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A Novel IoT Photovoltaic-Powered Water Irrigation Control and Monitoring System for Sustainable City Farming

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Abstract: In Singapore's limited land space, hydroponics, a soil-free method of that uses irrigation gained popularity for urban farming. Vertical farming can be made more sustainable by integrating Internet-of-Things (IoT) and solar photovoltaic (PV) as an intelligent system. This study aims to conduct a feasibility study on using PV cells to reduce energy consumption in IoT-enabled irrigation control and monitoring systems. In the experiment, an intelligent water irrigation system was designed for data collection including energy harvested from PV, climate conditions, and water quality. It was observed that a 45 Watt peak (Wp) solar PV was able to produce up to 460-watt hours of stored electricity in a day which can power a standalone hydroponic system that consists of a 19 W water pump and light emitting diode (LED) grow lights rated at 14 W/m. The climate monitoring system matched meteorological data from online sources proving to be applicable in the prototype. Water conditions such as water temperature and electrical conductivity (EC) also correlate to readings taken from traditional handheld water quality testers. Based on the fabricated prototype, integration is deemed to be feasible using power harvested from the sun.

Keywords: IoT; smart hydroponics; solar photovoltaic

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1. Introduction

1.1. Background

Like all living things, plants require water to thrive and grow. Water is essential for plants and requires proper and balanced water flow for optimal plant growth. Too much water can cause root rot and reduce oxygen levels in plant roots, while too little water can cause wilting, stunted growth and even plant death [1]. For millenniums, humankind has been making use of water irrigation for agricultural systems to increase crop production [2]. Irrigation is a crucial component of modern agricultural practices, playing a pivotal role in shaping the productivity and sustainability of farming systems worldwide [3–5]. Types of irrigation in agriculture include drip irrigation, sprinkler irrigation, surface irrigation, subsurface irrigation, micro-sprinkler irrigation, lateral move irrigation, and center pivot irrigation [6]. IoT (Internet of Things) technology has revolutionized irrigation by enabling the integration of sensors, automation, and data analytics, allowing farmers to monitor and control irrigation systems remotely for precise and efficient water management [7,8]. Due to the scarcity of land and the need for sustainable food production, the soil-free method that relies on irrigation to grow plants known as hydroponics has become quite popular in Singapore's urban farming community [9]. Urban agricultural methods in Singapore have recently undergone significant innovation thanks to IoT and hydroponics. Sensors, automation, and data analytics are used in IoT-enabled hydroponics systems to increase resource management, crop growth, and overall effectiveness [10,11]. Sensors are used in IoT-enabled hydroponics systems to keep track of elements including temperature, humidity, pH levels, fertilizer levels, and water quality. These sensors gather data, transfer

it to a centralized system, and then analyze it to produce insightful information. Through mobile or online applications, farmers may remotely access these data, enabling them to make educated decisions and change the growing environment as necessary [6,12]. The integration of hydroponics and IoT greatly benefits Singapore. It makes it possible to manage environmental factors precisely and dynamically, guaranteeing the best possible circumstances for plant development. Based on real-time data, automated systems may modify variables like water flow, fertilizer dosing, and lighting to optimize resource use and increase crop yields. IoT technology also makes it possible to identify abnormalities or departures from ideal circumstances early on, allowing for prompt crop loss prevention measures [13]. Singapore wants to produce at least 30% of its food domestically by 2030 [14]. This means that local farms have started adapting the above-mentioned urban farming techniques.

As seen in Figure 1, Singapore's urban farms consist of (A) conventional soil-based farming in a semi-enclosed greenhouse, (B) vertical farming with natural lighting in a semi-enclosed greenhouse and (C) indoor farming with artificial lighting in a controlled environment. These systems share one thing in common, which is to tackle the problem of land shortage. However, farms like (B) and (C) tend to use technologies to increase productivity, which comes with the expense of having to implement technologies that are costly in terms of energy consumption. This brings up the question of what solutions are there that will help reduce such costs.

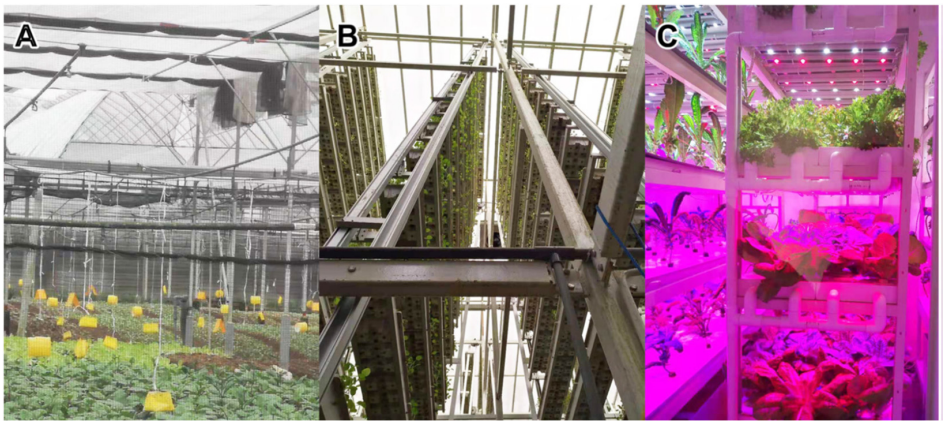

Figure 1. Types of urban farms in Singapore [15].

Due to Singapore's limited amount of available land and urban environment, farming has experienced considerable changes throughout time. Singapore has achieved tremendous advancements in sustainable and creative agricultural methods despite its small size and urbanization. Singapore is moving toward hydroponics and vertical farming to combat its lack of available land. According to [15], to make the most of available space and grow plants indoors with artificial lighting and regulated surroundings, vertical farms use multi-tier systems, frequently in tall buildings. Growing in popularity is hydroponics, which is a method of growing plants without using soil in an aqueous solution that is rich in nutrients. These techniques boost agricultural yields, use less water, and utilize less land [15]. Singapore has placed importance on local food production in recent years. By 2030, programs like 30 by 30 want to locally satisfy 30% of the nation's nutritional needs [14]. Agricultural technology parks, like the Sungei Kadut Ecodistrict, support innovation, research, and development in the food and agricultural industries as well as government, corporate, and science collaboration [16].

Solar photovoltaic (PV) technology involves harnessing the suns' energy through generating electric current via photovoltaic cells present in solar panels or modules constructed from semiconductor materials like silicon. Photons from sunlight strike these cells, thereby freeing electrons off the different atoms present, resulting in an electrical flow toward an external circuit capable of utilizing it to meet various needs including running appliances at

home or businesses and supporting farming-related operations locally or remotely without emitting any harmful emissions into earths' atmosphere, hence conserving the environment [17]. The sun does not stay in a single spot; it rises from the east and sets in the west. This means that if the solar PV panels are stationary and static, they will not be exposed to the optimal direct sun rays. A solution would be to implement a solar tracking system. Such systems will ensure that the panels are always angled toward the sun, harvesting the most energy possible. In research by [18], it is noted that having a solar-tracking system installed onto solar PV panels significantly increases the average power output of PV arrays (up to 22.58%). An article by [19] explains the effects of heat on solar PV panels. It was observed that temperature affects the open-circuit voltage of photovoltaic modules. It was noted that higher or lower temperatures affect the efficiency of the panels. One of the takeaways was that the optimal temperature for solar panels was 20 to 25 °C. Temperatures exceeding or below this range result in voltage drop. In 2014, researchers at Michigan State University developed a type of PV cell that was transparent. They named it the transparent luminescent solar concentrator. From a web article on the Michigan State University's website, it was quoted by Richard Lunt of MSU's College of Engineering that the "solar conversion efficiency [is] close to 1 percent", but they aim to reach efficiencies beyond 5 percent when fully optimized [20]. Four years into development, ref. [21] reviewed the technology of transparent solar photovoltaics and noted that this number for efficiency had increased approximately 7.8% to 8.4%.

The story shared by [22] mentioned how the research team, led by Professor Jacek Jasieniak from Monash University, had a breakthrough. The team created transparent perovskite class cells with an efficiency of 17% at 10% transparency, which is close to the 15 to 20% efficiency of conventional rooftop solar systems. These cells are seen in Figure 2. In recent years, this technology has begun to become readily available and can be found being sold commercially with options of varying transparency levels. Researchers such as [23] are beginning to explore how these can be used in agriculture and if the partial obstruction of sunlight affects the growth of leafy vegetables. As observed in his study, the impact is negligible. The implementation of see-through solar technology in buildings and other structures offers the potential to craft greener and power-saving spaces. This innovation enables the production of clean energy while maintaining the attractive appearance and usability of transparent surfaces, presenting opportunities in multiple fields such as automotive, architecture, electronics, and more. Crops can be grown year-round with the help of soilless farming techniques like hydroponics and aquaponics, which also effectively manage resources and regulate the environment. However, they have different practices for caring for their plants and removing waste.

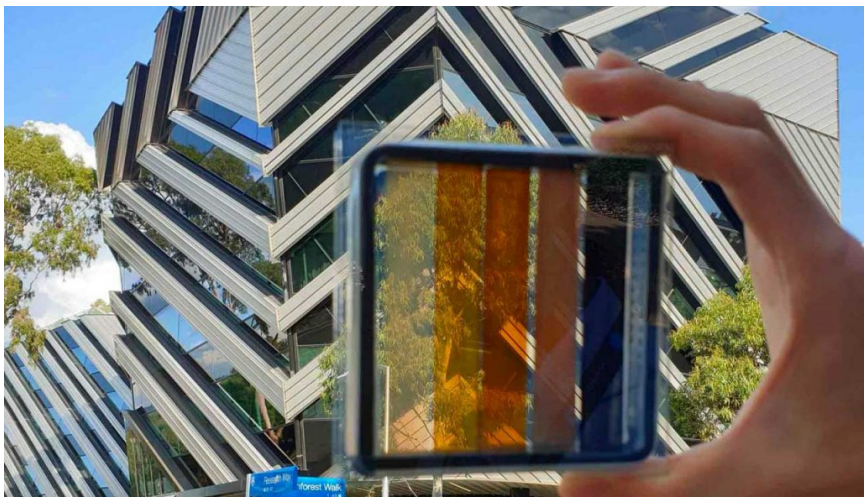

Figure 2. Solar PV with varying levels of transparency [22].

1.2. Research Statement

Vertical farming is an efficient way to achieve sustainable urban agriculture, especially for smart cities like Singapore. The Singapore Food Agency (SFA) supports numerous programs to help local farmers increase production using SMART technology. Singapore wants to produce at least 30% of its food domestically by 2030 [14]. The purpose of this project is to create a solar-powered irrigation control and monitoring system specifically for urban agriculture. The system will incorporate cutting-edge technologies to optimize resource utilization, increase agricultural yields and advance Singapore's goal of a resilient and self-sufficient food ecosystem.

1.3. Project Aim and Objectives

This paper aims to conduct a feasibility study on using photovoltaic (PV) cells to reduce energy consumption in IoT-enabled irrigation control and monitoring systems while maximizing crop production.

Objectives:

- Identify the required design specifications and features for a smart solar-powered water irrigation prototype.
- Design the specifications and features of the smart solar-powered water irrigation prototype.
- Design the circuitry for the smart solar-powered water irrigation system.
- Fabricate a prototype based on the design specifications.
- Evaluate the performance of the fabricated prototype.

2. Materials and Methods

The processes taken to address Project Aim and Objectives are represented in the below Figure 3. This facilitates the methodology used to gain results, which will be analyzed for the recommendation and conclusion of the feasibility study. The process starts with identifying the required design specifications and features for the prototype with the literature review in mind. This is followed by the design stage, which leads to the creation of Bill of Materials (BOM). The BOM helps keep track of components and raw materials that are needed to create the prototype. After the components and materials are acquired, the construction of the prototype can then commence, which is followed by testing and troubleshooting before employing it for experimentation for the feasibility study. This is the final step where the performance of the fabricated prototype is evaluated.

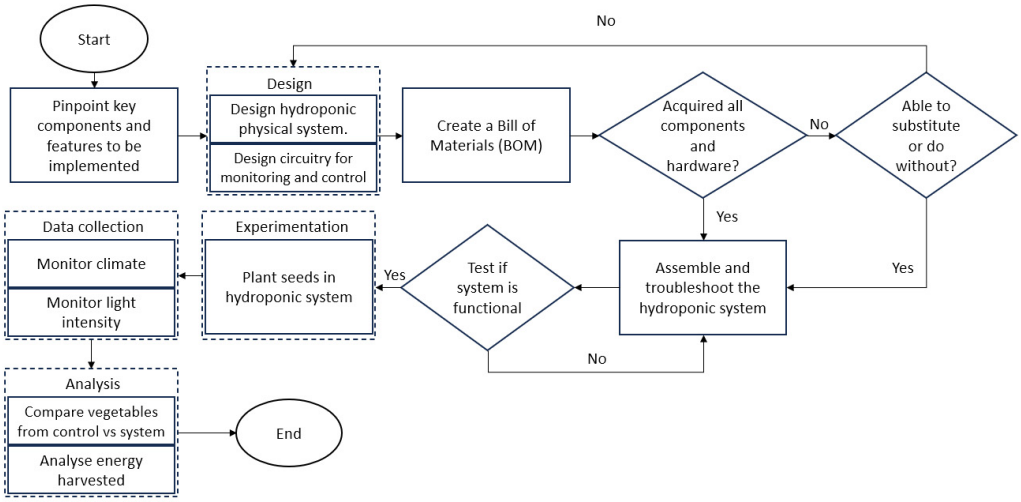

Figure 3. Flowchart of processes for the feasibility study.

2.1. Design Concept

The prototype is made up of the main structure and the circuitry. The main structure consists of the frame, water tank, grow tubes and plumbing. The frame, which is made of square mild steel hollow tubing (1 inch) is either welded or bolted at the connections. The water tank used is an off-the-shelf plastic box that has a capacity of 65 L. Grow tubes that are used to transport water and hold the plants are made using 3-inch diameter PVC pipes and pipe fitting caps. Plumbing consists of 10 mm flexible PVC hose and connectors.

Below in Figure 4 is a Computer-Aided Design (CAD) drawing using Google Sketchup that labels the materials and components that make up the main structure.

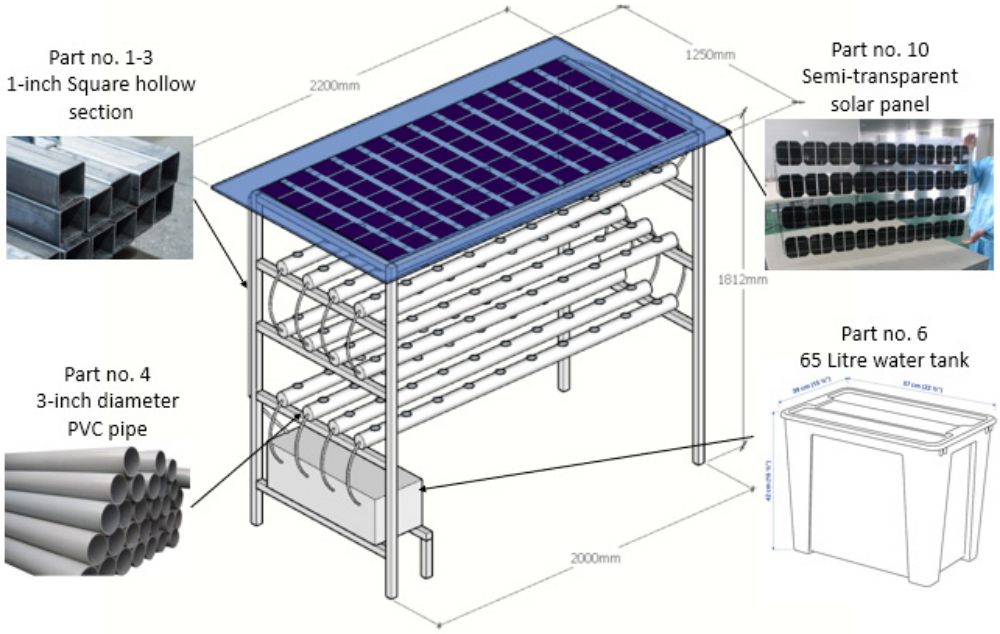

Figure 4. Diagram of components that make up the main structure.

Below in Figure 5 are components that make up the circuitry system. The circuitry system is categorized into two parts: seen on the left is the monitoring system, and on the right is the power and control system. The monitoring and control system are linked by the micro-controller, which is either an Arduino UNO or Raspberry PI. The monitoring system is made up of sensors for data collection and notifying if any conditions are off. The temperature and humidity sensor tracks climate; the TDS water quality sensor is used to monitor the nutrient levels in the water.

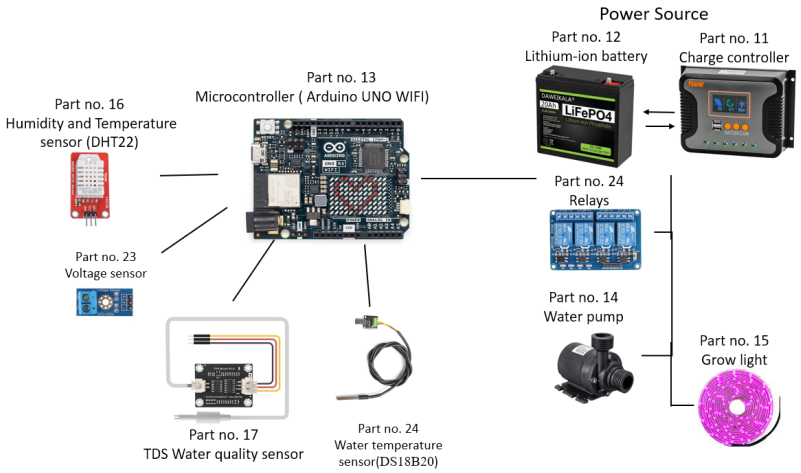

Figure 5. Diagram of components that make up the circuitry system.

The second group of components that make up the circuitry make up the power and control system. The solar panel is prioritized as the main source of electrical energy. A Pulse Width Modulation (PWM) charge controller is used to control and regulate the input and output of electrical energy. A 12-volt $LiFePO_4$ battery is used for electrical energy storage. Fans help create air circulation and regulate the temperatures of the plants. The water pump circulates water to the plants, and grow lights give additional light that will be beneficial to plant growth and production, as discussed in the literature review above. Figure 5 shows how the components will be connected to create the monitoring and control system.

Table 1 contains the Bill of Materials for the components. It gives further details of the components and helps keep track of the components and the quantities needed to create the prototype.

Table 1. Bill of Materials for prototype.

Part No.	Part Name	Part Description	Dimension	Qty
1	Main frame leg	1-inch square hollow section	1800 (mm)	4
2	Length-wise frame	1-inch square hollow section	1920 (mm)	4
3	Width-wise frame	1-inch square hollow section	925 (mm)	10
4	Grow tubes	3-inch diameter PVC pipe	2000 (mm)	12
5	Grow tube cap/fitting	3-inch diameter PVC pipe end cap	-	24
6	Water tank	IKEA SAMLA Box 65 L	-	1
7	Growing medium	Hydroponics sponge	-	As required
8	Water hose	10 mm flexible PVC hose	10 M	1
9	Water hose “T” joint	10 mm hose “T” connector	-	3
10	Semi-transparent solar panel	Solar panel from Kamtex	-	1
11	Charge controller	Minimum 15Amp	-	1
12	Battery	12 v $LiFePO_4$ Battery	-	1
13	Micro-controller	Arduino UNO WIFI	-	1
14	Water pump	19 W 800 L/min	10 mm output	1
15	Grow lights	14 W/M	2 m	6
16	Temperature and humidity sensor	DHT22	-	1
17	Water condition sensor	TDS water quality sensor	-	1
18	LCD display	12C LCD display for displaying status	-	1
19	Dupont line	Jumper wires linking sensors to board	-	As required
20	Power wires	Power wires connecting relays to pumps, etc.	-	As required
21	12 V Relay	4-channel relay for microcontroller 12 V	-	1
22	Sensor shield	More pins for several sensors	-	1
23	Voltage sensor	Sensor for reading voltage	-	1
24	Water temperature sensor	DS18B20 water temperature sensor	-	1

2.2. Pre-Result

At the time of acquiring the solar panel, it was temporarily set on the floor. This can be seen in Figure 6 below. In this position, it was tested for voltage and amperage, which were used to calculate wattage for a rough gauge of how much power it would generate, which helped determine the specifications needed for components such as the battery.

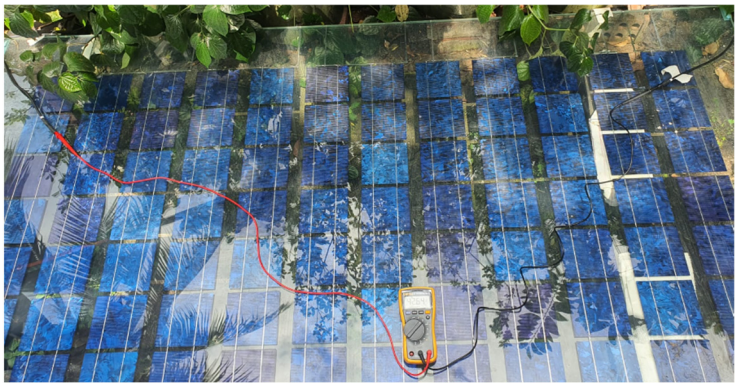

Figure 6. Acquired solar panel on the floor being tested for voltage and amperage.

The data collected were for 9 h of sunlight across 5 days. These data are used as a rough gauge to determine if the power harvested will be sufficient to power the system off-grid when using the right battery and charge controller. These data are plotted in Table 2 below. It was noted that full sun was not reaching the solar panel, as plants were in the way of the sunlight, and the location where the panel is situated only receives half a day of sun. When the path of sunlight is cleared, there was a significant increase in amperage, as seen in data from 5 August 2023 1200 H.

Table 2. Pre-data collection to determine solar power for developing system specifications.

Day	Time	Weather Conditions	Voltage (V)	Ampere (A)	Wattage (W)	Watt Hour Harvested
1 August 2023	0800 H	Overcast	33.93	0.33	11.13	14.28 W × 9 h = 128.52 Wh
	1200 H	Overcast	42.64	0.41	17.61	
	1700 H	Overcast	37.42	0.38	14.11	
2 August 2023	0800 H	Clear skies	42.40	0.40	17.09	17.97 × 9 h = 161.73 Wh
	1200 H	Partly cloudy	43.52	0.49	21.15	
	1700 H	Partly cloudy	41.33	0.38	15.66	
3 August 2023	0800 H	Rain	33.93	0.04	1.36	4.19 × 9 h = 37 Wh
	1200 H	Rain	40.80	0.17	7.02	
	1700 H	Rain	35.02	0.12	4.20	
4 August 2023	0800 H	Clear skies	43.32	0.39	16.98	14.33 × 9 h = 128.97 Wh
	1200 H	Overcast	44.20	0.48	21.22	
	1700 H	Overcast	39.84	0.12	4.78	
5 August 2023	0800 H	Clear skies	42.33	0.45	19.13	27.33 × 9 h = 245.79 Wh
	1200 H	Clear skies	43.60	1.05	45.78	
	1700 H	Clear skies	42.70	0.40	17.08	

2.3. Fabrication

The main frame which the solar panel sits on is made from a 1-inch mild steel hollow section. Dimensions were based on the 3D CAD model seen in Figure 4. The hollow

sections which came in 6 m lengths were first cut to the required lengths, as shown in Figure 7 below.



Figure 7. Fabrication process of main frame.

The hollow sections were then squared up and welded together using stick welding. During welding, an angle grinder allowed the smoothening and clean-up of messy welds as well as removal of flux build-up to expose imperfect welds that needed re-welding.

As the material used was mild steel, rust was prone to form. This can be seen in Figure 8. As such, the frame was sanded and then treated with several layers of metal paint, which prevents the formation of rust and protects the metal from the elements.



Figure 8. Welding process and paint protection.

A major challenge during fabrication of the prototype is the process of mounting the transparent solar panel on top of the main frame. The major concern was that the 12 mm thick glass solar panel weighed approximately 100 kg, and a safe method of lifting had to be employed. To visualize the lifting method, a rough 3D model was sketched before the hoisting system was built. A friend that offered help was shown the animated 3D sketch, which allowed him to understand how the lifting would work.

Figure 9 shows a modified scissor jack that sat atop the hoisting rig, which allowed the heavy glass panel to be lifted easily and safely bit by bit until the main frame could be placed under it. The transparent solar panel was then lowered and attached to the main frame with heavy duty foam tape adhesive to prevent any slipping of the glass. This can be seen in Figure 10.



Figure 9. Hoisting from digital to actual.



Figure 10. Lowering the transparent panel onto the mainframe.

As mentioned above, the deep flow technique (DFT) method of irrigation yields similar results to the nutrient flow technique (NFT) while using less power. Thus, the irrigation system in the prototype will have to be able to hold water when the pumps are not running.

Figure 11 shows the end caps of the PVC pipes used, as the tubes that hold the vegetables and water are drilled out to have a drain plug as well as brass fittings for the inlet and outlets.



Figure 11. Fabrication of grow tubes and irrigation fittings.

Figure 12 shows the water inlet and 3D printed mounting. The grow tubes are seated atop clips that were 3D printed to prevent rolling and allowed the adjustment and fine tuning of the heights of the tubes. This proved to be effective in adjusting the individual hydraulic heads of the inlets, which in turn allowed the control of flow into each of the 4 separate tubes. With this, the 4 tubes were set up to have even flow, and all 4 filled up approximately at the same time.



Figure 12. Water inlet and 3D-printed mounting.

2.4. Testing and Troubleshooting

With the irrigation system functional, a leak test was performed. It was observed that the end caps of the PVC pipes do not need glue to be watertight, as there is barely any water pressure being exerted onto them. On the other hand, few of the brass fittings had minor leaks at the threads; a simple application of Teflon tape fixed the leaks. Figure 13 shows the leak test being carried out.



Figure 13. Leak test.

The initial outlet configuration of the irrigation system that leads back to the water tank was made to be the same as the inlet. As the pump ran continuously, a problem arose. Water would not be exiting the outlet, resulting in an overflow out of the holes where the plants are meant to be seated. Initially, this was thought to be friction caused in the tubes resulting in low output flow. The output irrigation configuration was then changed from configuration A to configuration B, as shown in Figure 14, which reduced overflowing. However, from time to time, it would still overflow.



Figure 14. Different configurations of outlet.

Further research online revealed that many engineers face problems due to the phenomenon known as air lock/vapor lock [24].

When gas becomes trapped inside pipes and tubes, it causes a constriction known as air lock/vapor lock and stops flow. This can be seen in Figure 15. It is more prone to happen in small diameter pipes and tubes as well as irrigation systems used on farms. To address this issue, the high spots in the output tubes were reduced by linking them straight down to the water tank. This configuration seen in Figure 16 eliminated the issue of air lock.

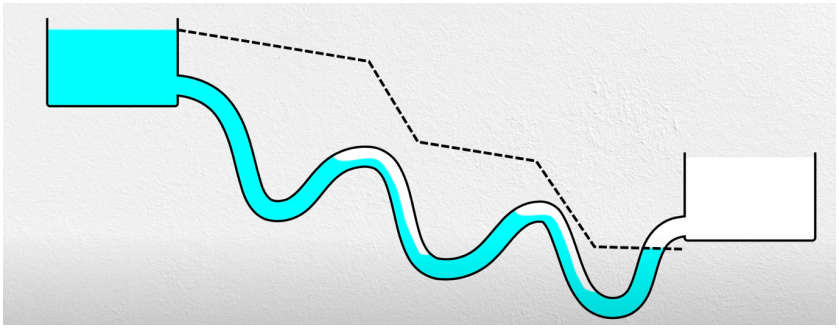

Figure 15. Diagram showing air lock stopping flow [24].



Figure 16. Final configuration of outlet.

Figure 17 shows the charge controller with the solar wattage and battery voltage. For an initial test, the solar panel, charge controller, and battery were connected. On a cloudy day, the pump was able to run constantly while the battery was being charged at the same time.



Figure 17. Charge controller showing solar wattage and battery voltage.

As the sensors and microcontroller are made for prototyping and hobbyists, it was observed that the sensors are not entirely accurate. Therefore, they had to be calibrated.

An initial comparison of readings from a TDS/EC reader and water PH reader were matched with the readings of the Arduino Water quality sensor. It was noted that there was a difference of approximately 20%. Further research on how the water conductivity function revealed that the temperature of the water affects readings, and thus, temperature compensation was needed for accurate readings [25]. To solve this issue, a water temperature sensor probe (DS18B20) was added to the system. This provided accurate water temperature readings that were used for temperature compensation in the code. After temperature compensation was added, the water quality readings were calibrated and gave the same readings from the TDS/EC reader and water PH reader, as seen in Figure 18.

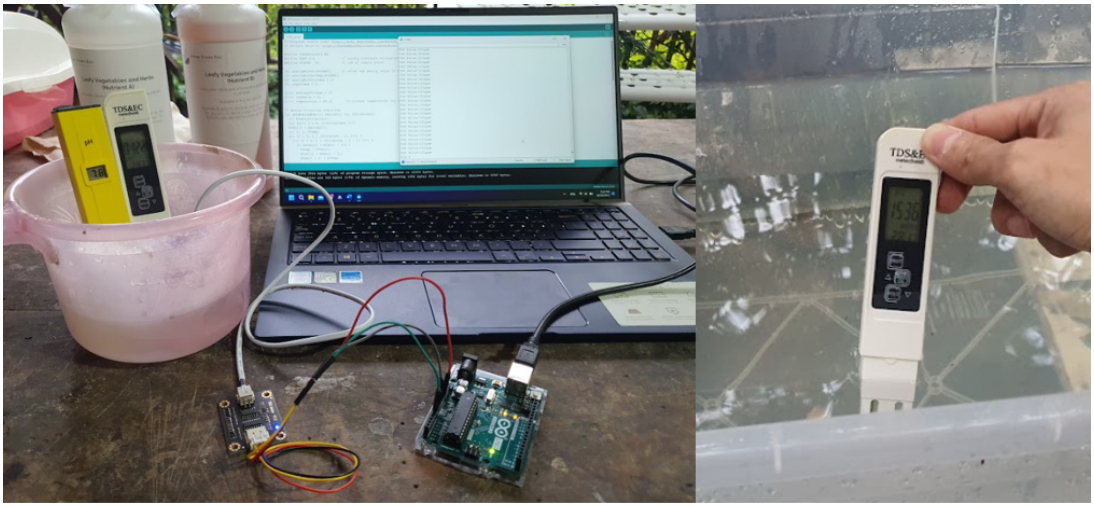

Figure 18. Calibrating water quality sensor.

As Arduino is an open-source electronic prototyping platform, codes for individual components were readily available online. However, an understanding of simple programming was needed to read and learn how each code works. This was crucial when it came to integrating several codes together to form the Smart IOT system. A screen capture of the program used is shown below in Figure 19.

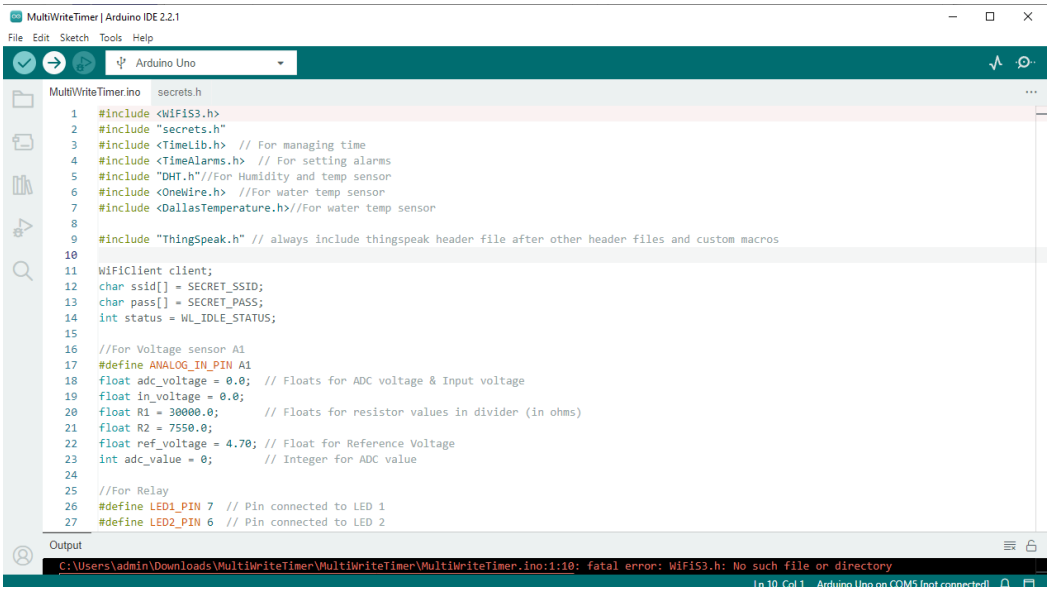

Figure 19. Arduino IDE.

The screen capture above shows part of the working code for the system used in the prototype. As there were several controls and sensors used, there were many iterations and rounds of debugging. In addition, this code allowed the board to be connected to the internet for data transfer and collection. The data collected were sent to ThingSpeak, as shown below in Figure 20.

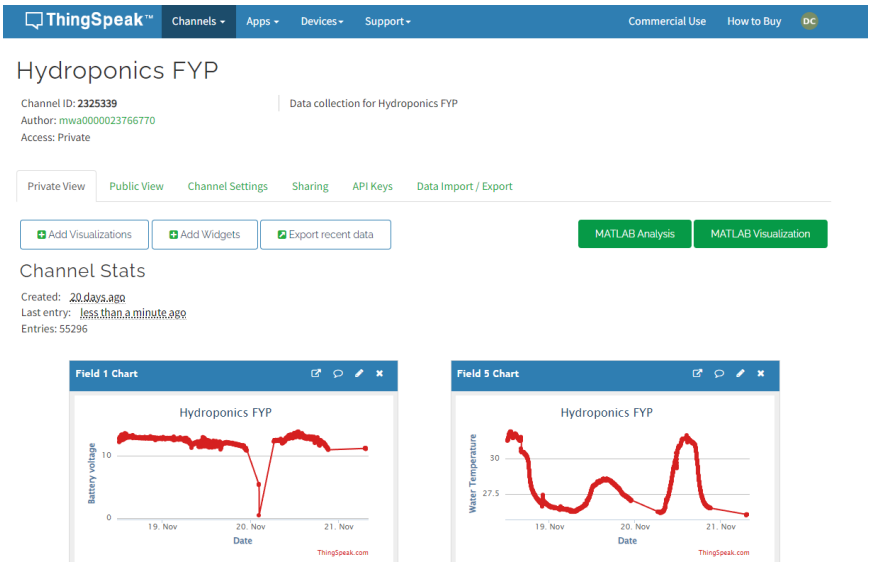

Figure 20. Screen capture of ThingSpeak.

ThingSpeak is an open IOT platform that allows sensor data from the Arduino microcontroller to be collected and stored through the internet. As seen above, data which were sent to the platform every 20 s allowed for real-time monitoring and as well as analysis of

the data collected. For even more detailed analysis, the data were exported to Excel for further processing. After the individual components were tested and an understanding of how each component functions was established, they were individually woven together into a smart system using the Arduino UNO WIFI microcontroller and Arduino IDE program.

The schematics in Figure 21 show how the individual components are wired up as well as the connections to the power source. The control system is powered by the semi-transparent solar panel, and electricity is stored in the battery. The charge controller controls the input energy from the solar panel to the battery. It also manages loads taken from the battery and has an added feature to cut off load if voltage reading from the battery is too low. This is crucial, as batteries can become damaged if they drop below certain voltages.

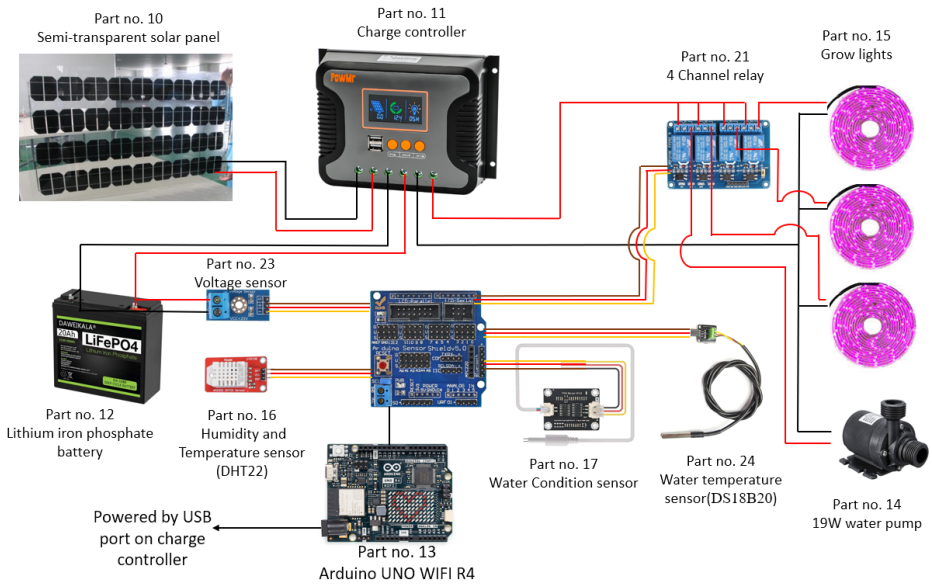

Figure 21. Schematics of the system used.

The output load passes through a 4-channel relay, which is controlled by the Arduino UNO microcontroller. This relay allows the lights and pumps to be switched on or off depending on the timings set in the code. For 1 h of the LEDs being on, it consumes 210 Wh, while the 19 W pump consumes approximately 25 Wh of power for the total time it is on in a day. As the model of the microcontroller used is the Arduino UNO WIFI R4, it has an in-built WIFI module which allows data to be transmitted through WIFI to the internet, which is collected on the ThingSpeak open platform.

2.5. Experimentation

During the process of gathering components such as nutrient solutions, growing media and seeds, the Co-Founder of Urban Green Dot Brandon Yeo gave recommendations based off his experience with hydroponic farming in Singapore. Accessing that the setup used in my feasibility study would be outdoor, he recommended I used the species Brassicaceae (Cruciferae), otherwise known as Nai Bai or Milk cabbage, as well as Brassica oleracea Alboglabra, otherwise known as Kai Lan or Chinese broccoli. This was due to their resistance to the hot weather of Singapore.

As instructed by Brandon, the seeds were put into the sponge and partially submerged in water for 2–3 days until the seeds started to sprout and roots start growing out the bottom. Figure 22 shows days 2 and 3 of this process.

On the fourth day, the roots began growing through the sponge, indicating that it was time for transplanting. The sponge media were then separated into individual blocks and put into the net cups. As seen in Figure 23, the cups were then placed into the hydroponic system.

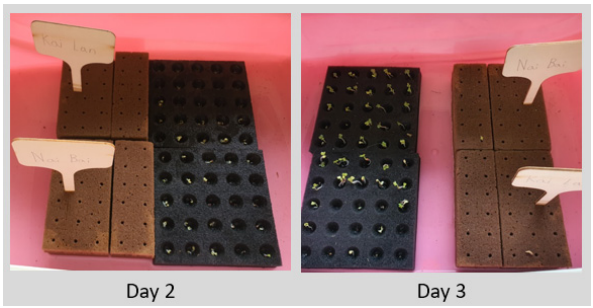

Figure 22. Germination progress.



Figure 23. Transplanting.

Raw data collected on ThingSpeak were exported in the Microsoft Excel format, where the data were processed. The raw data were used to calculate the daily watt hour of power generated as well as plotting the 5 different fields of data collected in daily charts, as seen in the screen capture in Figure 24.

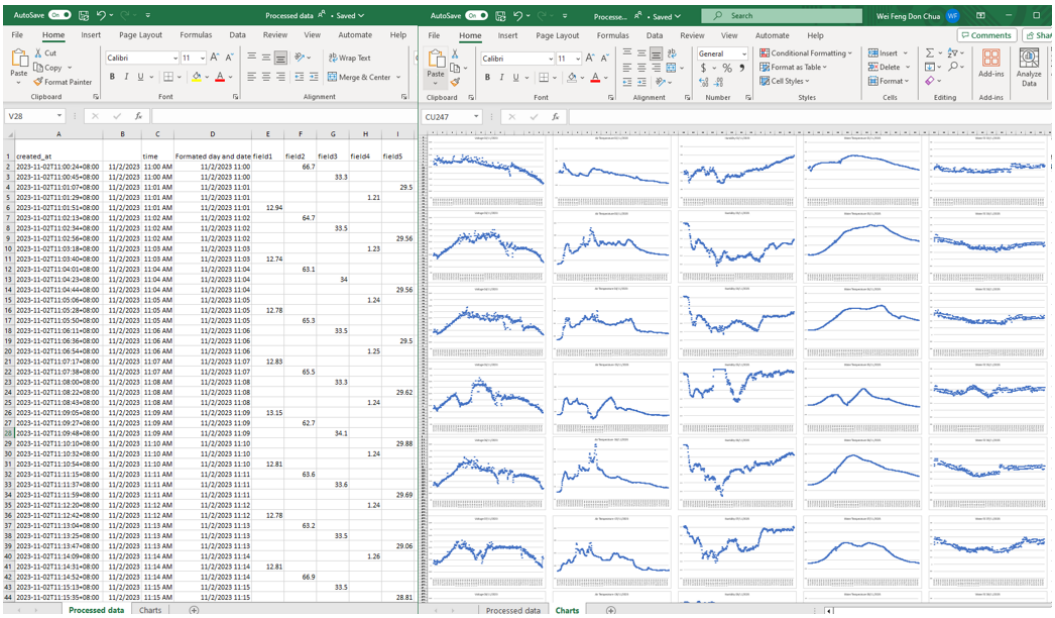

Figure 24. Data processing on Microsoft Excel.

The 5 different fields of data include battery voltage, air temperature, humidity, water temperature and water EC. Splitting these data into individual days allowed for monitoring trends and analysis on how they affect growth of the plants.

To evaluate the performance of the system, the main factor of power harvested had to be calculated. As the solar panel generates electricity, not all its generated electricity is stored into the battery. This is due to factors such as the battery needing time to charge and the battery only being able to hold up to a certain capacity. Therefore, it is only rational to evaluate the performance based off usable power that came in the form of finding out how much end power ended up in the battery. This was accomplished by making use of the battery voltage to determine the capacity increase in the battery. The chart seen in Figure 25 provides information on the relationship between battery voltage and its capacity.

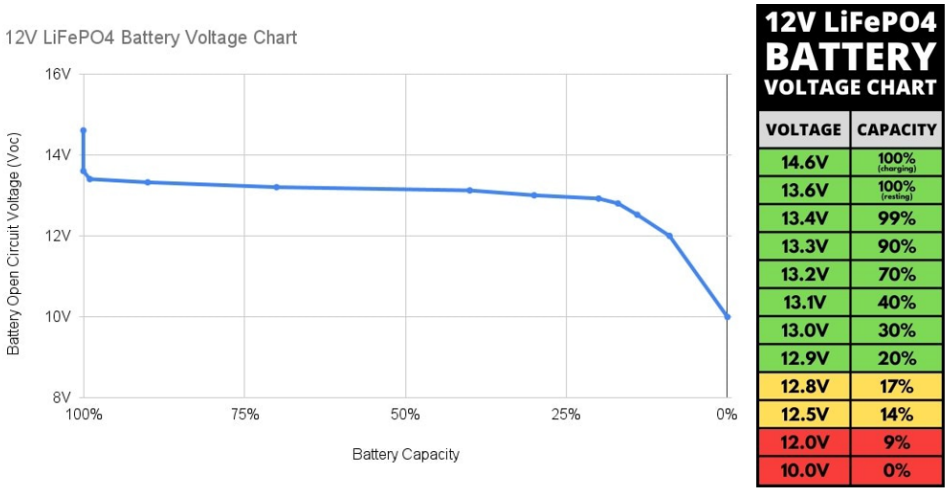

Figure 25. Battery voltage and charge percentage [26].

With the above chart and table, the average battery voltage between 7AM and 7PM (time between sunrise and sunset) is interpolated to give the percentage of capacity. This is then multiplied by the rated 256 Wh of the lithium iron phosphate battery used. Considering the power used during the day, the amount of usable energy is found.

Using the website timeanddate.com, weather data were used to tally against the daily charts. A comparison of one day of data is shown below in Figure 26.

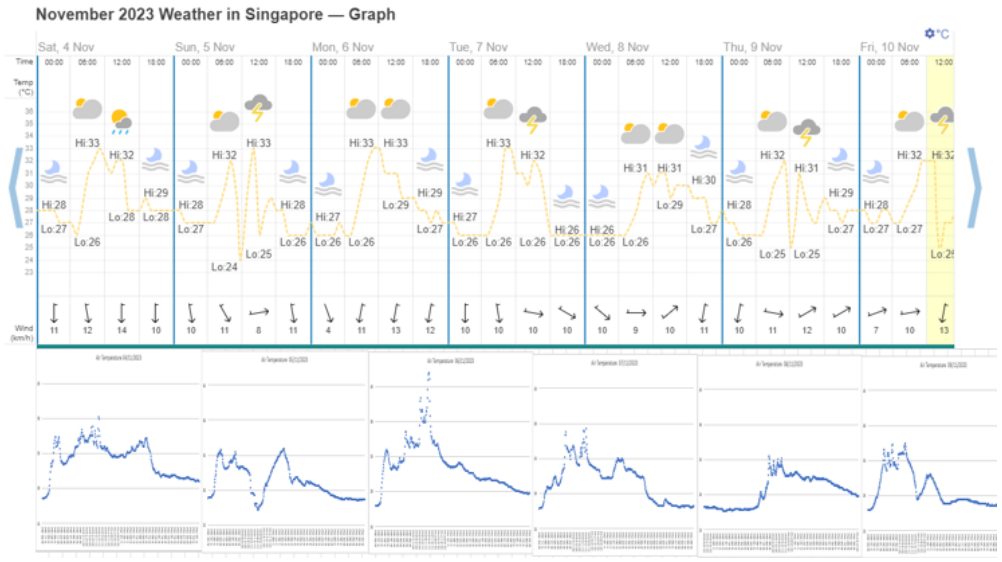

Figure 26. Screen capture of weather data from [27] vs. collected data.

By tallying the charts against a secondary source of data, the proficiency and accuracy of the prototype could be determined. As presented in Figure 26, the matching charts conclude that the readings achieved are valid.

3. Results and Discussions

As the two species of vegetables grew, both were assessed visually on how well they were doing. Factors such as leaf color, stem thickness and root mass gave an idea on how the plants were doing. The different stages are shown below in Figure 27.

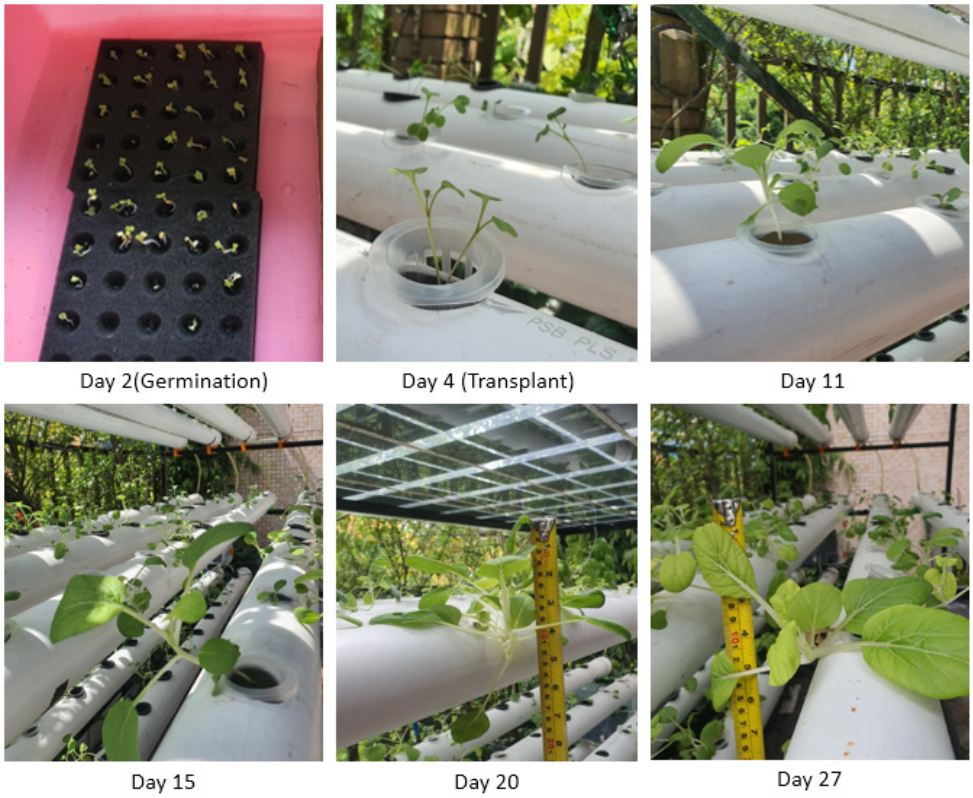

Figure 27. Stages of growth.

From day 1 to day 15, the vegetables grew at a steady healthy pace, leaves were thick and dark green, and root masses were forming well. On day 15, it was observed that algae was forming in the water tank. As the readings from the water EC monitoring were stable and within the range for leafy vegetables, no changes were made.

Day 15 was also the day a second batch of seedlings was planted in the extra slots in the system. However, this resulted in an unexpected result, as seen in Figure 28.

On day 20, the seedlings of the second batch were observed to be withering. A visual assessment showed algae forming on the sponge growing media. Ref. [28] studied the influence of microalgae on plant growth. In their study, results showed that the response of plant growth varied depending on the species of the vegetable. Negative effects were observed in the arugula species but not in the purple kohlrabi and lettuce groups. A possible culprit for the failure of the second batch was the presence of algae in the system [29]. A long-time homesteader wrote in his blog that algae growth is a common issue that comes along with hydroponic farming. Notable solutions to prevent the growth of algae would be to reduce sunlight exposure to the nutrient-rich water and growing medium.

Additionally, it was noted that mid-November marked the beginning of the monsoon season in Singapore. This meant that the plants were undergoing adverse temperature changes during this time. This could have subjected the plants to thermal shock. As discussed above, this would have affected the plants.



Figure 28. Withering of seedling.

For the 30 days of data collected in the month of November 2023, the daily watt hour of usable power harvested is presented in Scheme 1 below. Usable power harvested refers to the amount of power that ends up in the battery after losses such as passing through the charge controller. From the table below, it was observed that the usable power harvested is often larger than the battery capacity. This means that when the battery is fully charged, excess power is wasted.

Day	Date	Voltage average(V)	Average percentage	Average capacity(256Wh × percentage) Wh	Daily Wh (12h of sun)	Weather Condition	Remarks
1	02/11/2023	12.59	15%	38.4	348.16	Partly cloudy	
2	03/11/2023	12.30	12%	30.72	368.64	Rain	
3	04/11/2023	12.19	11%	28.16	337.92	Rain	
4	05/11/2023	12.23	12%	30.72	368.64	Rain	
5	06/11/2023	12.24	11%	28.16	337.92	Partly cloudy	
6	07/11/2023	12.26	12%	30.72	368.64	Rain	
7	08/11/2023	12.31	12%	30.72	368.64	Rain	
8	09/11/2023	12.39	13%	33.28	399.36	Partly cloudy	
9	10/11/2023	12.39	13%	33.28	399.36	Rain	
10	11/11/2023	12.55	15%	38.4	460.8	Partly sunny	
11	12/11/2023	12.47	14%	35.84	430.08	Partly sunny	
12	13/11/2023	12.47	14%	35.84	430.08	Partly sunny	
13	14/11/2023	12.04	9%	23.04	276.48	Rain	
14	15/11/2023	12.57	15%	38.4	460.8	Partly sunny	
15	16/11/2023	12.05	10%	25.6	307.2	Rain	
16	17/11/2023	12.38	13%	33.28	399.36	Rain	
17	18/11/2023	12.57	15%	38.4	460.8	Partly sunny	
18	19/11/2023	12.00	9%	23.04	276.48	Rain	
19	20/11/2023	12.77	17%	43.52	522.24	Partly sunny	External power connected for troubleshoot
20	21/11/2023	12.25	11%	28.16	337.92	Rain	
21	22/11/2023	12.30	12%	30.72	368.64	Partly cloudy	
22	23/11/2023	12.56	14%	35.84	430.08	Partly cloudy	
23	24/11/2023	12.34	12%	30.72	368.64	Rain	
24	25/11/2023	12.41	13%	33.28	399.36	Partly cloudy	
25	26/11/2023	12.49	14%	35.84	430.08	Partly cloudy	
26	27/11/2023	12.51	14%	35.84	430.08	Partly cloudy	
27	28/11/2023	12.51	14%	35.84	430.08	Partly cloudy	
28	29/11/2023	12.39	13%	33.28	399.36	rain	
29	30/11/2023	12.52	14%	35.84	430.08	rain	
30	01/12/2023	12.47	14%	35.84	430.08		
	Maximum	12.77	15%	38.40	460.80		
	Minimum	12.00	9%	23.04	276.48		
	Average	12.38	13%	33.02	392.53		

Scheme 1. Table of power harvested in November.

Figure 29 presents the data from Scheme 1 in a visual form. In the data presented, it is to be noted that the voltage and power-generated data on the 20th of November are to be neglected, as the battery was manually charged for troubleshooting and thus is inaccurate.

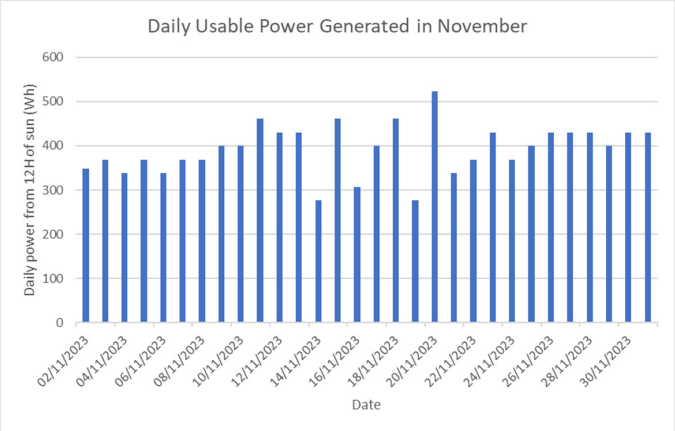

Figure 29. Daily usable power generated in November.

Overall, the maximum usable power generated of 460 Wh was observed on 3 days with partly sunny skies. Meanwhile, the minimum usable power generated of 276 Wh is seen on the 14th of November where rain was observed for almost the whole day. The monthly average per day was 392 Wh. From these data, it was concluded that there was a need for a secondary battery or a battery with higher capacity, so excess power does not go to waste. It is also shown that even during days with inclement weather, the solar PV is still able to generate power with daylight on a cloudy day.

As the battery capacity of 256 Wh was observed to be insufficient, it was important to find out if a secondary battery would increase the performance of the system. This was achieved through simulation software for photovoltaic systems known as PVsyst (Version 2.4). The software gives recommendations and prompts if there is a flaw in the simulated system. Figure 30 shows a prompt that the setup with a single battery is undersized for the PV array that is being used in the prototype.

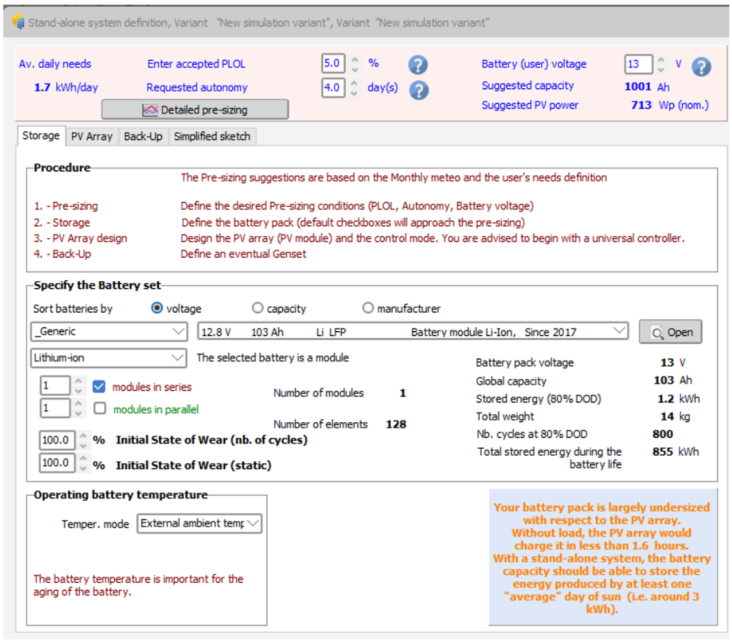

Figure 30. Simulation with PVsyst.

Simulating for one battery alone gave a poor performance ratio of 0.383. With an additional battery simulated into the system, the performance ratio was greatly increased to 0.598, as seen in the screen capture of the two simulations performed in Figure 31.

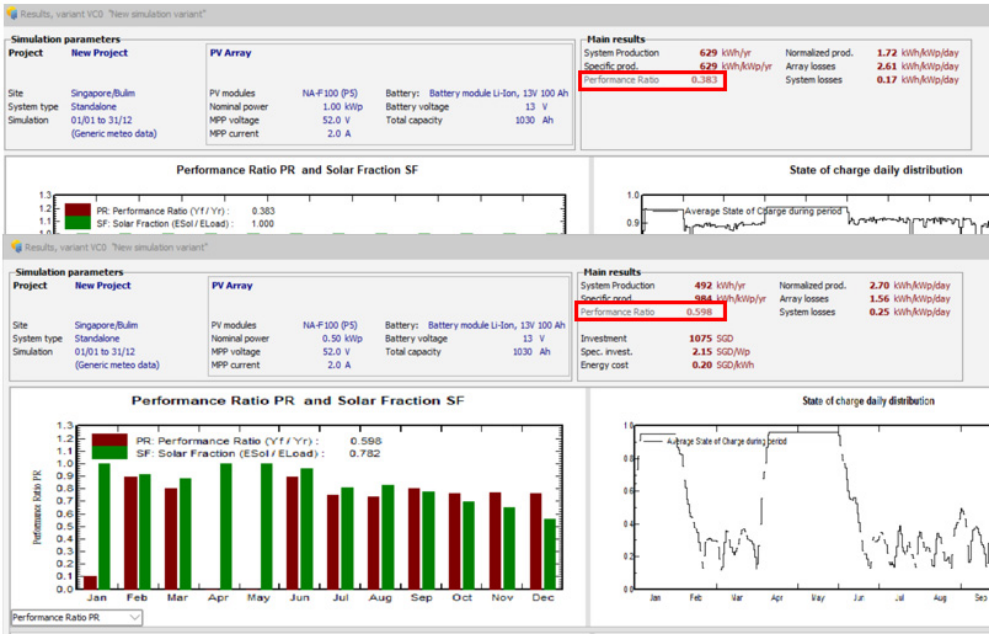

Figure 31. Performance ratio increase with extra battery.

4. Conclusions

Through the presented literature review, the required design specifications and features for the smart solar-powered water irrigation prototype have been identified. Based on those design specifications, a prototype has been successfully fabricated for the feasibility study. In a day, the prototypes' 14 W/m grow light LED totals 210 Wh of power usage while the pump uses approximately 25 Wh. The controller and sensor system are estimated to use 10 Wh of power. This totals 245 Wh of power needed. Theoretically, the 256 Wh battery will be able to support this system. However, it was observed that the battery is not always able to be at full capacity. Factors affecting this include charge time and the lights and pumps having to draw power concurrently while the battery charges. Simulating with PVsyst shows that the battery capacity used in this application is too small and the performance ratio is only 0.383. According to the simulation software, an additional battery will greatly increase the performance ratio to 0.598.

The monitoring and control system proved to be effective for data collection as well as for pump and lighting. The climate data collected match meteorological data from online sources, showing no discrepancies. Pumps and lighting operated on the exact timings that they were programmed to. In the initial stages, an automatic water refilling system was planned to cater for evaporation. However, this implementation proved challenging, as not only water has to be added, but the right amount of nutrient solution also must be added and mixed into the water tank to match the needed water conditions. In view of future work, further improvements to the controls system could be added. Heating and cooling to both water and ambient temperature could be explored in the hopes of providing the optimal growing conditions. Additionally, the entire system could be covered up like a greenhouse to help with this. This feasibility study serves as a proof of concept that could be implemented on a larger scale.

Overall, the fabricated prototype that was made in accordance with the specified requirements in Section 2.1 proved that the integration of solar PV in a smart solar hydroponic system allowed for crops to be grown using a sustainable source of electricity by producing an average of 392 Wh of usable electricity daily as observed in the month of

November. This amount of power generated meets the 245 Wh of power needed to run the smart hydroponic prototype. Hence, all the required objectives have been successfully achieved together with the project aim.

In the prototype, the primary source of energy storage is in the form of a lithium iron phosphate battery. The feasibility study proved that the 256 Wh battery was able to store energy and power of the smart farm prototype if weather conditions were ideal. Further study using PVsyst suggests that a secondary battery would have greatly increased the performance ratio of the setup, as any excess power could have been harvested rather than being wasted due to the maximum capacity of 256 Wh.

Other than a second battery, other viable forms of energy storage that could have been implemented include pumped storage hydropower. A secondary water tank and pump could have been implemented into the prototype. Here, when the battery is at full charge and the solar PV is still producing electricity, water could be pumped into the auxiliary tank at the high elevation for storage. This means that to create flow, the system will only have to need a low-powered solenoid valve to be opened, and gravity will do the work, saving the need for more stored energy in the form of a battery. A simple mock-up of the concept is shown in Figure 32.

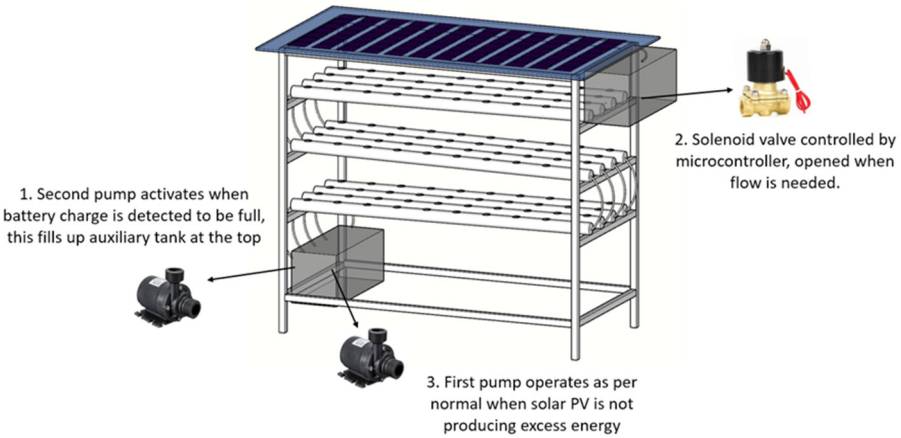

Figure 32. Concept for pumped storage hydropower.

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