskandar *[27]*

4.2 WIRELESS COMMUNICATION

As established before, Xbee Pro Series 1 is used as the communication module to send data from the sensor node to the sink node. Two Xbee Pro Series 1 is used to send data using the Zigbee protocol. Figure 25 shows the connection of the sensor node. The Xbee module's Tx and Rx is connected to the Arduino's Tx and Rx. The data will be sent wirelessly using the serial port.

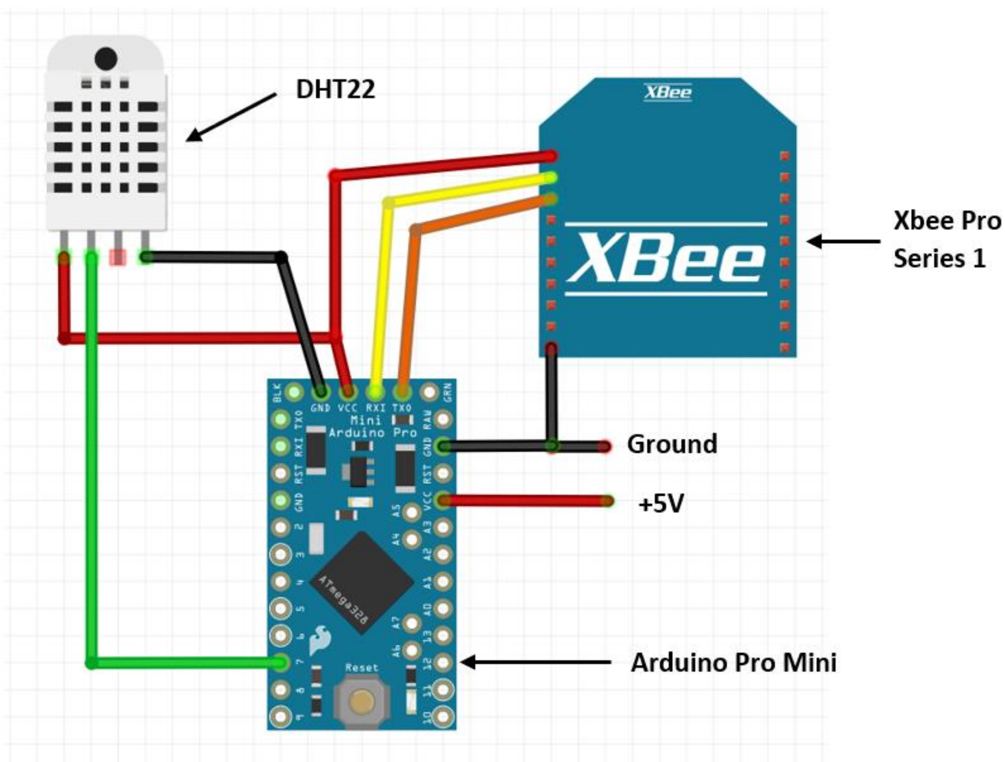


Figure 25: Sensor Node

Next, the sink node is to be configured. The sink node only consists of a Raspberry Pi 3 Model B, which is connected to an Xbee module that acts as a receiver. The Xbee's Tx and Rx pin is also connected to the Raspberry Pi's Tx and Rx pin.

Figure 26 shows the pinout of the Raspberry Pi. Using the figure, the Xbee can be connected to the Raspberry Pi 3 as per Figure 27. Figure 27 is the sink node.

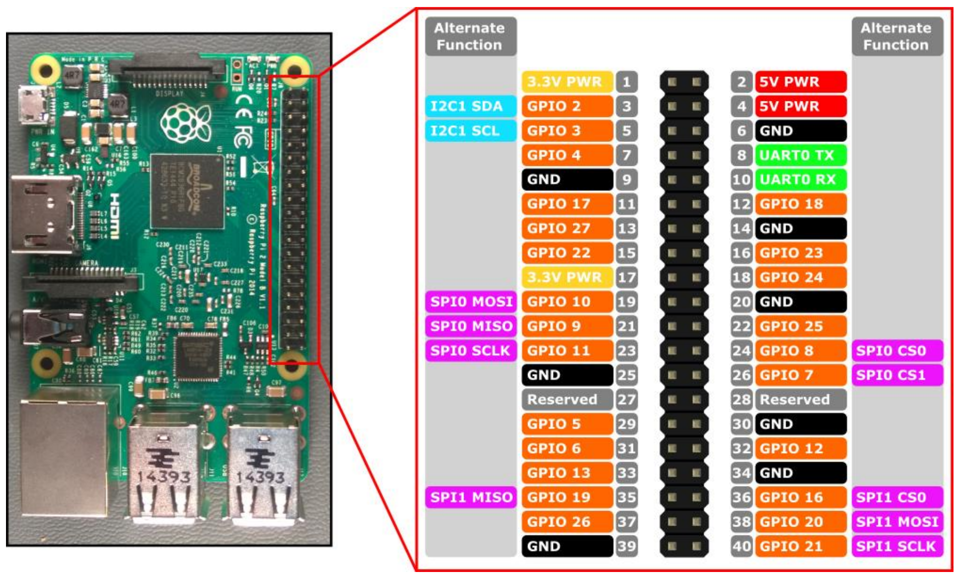


Figure 26: Raspberry Pi 3 Pinout

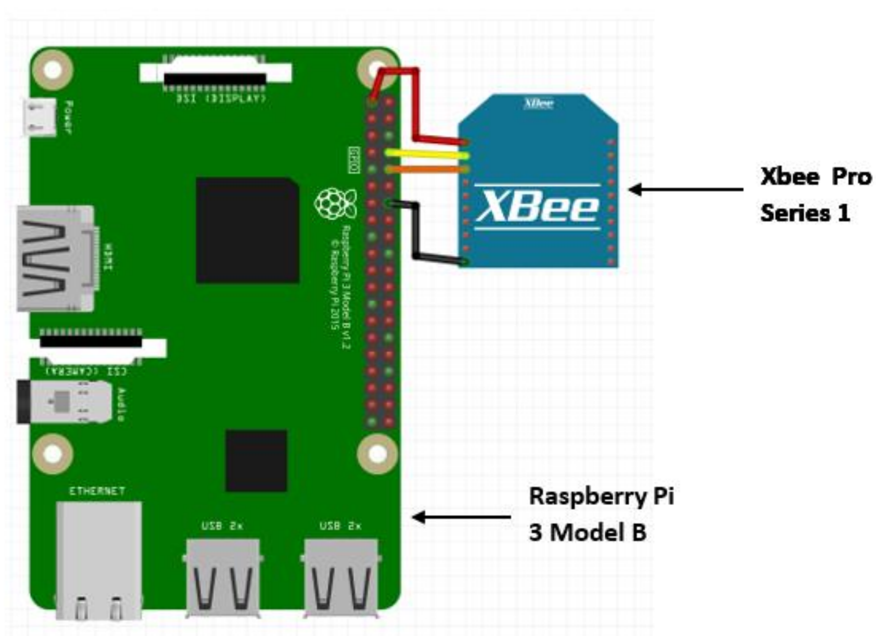


Figure 27: Sink Node

The Arduino transmits data from the DHT22 (humidity and temperature values) to the sink node using the Xbee module. To validate the transmission, data is observed at the sink node. Using a simple python program on the Raspberry Pi 3, data can be extracted from the serial port. Figure 27 shows the results of the program.

```
Shell ×

Python 3.7.3 (/usr/bin/python3)
>>> %Run dht22.py
  b'Humidity: 78.00 %, Temp: 28.80 Celsius'
  b'Humidity: 78.00 %, Temp: 28.80 Celsius'
  b'Humidity: 78.00 %, Temp: 28.80 Celsius'
  b'Humidity: 77.90 %, Temp: 28.80 Celsius'
  b'Humidity: 77.90 %, Temp: 28.80 Celsius'
  b'Humidity: 77.90 %, Temp: 28.80 Celsius'
  b'Humidity: 77.90 %, Temp: 28.80 Celsius'
  b'Humidity: 77.80 %, Temp: 28.80 Celsius'
  b'Humidity: 77.80 %, Temp: 28.90 Celsius'
  b'Humidity: 77.80 %, Temp: 28.90 Celsius'
  b'Humidity: 77.80 %, Temp: 28.80 Celsius'
  b'Humidity: 77.80 %, Temp: 28.80 Celsius'
  b'Humidity: 77.80 %, Temp: 28.80 Celsius'
```

Figure 28: Sink Node Transmitted Data

4.3 DATA TRANSMISSION TO UBIDOTS

Ubidots is an open-sourced Cloud platform that enables data access across the internet. To enable the data transmission to Ubidots, an account is created to obtain a unique API credential to access the dashboard. The API Key is shown in Figure 29.

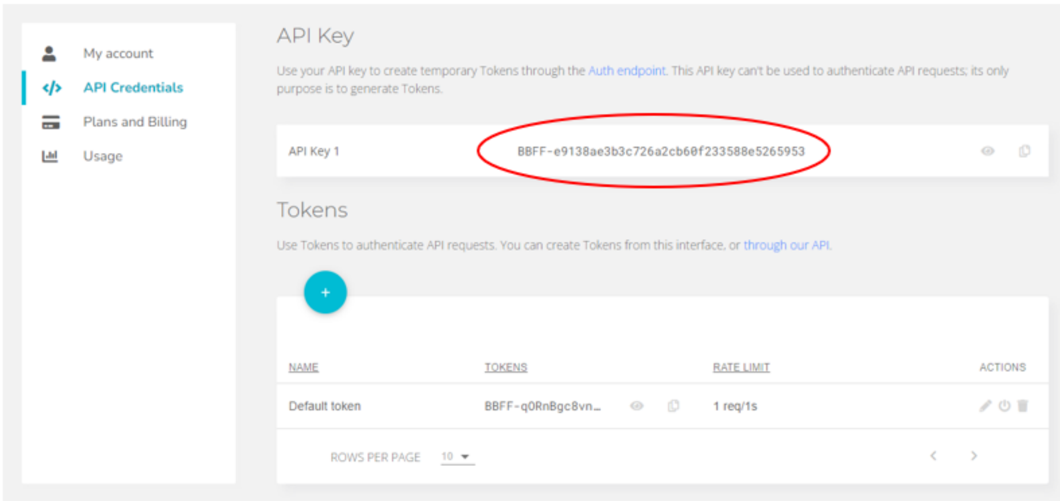


Figure 29: Ubidots API Key

Using the API Key, data can be transmitted from the Raspberry Pi 3 to Ubidots through the internet. Figure 30 shows dashboard of Ubidots which contains a User Interface model to show the most recent values of the temperature and humidity levels.

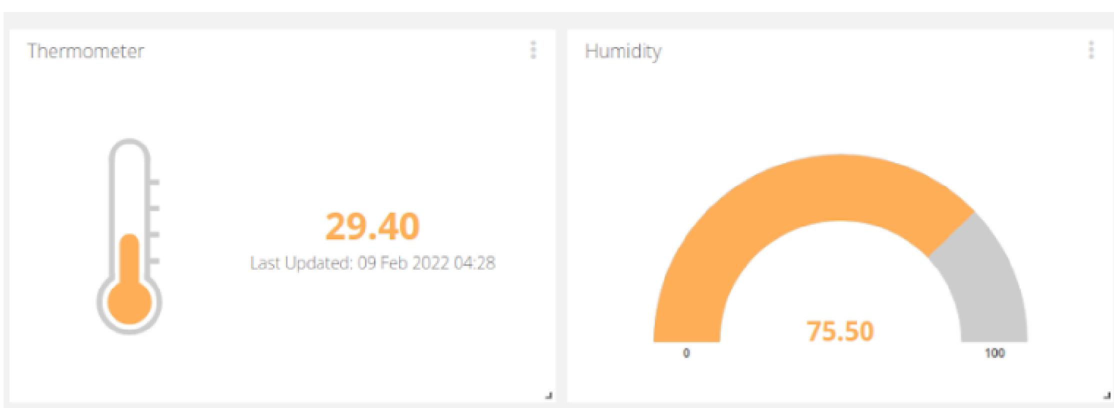


Figure 30: Ubidots User Interface

In addition to the User Interface, Ubidots also features a subsite that contains all the raw data received from the sink node. Figure 31 shows an example of the raw temperature data that was received from the sink node. It can be seen that Ubidots saves all of the values and compiles them to a graph. This graph can be used as an excellent tool to visualize any disturbances occuring in the system.

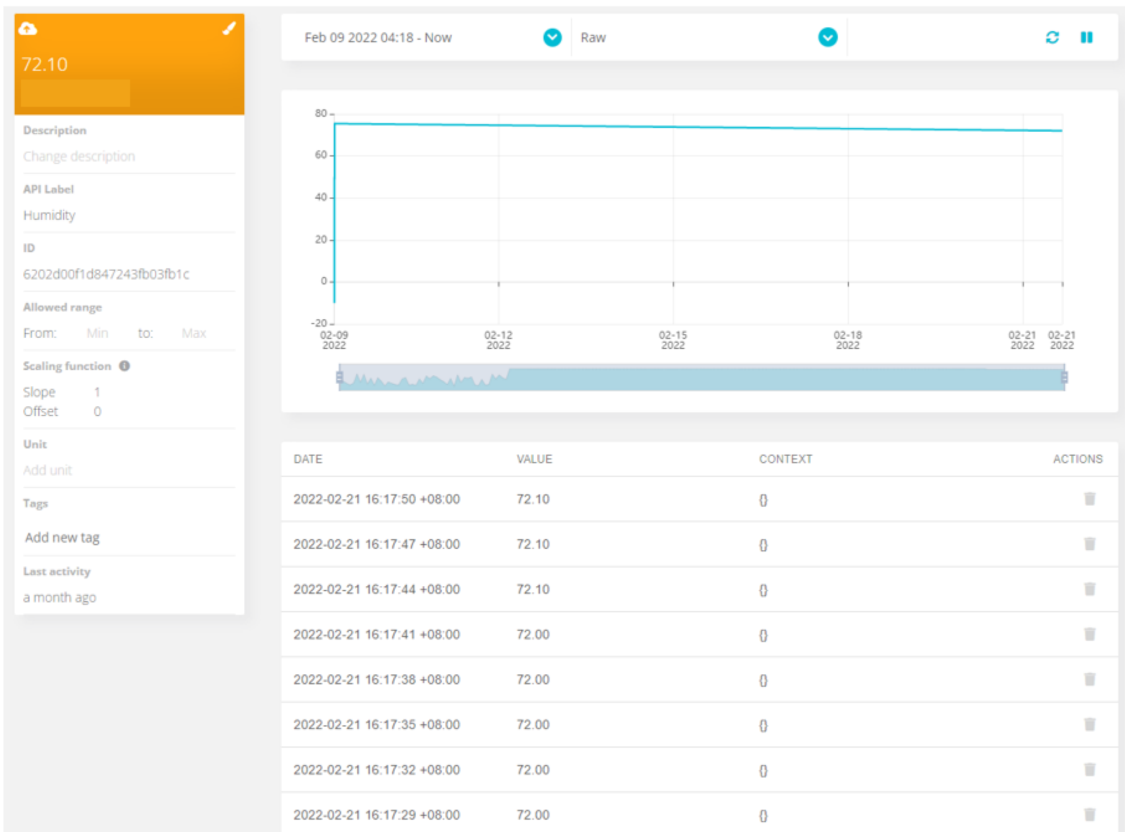
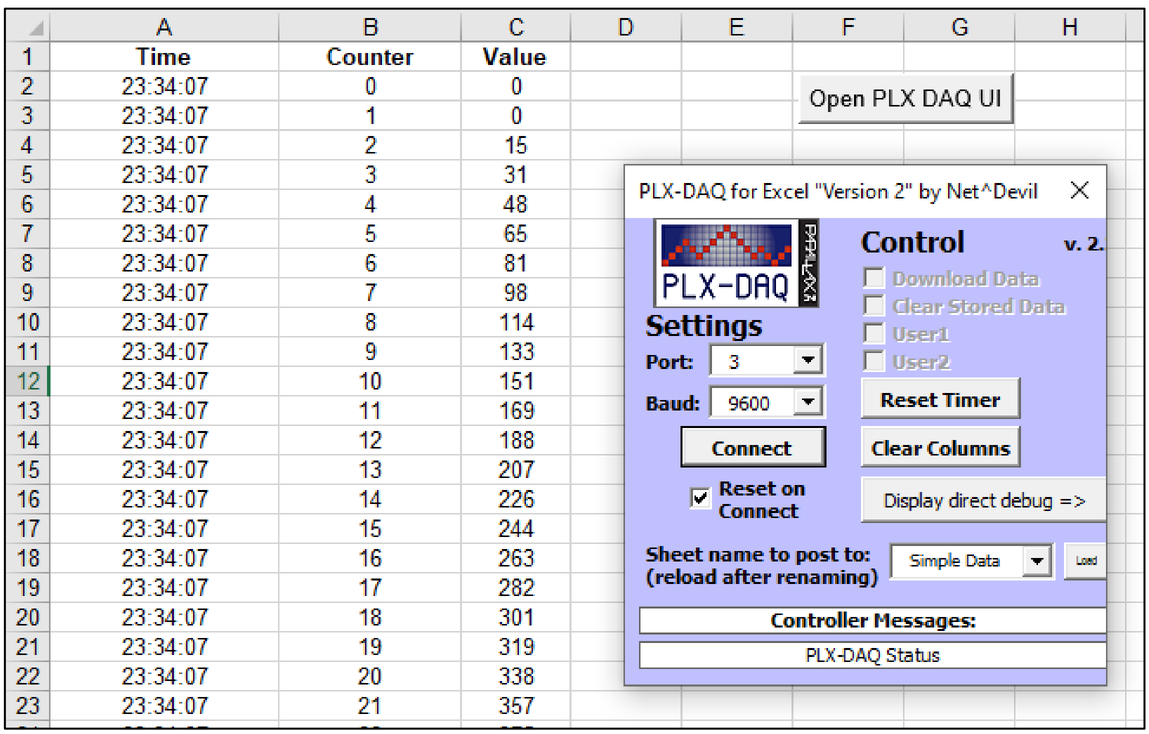


Figure 31: Ubidots Raw Humidity Data

4.4 SENDING DATA FROM ARDUINO TO EXCEL

The data acquired from the DHT22 sensor is displayed using the serial monitor. The serial monitor is useful for real time monitoring; however, it cannot be used to plot cohesive graphs. Therefore, the data needs to be extracted to Microsoft Excel to observe precise data parameter and to contract understandable graphs.

To send the data from Arduino to Excel, an external software is used. The Parallax Data Acquisition tool (PLX-DAQ) automatically extracts the data in the serial monitor to a Microsoft Excel file. Figure 32 shows the output of the software. The parameters of the Arduino's serial monitor are extracted as well as the time that it was extracted. Using this, exact calculations as well as graphs can be produced.



	A	B	C
1	Time	Counter	Value
2	23:34:07	0	0
3	23:34:07	1	0
4	23:34:07	2	15
5	23:34:07	3	31
6	23:34:07	4	48
7	23:34:07	5	65
8	23:34:07	6	81
9	23:34:07	7	98
10	23:34:07	8	114
11	23:34:07	9	133
12	23:34:07	10	151
13	23:34:07	11	169
14	23:34:07	12	188
15	23:34:07	13	207
16	23:34:07	14	226
17	23:34:07	15	244
18	23:34:07	16	263
19	23:34:07	17	282
20	23:34:07	18	301
21	23:34:07	19	319
22	23:34:07	20	338
23	23:34:07	21	357

Figure 32: PLX-DAQ Output

4.5 SENSOR NODE POWER CONSUMPTION

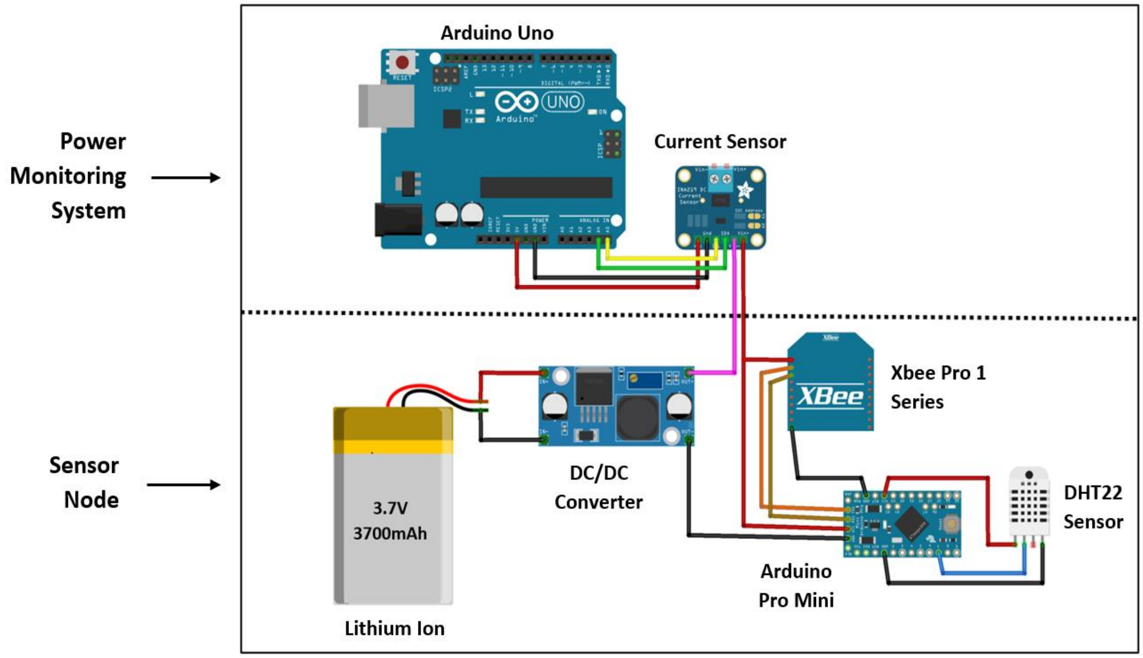


Figure 33: Sensor Node Power Monitoring

The power consumption of the sensor node is monitored in order to determine the sustainability of the system's power. Figure 33 shows the connection to track the power consumption of the system. A current sensor (INA219) is connected to an Arduino Uno, which acts as an external system to observe the current and voltage of the Arduino Pro Mini, DHT22 and Xbee Pro Series 1. The current sensor monitors the V^+ of the system.

The output of the current sensor is displayed on the serial port (9600 baud). The data is then extracted to a spreadsheet to determine the average power consumed by the sensor node. The sensor node is set to transmit data to the sink node (though the Xbee) every 1 seconds or so. Figure 34 shows a part of the spreadsheet.

1	Time	Started Time	Voltage	Current	Power	Changes in Time	Energy
2	6:18:31	0.03515625	3.3	73.5	242.55	0.03515625	0.008527148
3	6:18:31	0.10546880	3.3	73.5	242.55	0.07031255	0.017054309
4	6:18:31	0.20898440	3.3	73.3	241.89	0.10351560	0.025039388
5	6:18:31	0.31054690	3.3	73.1	241.23	0.10156250	0.024499922
6	6:18:31	0.41210940	3.3	73.2	241.56	0.10156250	0.024533438
7	6:18:31	0.51953130	3.3	76.9	253.77	0.10742190	0.027260456
8	6:18:31	0.62109380	3.3	77.1	254.43	0.10156250	0.025840547
9	6:18:31	0.72460940	3.3	73.5	242.55	0.10351560	0.025107709
10	6:18:31	0.82617190	3.3	73.6	242.88	0.10156250	0.0246675

Figure 34: Sensor Node Raw Data

The figure shows that the data extracted includes the voltage, current and power of the system. Furthermore, the time as well as the timer for each data instances is taken as well. Using the timer, each power instances' time period can be calculated as well. Using the changes in time in each data, as well as the power (in Watts); the energy (in Joules) can be calculated. The serial port is monitored for a total of 60.94 seconds. Figure 35 shows the total energy of the sensor node in the span of 60.94 seconds. Using this value, the average power can be calculated.

1	Time	Started Time	Voltage	Current	Power	Changes in Time	Energy
583	6:19:31	59.99805000	3.3	74.1	244.53	0.10157000	0.024836912
584	6:19:31	60.10156000	3.3	73.9	243.87	0.10351000	0.025242984
585	6:19:31	60.20313000	3.3	73.6	242.88	0.10157000	0.024669322
586	6:19:31	60.30469000	3.3	73.6	242.88	0.10156000	0.024666893
587	6:19:31	60.41211000	3.3	57.3	189.09	0.10742000	0.020312048
588	6:19:31	60.51367000	3.3	73.5	242.55	0.10156000	0.024633378
589	6:19:31	60.61719000	3.3	73.3	241.89	0.10352000	0.025040453
590	6:19:31	60.71875000	3.3	73.3	241.89	0.10156000	0.024566348
591	6:19:31	60.82031000	3.3	73.7	243.21	0.10156000	0.024700408
592	6:19:32	60.93555000	3.3	78.1	257.73	0.11524000	0.029700805
593	Total Energy						14.33716708

Figure 35: Sensor Node Total Energy Consumed

$$Total\ Energy = 14.34\ J$$

$$Total\ Time = 60.94\ seconds$$

$$Average\ Power = \frac{Total\ Energy}{Total\ Time}$$

$$= 235.31\ mW$$

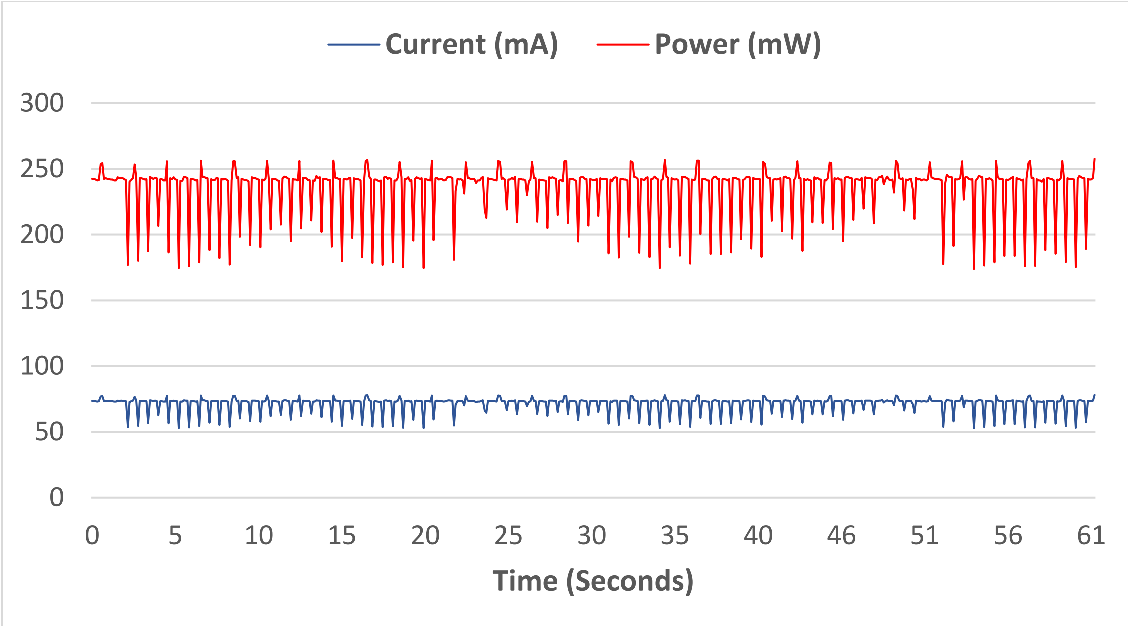


Figure 36: Sensor Node Power Consumption

Figure 36 shows the visualization of the sensor node power consumption. The figure shows that the power consumption is between 170mW to 260mW. The average power consumption being 235.31mW. To verify this value, the power consumption based on the components' data sheets is calculated.

Table 9: Sensor Node Calculated Power

	Operating Voltage	Current	Power
Arduino Pro Mini	3.3V	4mA	13.2mW
DHT22	3.3V	1.5mA	4.95mW
Xbee Pro Series 1	3.3V	70mA	231mW
Total Power Consumption			249.15mW

Table 9 shows the power consumption that is calculated based on the voltage of the data sheet. The calculated power of the sensor node is 249.15mW while the average actual power of the sensor node is 235.31mW. The overall values are very similar.

4.6 SENSOR NODE POWER CONSUMPTION WITH SLEEP MODE

The average power consumption of the sensor node is 235.31mW. This where the Arduino Pro Mini is always active and constantly mesuring temperature and humidity values while transmitting the data to the sink node every 1 seconds. Based on Table 9, it can be seen that the device with the highest power consumption is the Xbee Pro Series 1 (231mW). To decrease the power consumption of the overall system, the Xbee Pro Series 1 is to be put into sleep mode periodically. The Arduino Pro Mini will initialize by sensing data using the DHT22, sending the said data to the sink node via the Xbee Pro Series 1, and then force the Xbee Pro Series 1 to sleep for 5 seconds. The cycle will then be repeated indefinately. Figure 37 shows the new data that is collected where the sleep mode is implemented. The data is extracted over the course of 61.39 seconds.

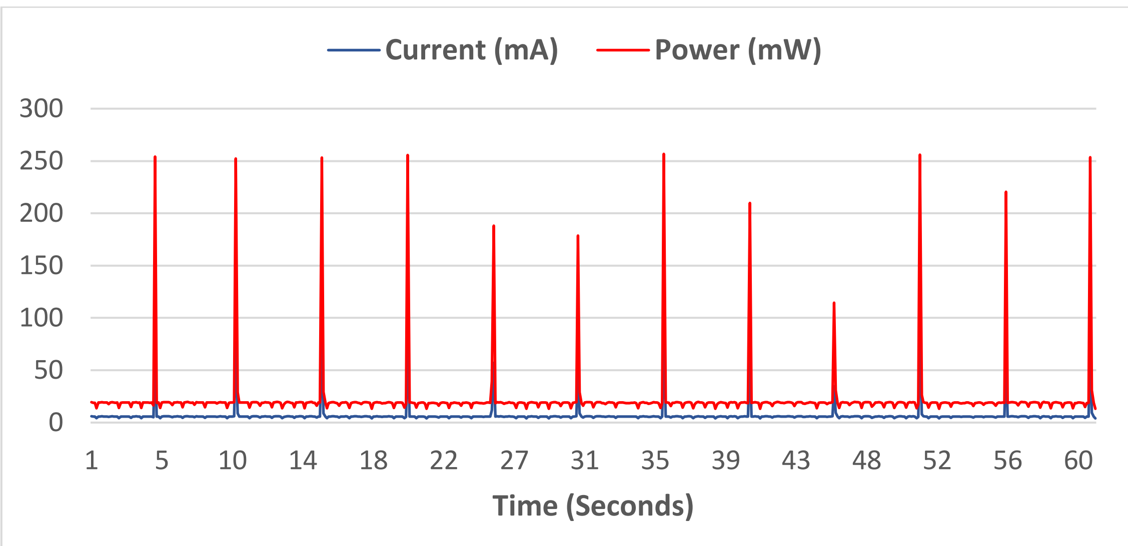


Figure 37: New Sensor Node Power Consumption

As observed in Figure 37, the power consumption of the sensor node is much lower when the sleep mode is implemented. When the Xbee module is put into sleep mode, the average power consumption of the sensor node is 19mW. The peak power consumption of the sensor node when the Xbee module is active is 253mW. Based on this, the sleep time can be configured to ensure the energy sustainability of the sensor node.

1	Time	Started Time	Voltage	Current	Power	Changes in Time	Energy
590	10:43:09	61	3.3	5.6	18.48	0.10157	0.0018770136
591	10:43:09	61	3.3	4.5	14.85	0.10547	0.0015662295
592	10:43:09	61	3.3	5.6	18.48	0.10546	0.0019489008
593	10:43:09	61	3.3	5.7	18.81	0.10157	0.0019105317
594	10:43:09	61	3.3	76.8	253.44	0.10156	0.0257393664
595	10:43:10	61	3.3	9.3	30.69	0.10156	0.0031168764
596	10:43:10	61	3.3	5.7	18.81	0.10547	0.0019838907
597	10:43:10	61	3.3	4	13.2	0.10547	0.0013922040
598	Total Energy						1.3971751991

Figure 38: New Sensor Node Total Energy Consumed

Figure 38 shows the total energy of the sensor node (with sleep mode) over the course of 61.4 seconds. Using this data, the new average power for the sensor node can be calculated.

$$Total\ Energy \quad = \quad 1.397J$$

$$Total\ Time \quad = \quad 61.39\ seconds$$

$$Average\ Power \quad = \quad \frac{Total\ Energy}{Total\ Time}$$

$$= \quad 22.76\ mW$$

With only 5 seconds sleep between each cycle, the sensor node's power consumption dropped from 235.31mW to 22.76mW. Using the new average power, the energy needed for the sensor node to function in a day can be calculated.

$$22.76mW = \quad 22.76mJ/s$$

$$Sensor\ Node\ Energy\ Consumption\ per\ Day$$

$$= 22.76\ mJ\ x\ 60\ seconds\ x\ 60\ minutes\ x\ 24\ hours$$

$$= 1966.46\ J$$

4.7 LIGHT ENERGY HARVESTING

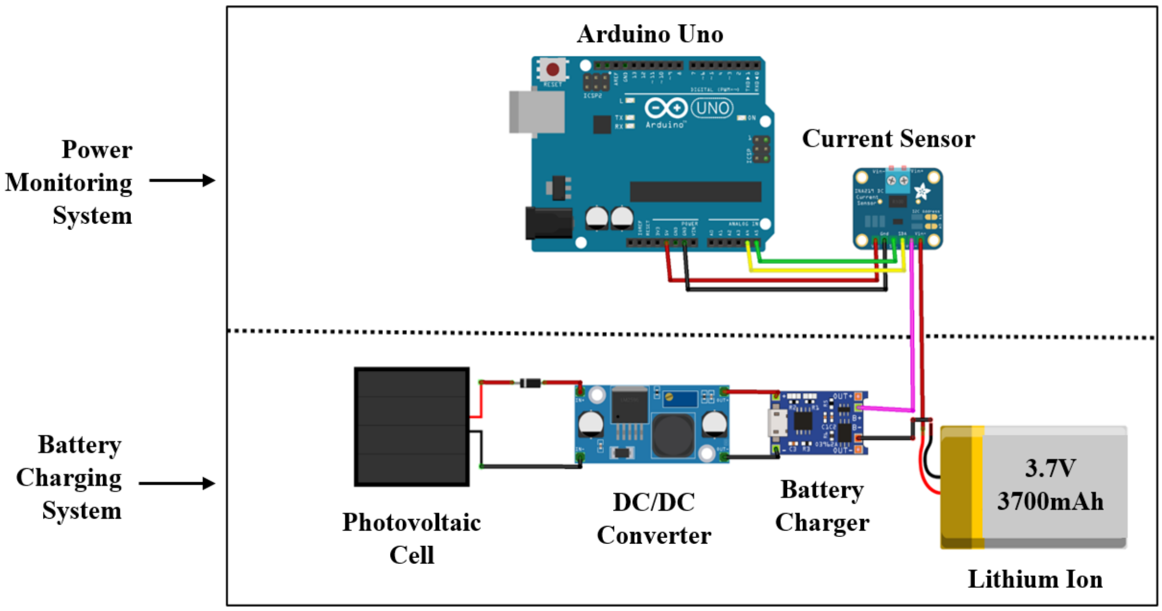


Figure 39: Light Energy Harvesting Monitoring

The power generation can be monitored using the configuration of Figure 39. The current sensor is connected to an Arduino Uno, which acts as an external power monitoring system. The current sensor tracks the V^+ of the Li-on battery. Therefore, the battery charging system can be monitored to determine the total usable energy that was extracted from the photovoltaic cell and stored in the Lithium Ion battery.

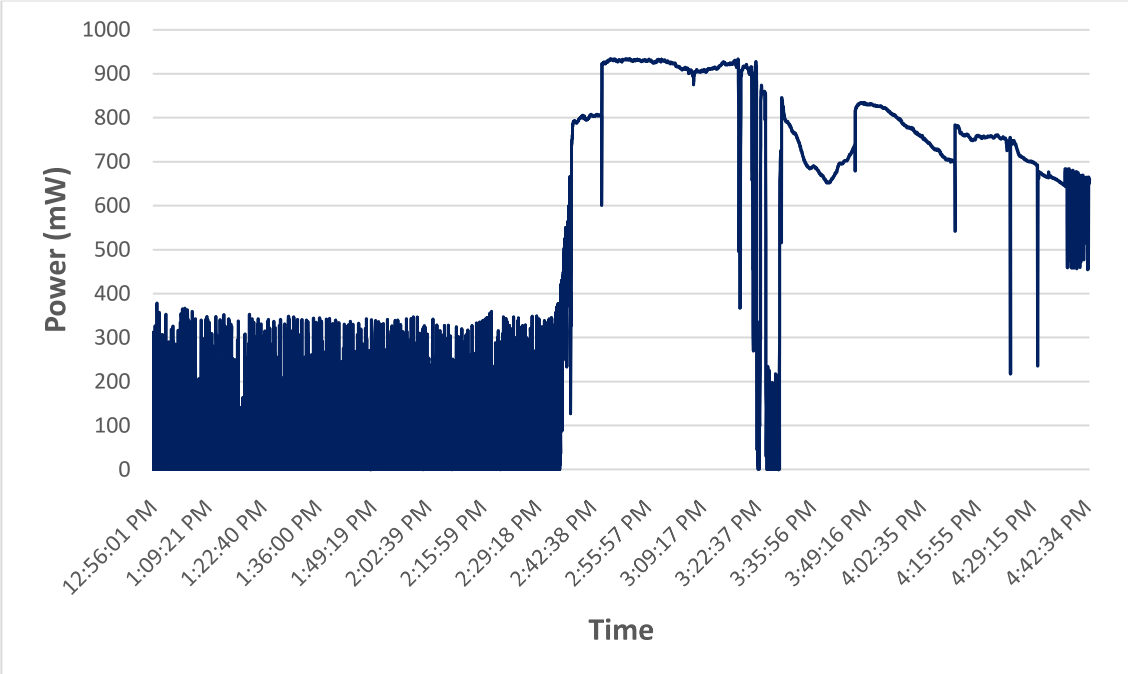


Figure 40: Light Energy Harvesting Output

Figure 40 shows the generated power from the photovoltaic. The data is taken on the 5th March 2022, at Universiti Teknologi PETRONAS, Seri Iskandar; at 12:56PM – 4:43PM; with a 2 seconds interval between each data instances. Figure 41 shows the PV cell being exposed to indirect sunlight, which is from time 12:56PM – 2:30PM and direct sunlight, i.e., from 2:30PM – 4:43PM.

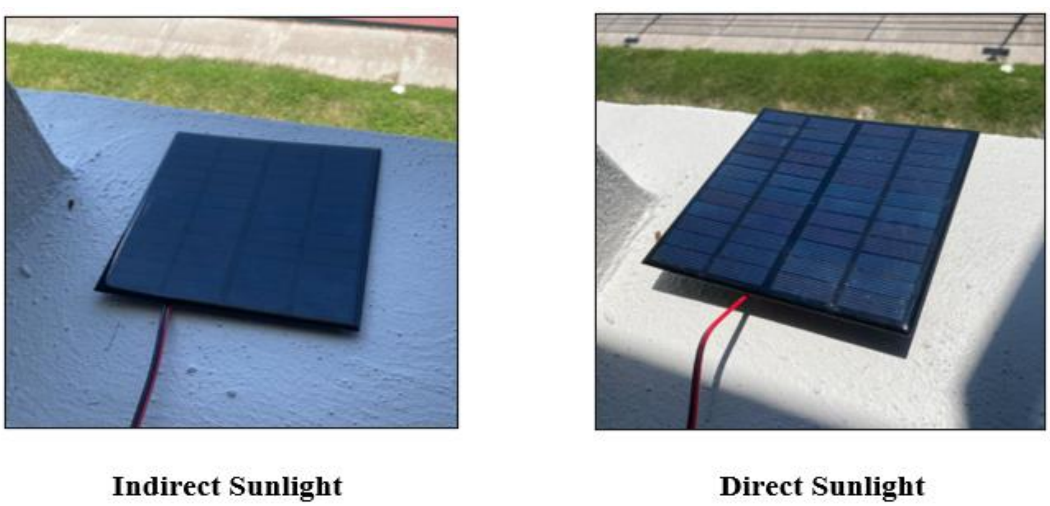


Figure 41: PV Cell Exposure

1	Date	Timer	Voltage	Current	Power	Changes in Time	Energy
6811	4:42:52 PM	13611	3.72	177.9	661.79	2.00	1.32358
6812	4:42:54 PM	13613	3.72	122.6	456.07	2.00	0.91214
6813	4:42:56 PM	13615	3.72	178.8	665.14	1.99	1.32363
6814	4:42:58 PM	13617	3.72	177.4	659.93	2.01	1.32646
6815	4:43:00 PM	13619	3.72	174.7	649.88	2.00	1.29976
6816	4:43:02 PM	13621	3.72	178.3	663.28	2.00	1.32656
6817	4:43:04 PM	13623	3.72	174.7	649.88	2.00	1.29976
6818	4:43:06 PM	13625	3.72	174.8	650.26	1.99	1.29402
6819	4:43:09 PM	13628	3.72	174.8	650.26	2.64	1.71669
6820	4:43:10 PM	13629	3.72	177.6	660.67	1.36	0.89851
6821	Total Energy						6327.78825

Figure 42: PV Cell Total Energy Generated

Figure 42 shows the total energy generated. The data is taken from for a total of 3 hours and 47 minutes. As seen in Figure 42, the total energy generated is 6327.79J.

$$Sensor\ Node\ Energy\ Consumption\ per\ Day\ = 1966.46\,J$$

Therefore, the energy generated from the PV cell can last for:

$$\frac{6327.79J}{1966.46J} = 3.22\ days$$

The data shows that with only 3 hours and 47 minutes of charging time, the energy is enough to sustain the sensor node's operation for more than 3 days. This is enough to ensure that the sensor node can self sustain its energy consumption. It can also be seen that the PV cell generates energy not only when exposed to direct sunlight, but indirect sunlight as well.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

4.1 CONCLUSION

In conclusion, the light energy harvester for sustainable internet of things devices is a project that solves the problem of disposable batteries in Wireless Sensor Nodes. The sensor node stores more energy than its consuming. The result shows that the PV cells are able to generate energy from direct and indirect sunlight. Furthermore, the amount of energy generated in less that 4 hours of sunlight is enough to sustain the sensor node's operation for more than 3 days. This is mostly due to putting the wireless communication module (which has the highest power consumption in the sensor node) to sleep for 5 seconds every data transmission cycle. A self-sustaining sensor node can fix the problem of Wireless Sensor Nodes that constantly need regular maintenance, which can be expensive and hazardous depending on the location. Furthermore, this will aid in enabling the realization of the Internet of Things concept, which aims integrate the parameters of the physical world into the cyber space.

4.2 RECOMMENDATION

For future improvements, the prototype can incorporate indoor based PV cells to enable the sensor node to operate in indoor conditions as well. Furthermore, the prototype can be improved by using even lower power consuming devices.

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