STUDY OF SMALL-SCALE OFF-GRID PHOTOVOLTAIC AQUAPONIC SYSTEM FOR DOMESTIC SELF-CONSUMPTION APPLICATION

By

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A project report submitted in partial fulfilment of the requirements for the award of Master of Engineering (Electrical)

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled "**STUDY OF SMALL-SCALE OFF-GRID PHOTOVOLTAIC AQUAPONIC SYSTEM FOR DOMESTIC SELF-CONSUMPTION APPLICATION"** was prepared by **Au Yong Wai Tack** has met the required standard for submission in partial fulfilment of the requirements for the award of Master of Engineering (Electrical) at Universiti Tunku Abdul Rahman.

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ABSTRACT

Inflation of food are increasing due to global and local food insecurity. Availability and shortage of food supplies has been evidently affected due to unforeseen global and local events. Therefore, it is sensible to look into alternatives or solutions to secure essential food such as vegetables, especially in urban areas. Relatively big land area is required for conventional home farming. Therefore, it is interesting to study the use of aquaponics farming system as an alternative to tackle the issue described. Considering long-term benefits, and reduce the likeliness to be affected by external factors such as shortage of power supply or increase in power supply cost, the system should be powered by PV system in order to be self-sustained. A small-scale prototype PV Aquaponic (PVA) is to be assembled with minimum cost as a prove-of-concept experiment in this study. Lettuce will be grown to estimate the yield in 3 months. A 300 W PV system with a 3-tier aquaponic planter is found suitable for home growers. The cost of installation, maintenance cost is calculated and yield is recorded. Breakeven period is calculated to be around 4 years based on NPV, LCOE is around RM 3.5 kWh^{-1}, advantages and disadvantages of the system is discussed.

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LIST OF SYMBOLS / ABBREVIATIONS

PV System	Photovoltaic System
VF	Vertical Farming
PVA	Photovoltaic powered Aquaponic
DIY	Do-It-Yourself
LECA	Lightweight Expanded Clay
PAR	Photosynthetically Active Radiation
PPFD	Photosynthetic Photon Flux Density
DLI	Daily Light Integral
IoT	Internet of Things
P	Power
W	Wattage
η	Efficiency
V	Voltage
I	Current, Ampere
kWh	kilo-watt-hour
PSH	Peak Sun Hour
STC	Standard Testing Condition
AC	Alternating Current
DC	Direct Current
DoD	Depth of Discharge
AI	Artificial Intelligent
AH	Charge Capacity

SLA	Sealed Lead Acid
LMP	Lithium Metal Polymer
NPV	Net Present Value
LCOE	Levelized Cost of Energy
GBI	Green Building Index
A.Day	Days of Autonomy
AH_{actual}	Actual battery capacity required with losses
AH_{demand}	Battery capacity solely according to maximum demand
η_{chr}	DC charger efficiency
η_{rt}	Battery round trip efficiency
η_{pv_pr}	PV module performance ratio
η_{pv_temp}	PV module efficiency due to temperature
C_t, A_k	Annual Cash Flow
C_0	Initial Investment Value
r, i_r	Discounted Rate
M	Energy Generated in kWh over calculated period

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

In recent years, it is apparent that food security is surprisingly easily affected, due to the COVID pandemic, local issues and international conflicts. World economy, commodities supply chains, logistics and so on has been drastically affected due to the chain effects of these major events. These problems are often long lasting and not easily solved.

One of the effects specifically is, availability of food supplies such as livestock, vegetables and so on also has been affected causing increase of prices of food due to high demand low supply. Apart from that, prices of energy are also drastically affected especially in European and Western countries. (Kate, 02 September 2022) In addition, there are also reports of shortage of fertilizers which also contributing to increase of operating cost of farmers or growers. (Patti , 06 April 2022) As result, end users; individuals or families are most affected from the after effects.

In case of major impact from future events, it is sensible be prepared and to look into solutions or abilities to secure basic minimum food security and be less reliant to external sources, for individuals and small families especially in urban areas. Although it is unlikely to raise chickens or dairy cows or grow medium to large vegetation farms in urban homes due to absence of space for conventional farming, it is possible to have a small farm at home to secure minimum sustenance such as vegetables or fruits. However, adequate land size and soil are still required to achieve this. Hence it is interesting to study the methods of small-scale soilless farming system as an alternative to tackle the issues described. For the sake of self-sustainability, and to be environmentally friendly, green energy like the Photovoltaic system (PV) can be considered as alternative to tapping power from the power grid.

1.2 Problem Statement

There were studies on aquaponics around the world. In fact, some country has successfully deployed large-scale commercial vertical farming (VF) using aquaponic method like Singapore, Thailand, and even in Malaysia (Sengodan, 2022). Such as in the study in Malaysia by (Sengodan, 2022), the study focuses on commercial vertical farming around the world, briefly explore various innovative farming system like hydroponic, nutrient film, including aquaponic used in these VF. The study also explores various methods to implement VF and various factors and constraint that might affects the implementation, including financial aspect. This included study of high-rise roof top VF, high-rise balconies, refurbish of existing building into VF, conceptual holistic building design. The study concludes that commercial VF is a niche market due to high initial cost and operation cost, and high-power cost remains a challenge due to various control system, lighting and especially when air-conditioning is used. Therefore, the potential in Malaysia is huge considering the abundance of solar irradiation for plant growth, the use of solar energy to offset high energy cost and plenty of rainwater for irrigation. The study like many others did not include nor focused on solar-powered aquaponic system, nor the detailed technicality behind it.

Therefore, due to the research gap described, it is interesting to investigate and evaluate the actual data and information provided from actual experiments, such as qualities of crops compared to conventional planting method when setup is partially shaded like a balcony. The considerations on the installation such as planter design, essential equipment, PV system calculation and setup. And the cost involved and cost benefits it offers to home growers.

1.3 Aims and Objectives

The objective of this study shall be as below, as further explained in the introduction and problem statements: -

- Prove-of-concept with results with evaluations showing PV Aquaponic (PVA) system works as intended for home and small family growers with experimental setup based on theoretical model.
- To calculate initial cost and maintenance cost of small-scale PV Aquaponic (PVA) system for self-consumption urban farming in Malaysia.
- To calculate and evaluate the breakeven period base on NPV calculation, and the Levelized Cost of Energy (LCOE) of the system from the collected data.
- Investigate the pros and cons of the system and provide recommendations for future studies.

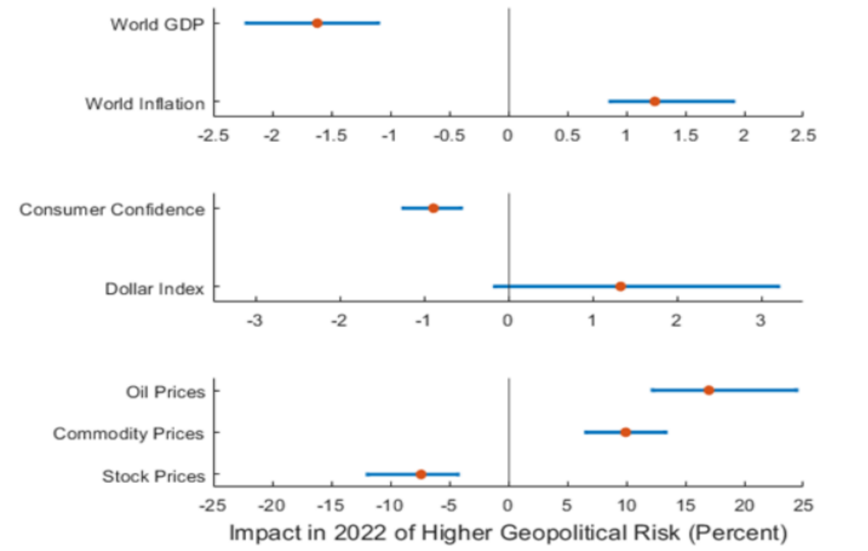
CHAPTER 2

LITERATURE REVIEW

2.1 Food Security

Livelihood of families are easily affected destabilized by local or global events. Especially when these events happen abruptly. It is often hard to predict nor prevent these major events, therefore without preparation one is likely to be affected by direct or indirect consequence result from these events. These events for example may be epidemic or pandemic, like the recent Covid-19 outbreak that have been causing severe impact globally with long-term effects that spans over several years. Another example is unstable politics between countries and regions, and outbreak of war such as the ongoing Russian-Ukraine war which was started in 24 February 2022. In addition, factors like climate and natural disaster or with the combinations of either of the mentioned. These events cause loss of life, social & political impacts, disrupt local and global economies. Evidently food security is one of the major setbacks as well.

Throughout history, heightened geopolitical risks have had significant adverse impacts on global economic activity. Wars, for example, lead to the destruction of human and physical capital, as well as the diversion of resources to less efficient uses, disrupting capital flows, international trade, and global supply chains. Furthermore, the concerns regarding the potential outcomes of adverse geopolitical events can also negatively affect economic activity by delaying investment and hiring, reducing consumer confidence over time, and spending. (Caldara, et al., 2022) Analysis from The Federal Reserve of United States in Figure 2.1 indicated the affects in percentage various aspects affected by the Russian-Ukraine war such as decrease in world GDP, increase in world inflation, decrease in consumer confidence, decrease in stock prices and increase in both oil and commodity prices.



Note: The figure plots the maximum impact in the first year of a rise in geopolitical risks sized to mimic the increase occurred between January and April 2022. For each variable, the red dots plot the central estimates of the maximum impact in the first year. The blue bars denote 70 percent confidence intervals. The effect is measured in percent deviation from a no-war baseline for all variables except inflation, for which it is measured in percentage points.

Figure 2.1: Transmission Mechanism of Higher Geopolitical Risk on Macroeconomic Variables (Caldara, et al., 2022)

Moreover, it was reported that series of events like unprecedented turbulent weather and downpours of rain, laborer issues, pressure from post-pandemic consumer demand etc. has contributed to the high food inflation in Malaysia after the Covid-19 lockdown (Amanda Yeo, 2022) (Kong, 2022), where the country struggles to fill the void of food supply. In addition, report in (Nur Hanani Azman, 2022) and other news media sources that commodity price including food and chemical fertilizers will be affected due to the after-effects of the chain of events from Covid-19 and the war.

Figure 2.2 shows the inflation rates of food pre-pandemic and post-pandemic, before and after the happening of the war, and in addition to local events described. We observe the food inflation in Malaysia from year 2012 to 2018 fluctuates around 3 % to 5 %, food inflation from year 2022 to 2023 jumps from around 1.8 % to around 7 % in just one year due to the chain effects from these major events. Noting that the deflation from year 2018 to around end of 2021 was due to complex factors including consumer demand, supply chain disruptions and government policies during the time of Covid-19.

Figure 2.2: Food Inflation Year 2021 - 2023

(Department of Statistics Malaysia, 2023) (Trading Economics, 2023)

2.2 Introduction to Aquaponics

Aquaponics is an innovative system that uses aquaculture and hydroponics to grow plants and farm fish at the same time. Fish wastes produced are used as nutrients for plants, reducing the need to fertilize the plants. (Baiyin, B., et al., 2020) As the result, both plants and fishes can be farmed for food or other purposes. Many designs are available, be it off-the-shelf system available for purchase or do-it-yourself (DIY) setup. There is no fixed design for aquaponic farming system. Nevertheless, Figure 2.3 and Figure 2.4 show the basic concept of aquaponics.

Basically, fishes are raised in a suitable tank or container at the bottom, where submersible pump is used to pump the water from the bottom tank to planters above. The planters can be trays filled with Lightweight Expanded Clay Aggregate (LECA) or simply covered containers with holes above. It can also be modified PVC pipes with holes on it. The aquaponic pots are fitted into the holes or planted direct if LECAs are used. The water pumped to the trays or PVC pipes will flow back into the tank to complete the cycle. While water is passing through the trays or pipes, nutrients contained in the water column will be made accessible to plants. The trays can either be stacked; also known as vertical farming, or can be placed horizontally in a single level if space is not an issue. However, the current trend prefers vertical farming to save precious space in properties, and to fully utilize available space especially in commercial farms to maximize yield. Figure 2.5 shows example of vertical aquaponic farming, where water is pump to the top of the PVC pipe or hose and sprinklered down, the wools or roots of plants gets hydrated.

Compared to conventional irrigation, the system is efficient in the use of water, as the water flow in a closed-looped system. Therefore, fresh potable water will only be added due to evaporation, absorption by plant or periodic partial water change to maintain fish health. Another important element that increases the success of the system lies with the lighting. For outdoor application, sunlight is abundance in Malaysia, however for indoor or shaded application artificial lighting is required. Previous study indicated that LED may be the best lighting option for maximum yield and growth, where the plants grown are generally has significantly higher average individual weight, higher production per unit area, and higher production per unit energy. This appears to be due to greater production of red spectra and higher Red:Blue ratios by LED lights compared to other lightings like metal halide, fluorescent and induction light. (Shultz, R.C., et al., 2022) In addition, LED also more energy efficient and has longer lifetime than conventional lightings.

Lighting in agriculture is usually defined by the amount of Photosynthetically Active Radiation (PAR) on the plants. It is electromagnetic radiation of wavelength between 400-700 nm used by plants to perform photosynthesis. It is expressed in Photosynthetic Photon Flux Density (PPFD) or Daily Light Integral (DLI). PPFD is the measure of PAR photons that actually reaches the canopy area of plants represented by µmol/ m^2/ s. DLI is a measure of PAR photons that actually reaches the canopy area of plants in a number of hours with light in a day, in mol/ m^2/ day (in hours).

Leafy vegetables like lettuce, spinach and pak choi and fruity plants such as tomato and cucumber are selected for aquaponics. Tilapia, catfish and common carp are usually selected for medium to large scale aquaponics. Source in Figure 2.6 shows the type of fish and general application. Practically, the species of plants and fishes varies depending on the system need and scale, making aquaponics ideal in terms of flexibility to be modified to fit various needs and regions (Bu, Z, et al. as cited by (Baiyin, B., et al., 2020). Besides, the system can be placed outdoor or indoor making it appealing for installation in condominiums or apartments where outdoor spaces are restricted to either the balcony and/or sometimes the yard area.

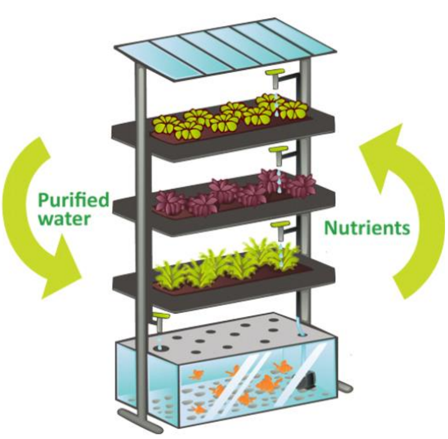


Figure 2.3: Aquaponics System (illustration)
(Reid, 2022)

Figure 2.4: Aquaponics System (example of setup)
(Shannon, 2022)

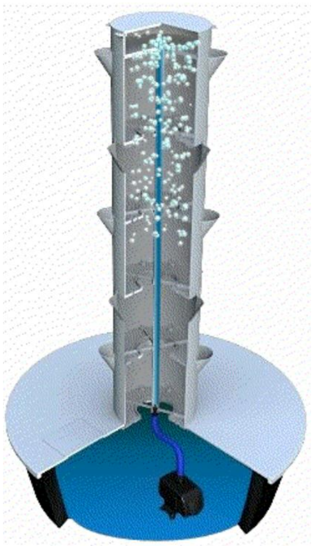


Figure 2.5: Vertical Farming Aquaponic System (Vertical Tube/PVC Pipe)
(Naylor-Smith, n.d.)

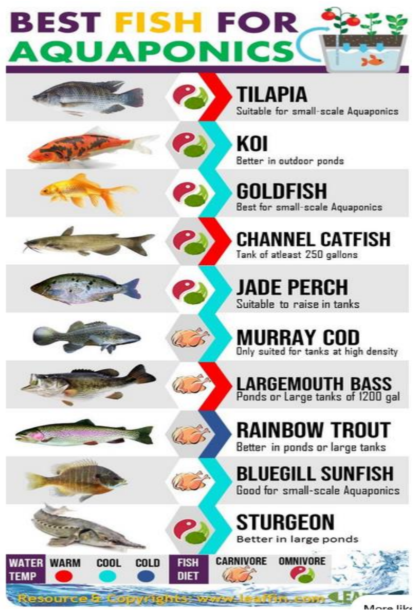


Figure 2.6: Fishes for Aquaponics
(Leaffin, 2019)

In addition to study by (Sengodan, 2022) mentioned in problem statement, study by (Alam, M.N.H.Z., et al., 2023) studied the possibility and potential of harnessing solar energy for aquaponic system, including various PV technology available in the market, essential equipment and needs for aquaponic system and proposed to monitor solar-related parameters and devices to ensure optimal system performance using Internet of Things (IoT) technologies. However, the study was focused on feasibility study rather than actual implementation or experiment. Other case study by (Teo, Y.L. & Go, Y.I., 2021) regarding the techno-economic-environmental analysis of solar, hybrid system for vertical farming, again focused on commercial vertical farming in Malaysia.

A study by (Ali, M.F.M., et al., 2021) developed prototype and investigated small scale smart aquaponic system by using IoT technologies. The prototype system developed was powered by a 25 W PV panel with 10 Ah lithium-ion battery. But the study did not elaborate the load profile of the system nor proves that the system works accordingly to design intent of aquaponic system. The pump load and especially lighting load was very low and would be consider inadequate to grow plants. Therefore, it is unknown is the system will work in practical. Besides it is not sensible to deploy smart system for small-scale aquaponic system especially for domestic application due to the additional initial cost, maintenance cost and complication of the system to be implemented and maintained, unless by professionals or experts.

Besides the above-mentioned studies, many other studies too are either focused on commercial VF, feasibility studies or it is studied based on climates other than tropical countries. It appears that there are apparent experimental based studies regarding small scaled PV aquaponic systems specific for domestic applications; in houses or apartments, recorded in Malaysia.

2.3 Introduction to Photovoltaic (PV) System

Energy consumption increases due to increase of population, improvement of living standards, and industrial development. However, the energy generation relies mainly on non-renewable energy sources such as Fossil fuels, coal, crude oil, and natural gas supplies, which account for more than 80% of primary energy sources as of 2018 globally. (Sayed, E.T., et al., 2021) Despite the fact that these resources are fast depleting, their usage in energy generation also increases the carbon footprint, and consequently increasing global temperature, not to mention the production of harmful waste and pollution of the air. (Dincer, 2000) In Malaysia, the consumption of conventional energy sources as of year 2019 is 94%; 36% natural gas, 37% petroleum

& other liquids and 21% coal, with only 6% energy was contributed by renewable energy as shown in Figure 2.7.

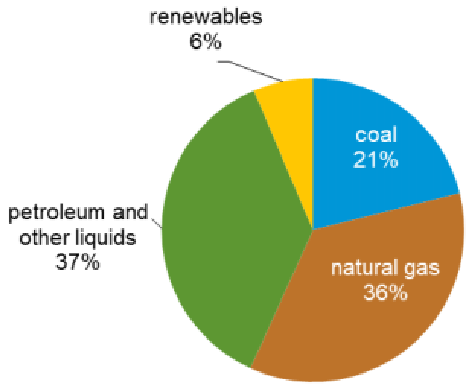


Figure 2.7: Primary Energy Consumption in Malaysia, 2019 (BP 2020 Statistical Review of World Energy) (Shafie, et al., 2011)

Rationally, alternatives are required to mitigate these issues. Micro hydro, wind, and solar energy are popular amongst renewable energy generation. Solar energy power generation is one of the highly promising alternatives in Malaysia the country has average daily solar radiation of 4500 kWh/ m^2 and daily average sunshine duration of approximately 12 hours. (Shafie, et al., 2011) (Sriram, 2006).

Basically, a PV system is a system that converts solar energy to electricity. Figure 2.8 illustrates a PV system and the major components. The main components consist of PV panels or PV modules, inverter module, and/or battery charger and battery set depending on application. PV panels or modules convert solar energy incident on them to electricity which is technically DC voltage power supply. Inverters are used to convert DC voltage power supply to AC voltage power supply. The AC voltage is then fed to a local system; self-consumption or fed to the power grid. Usually, the inverter will come with MPPT feature to regulate and maximize the power obtained from the PV modules because the output from PV modules varies with temperature of the modules and the irradiance. Battery charger and batteries can be used to store power to meet power consumption requirements for extended power supply duration.

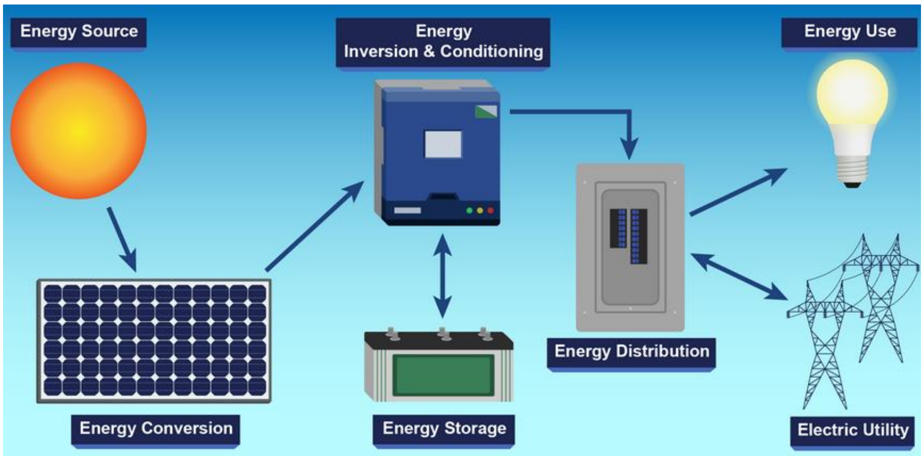


Figure 2.8: Major Components of PV System
(University of Centre Florida, 2022)

2.3.1 Off-Grid PV System for Self-Consumption

An off-grid PV system basically is a system that is not connected to the power grid. The system generally is suitable to be installed at remote or isolated areas without permanent power supply, an island or remote village for example, or simply used to supply power to local load or specific equipment as shown in Figure 2.9. In this case, the inverter is connected to the aquaponic system and local distribution board.

When sunlight is incident on the PV panels, solar energy is converted to electricity to power up the aquaponic system while charging up the battery bank with any excess energy, managed by the charge controller. The more intense the sunlight incident on the solar panels, the faster the battery bank is being charged. Since the electricity generated by the PV modules and from the battery system is in DC voltage, inverter is used to convert DC voltage to AV voltage.

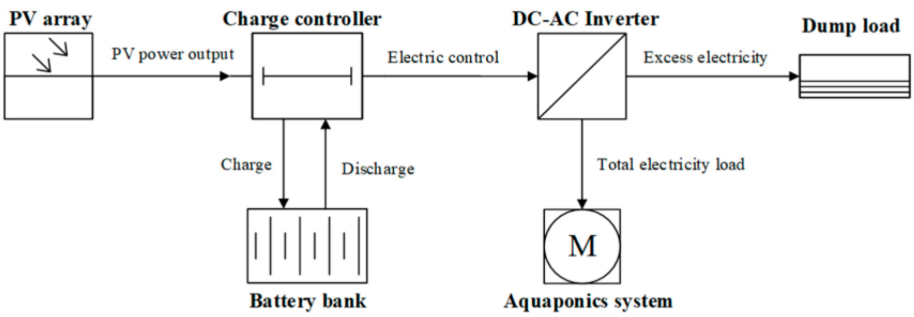


Figure 2.9: Photovoltaic Aquaponic (PVA) System
(Baiyin, B., et al., 2020)

When the energy produced by the PV system is more than required to charge the battery and used by the aquaponic system or if the aquaponic system is offline, the excess power can be delivered to other loads also known as load dump, connected through a distribution board as shown in the Figure 2.9. Alternatively, if the load of the system consists of only DC components, then the inverter is not required. The distribution board may be connected directly to the charge controller.

2.3.2 Off-Grid PV System Sizing and Calculation

To size an Off-Grid PV System, it is essential to identify the load profile and total consumption of the connected loads as shown in eqn. (1). Total Consumption per day shall be the summation of all the individual consumption of equipment or devices involved, Wh_{Total}.

Daily Equipment Consumption, $\textit{Watt-hour}_{demand} = (P_{rated} \times \textit{Operation Hours})\ Wh$
where P_{rated} is equipment rated power in *Watt,W*-------------------------------- *(1)*

Total Watt-Hour, *Wh* per day shall be the consumed power required from the PV modules to power up the system every day. However, in practical, losses occur in the different components, therefore they are required to be included into the calculation as in eqn. (2) and eqn. (3). Basically, the PV modules have to generate more power on top of the equipment consumption to ensure sufficient power generation for the system.

Required PV Array Output, $Wh_{array} = Wh_{Total} / \eta_{Total}\ Wh$------------------------ *(2)*
Total efficiency, $\eta_{Total} = \eta_{rt} \times \eta_{chr} \times \eta_{pv\_pr} \times \eta_{pv\_temp}$ ------------------------------- *(3)*

where, η_{rt} = *Battery round trip efficiency,* η_{chr} = *Battery charger efficiency,* η_{pv_pr} = *PV module Performance ratio,* η_{pv_temp} = *PV module efficiency due to temperature,*

The guaranteed power output from a selected PV module can be calculated from eqn. (4).

$P_{PV} = V_{mp} \times I_{mp}\ Watt$ -- *(4)*

where, V_{mp} = *PV voltage at maximum power, and* I_{mp} = *PV current at maximum power, both at standard testing condition (STC).*

The consumption covered by a PV module is by multiplying the guaranteed power with the peak sun hours (PSH). PSH in Malaysia is generally 4 hours per day as in eqn. (5).

$Wh_{PV} = PSH \times P_{PV}\ Wh$ --- (5)

Therefore, by dividing the required PV array output in eqn. (2) with the PV module output in eqn. (5), the total numbers of PV modules require by the system can be obtained as per eqn. (6).

$Pieces\ of\ PV\ modules = Wh_{array} / Wh_{PV}$ --- *(6)*

Number of strings of a system can be determined by the system voltage in DC and the PV output voltage as in eqn. (7).

$Number\ of\ PV\ Strings = V_{bus} / (V_{mp} \times \eta_{pv\_pr} \times \eta_{pv\_temp})$ ------------------------- *(7)*

2.3.3 Battery Storage System

Generally, it is advisable to have a battery storage system to ensure reliability of the system (Krieger, 2013), due to the fact that solar energy level is not consistent, and only available during the day. In the market there are many battery technologies can be used for such application such as lead acid, lithium-ion, nickel cadmium and sodium. Lead-acid and lithium-ion are commonly used because of advantages such as low cost, maintenance free during operation, and typically are high in efficiency. The down-side on this technology is that they degrade fast and needs to be replaced frequently, resulting in higher maintenance cost in long run. Lead-acid battery further split into two types which are flooded type and sealed types, the first is less expensive while the latter needs less maintenance, better at handling temperature and spill-proof and non-hazardous. (Hlal, M.I., et al., 2019) Two main factor that cause degradation is high temperature and depth-of-discharge (DoD) of batteries. While temperature factor is costly to solve in most cases, careful optimization or control of DoD can be more achieved.

The cost of battery system in the current Malaysia market is consider high, therefore, there is a need to properly calculate or perform optimization to ensure battery longevity to reduce maintenance cost while providing sufficient power to the system. Various method of optimization techniques has been suggested to design a standalone PV system which include numerical, analytical, intuitive, and artificial intelligent (AI) method as mentioned in journal by (Hlal, M.I., et al., 2019). The proposed optimization method was to obtain the most ideal battery depth of discharge (DoD) based on the characteristics of a cycling battery in a standalone PV system. Similar approach has been conducted by (Shen, 2009).

2.3.4 Depth of Discharge (DoD) of Battery

Battery Depth of Discharge (DoD) measures how far discharged a battery is as compared to its total nominal capacity. It can be calculated by dividing available capacity, C with total capacity, Ct.

DoD = C / Ct × 100% ; C and Ct in AH --*(8)*

Generally, the deeper or further a battery is frequently discharged, the shorter the life cycle the battery becomes. This characteristic happens in most battery types including the commonly used sealed lead acid (SLA) batteries. For instance, study on a Lithium Metal Polymer (LMP) battery shows that cycling at low DoD improves the life time of the battery, reduces capacity fade and also reduces the stress when discharging as compared to full cycles discharge test. Battery will be damaged caused by stress during the phase transformations taking place at low voltage during low battery capacity. Lower battery DoD prevents this phase transition, thus lessens the resulting stress to the battery cells.

Besides, the study shows that micro cycling of the battery capacity being tested did not reduce the performances of the battery for at least 4 months period. Frequent discharges of a few minutes also had no measurable effects on current efficiency or capacity fade of the battery. In addition, formation of dendrites is delayed by reduced DoD. (Leblanc P & Guena T, 2006)

Typical number of discharge/charge cycles tested at 25 Celsius for SLA battery is as follows (Hutchinson, 2004):

100% DoD : 150 – 200 cycles
50% DoD : 400 – 500 cycles
30% DoD : >1000 cycles

In order to extend battery life-time. Besides proper calculation and optimization based on application. In general, larger battery capacity can be used or special deep-cycle batteries can be used. Some claimed by manufacturers can maintain high life-cycle even with deep discharge from 50% to 100%.

2.3.5 Battery System Sizing and Calculation

The first step in battery calculation is to determine the daily consumption as in eqn. (1). Next, the number of days autonomy backup is to be determined. Following that, the total AH demand from the battery for the equipment is calculated in eqn. (9).

$$\text{Amp-Hour}, AH_{demand} = A.Days \times Wh_{demand} / \text{Bus DC Voltage AH} \quad \text{------------------} \quad (9)$$

A.Days = number of autonomy days.

Practically, losses occurs and the actual battery capacity shall take consideration of the allowable depth of discharge, DC charger efficiency and battery round trip efficiency, as eqn. (10).

$$AH_{actual} = AH_{demand} / DoD / \eta_{chr} / \eta_{rt} \quad \text{--} \quad (10)$$

Suitable battery capacity and ratings can then be selected according to the calculation.

2.3.6 PV Panel Types and Grades

Different types of PV panels technology available in the market such as Monocrystalline, Polycrystalline and Thin-film. Monocrystalline is more expensive but has higher efficiency. It performs better under high temperature compared to the other types. Polycrystalline is cheaper but compromised in performance and efficiency. Thin-film is low in efficiency and performance but they are flexible and can be used to integrate onto building and roof of various shapes while the former types are in fixed panel shape.

Besides determining the type of solar panels used. The grade of solar panels used also should be considered depending on situations. Grade of PV panels or rather solar cells are categorized into Grade A, B, C, D. Grade A solar cells are manufactured without visible defects and deviates little from the desired specs, basically flawless. Grade B solar cells have visible but tiny defects, such as slight bend, slight deviation in colour, small watermarks and scratches or paste leakages. However, the performance does not deviate from specifications. Lastly, Grade C solar cells have visible defects with affected performance and deviation from the desired specifications. The defects may have those in Grade B solar cells and worst like chipping and missing busbar. Grade D solar cells are used to categorize broken cells and are totally unsalvageable.

Grade A and Grade B panels are known to be sold in the market. Usually, high profile projects such like PV farms, and new installation on housing/apartment projects will use Grade A PV panel and the price of these panels are much higher than Grade B panels. Therefore, for economic consideration these panels can be used for domestic application. Even so, in generally most solar panels have lifespan of 25 years or more. The performance warranties given by manufacturers usually helps to determine the lifespan. (Dricus De Rooij, 2013)

CHAPTER 3.0

RESEARCH METHODOLOGY

3.1 Project Flow & Project Milestones

The research method is quantitative type because numerical measurement and numerical data were collected from experiments and to be analyzed. Figure 3.1 & 3.2 shows the overall project flow. The project started with detailed case studies, literature reviews in order to finalize the objectives, design, calculations and parameters. Once finalized, materials and equipment were sourced for construction of the experiment. The setup was optimized, tested and troubleshoot. Along the process, material sourcing and construction processes were revisited for fine-tuning, or improvement of the design. After the setup was verified to work according to design intent, and experiment was conducted. Data was collected, leading to analysis of data to turn them into useful information. Finally, the project ended with discussion and conclusion based on the findings of the experiment. The above mentioned are elaborated in later sections of this report.

Figure 3.3 and 3.4 shows the activity and milestone taken to complete this project. The first part in Figure 11a mainly focused on preliminary studies and up to construction of the PV aquaponic system. The first part took 14 weeks to complete. Second part of the project focused on the experiment, data collection and completion of analysis and report writing.

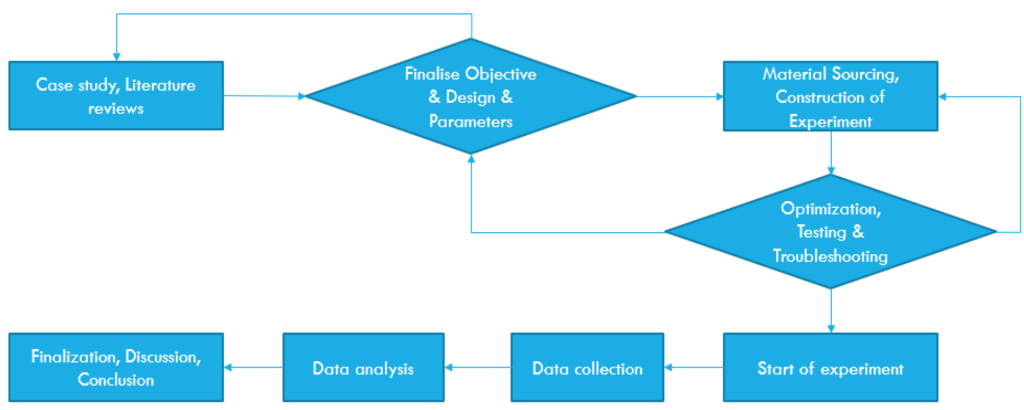


Figure 3.1: Overall project flow chart

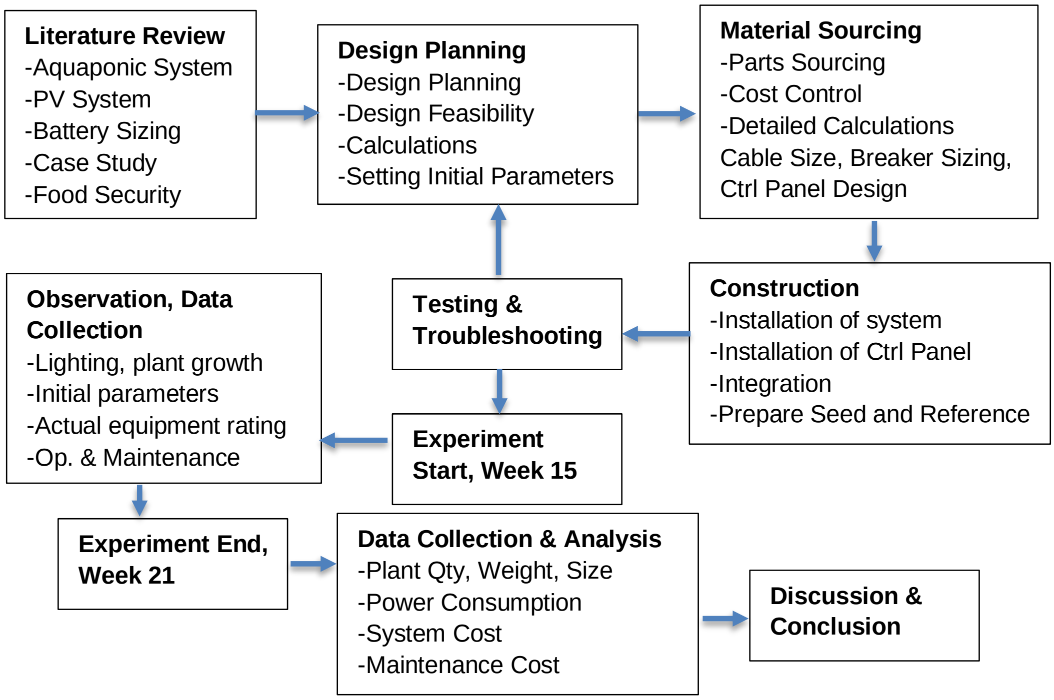


Figure 3.2: Detailed Project Flow Chart

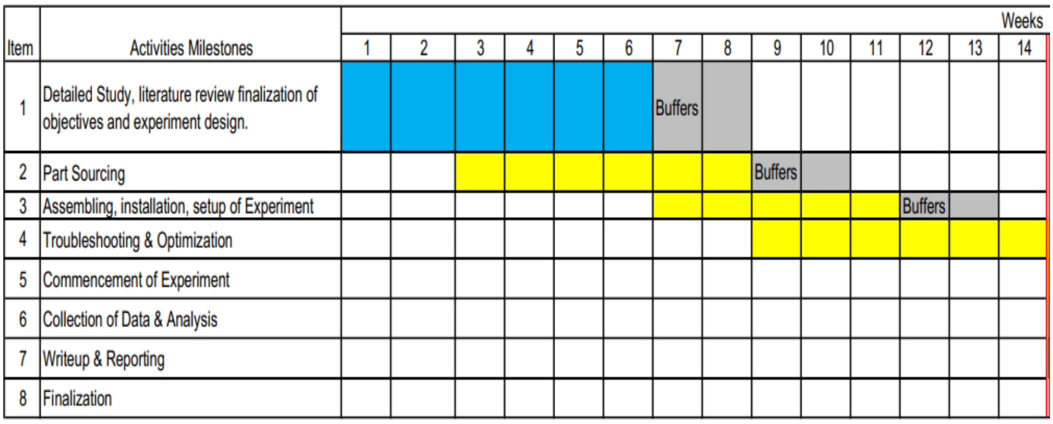


Figure 3.3: Project Milestone Part 1

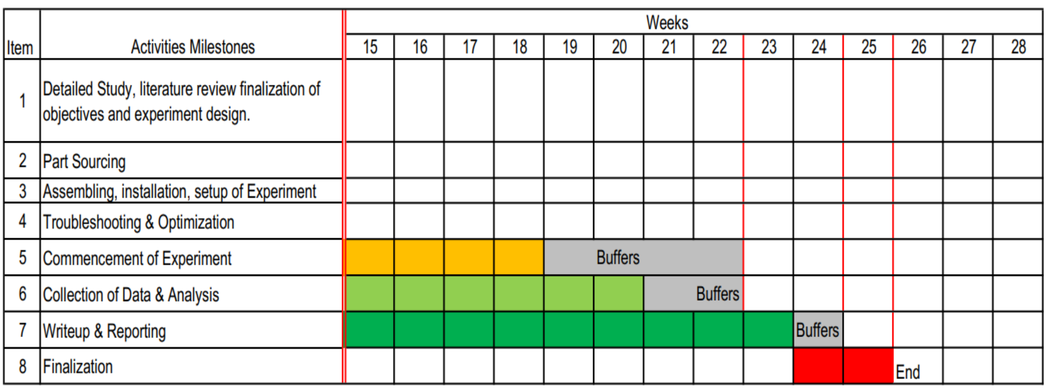


Figure 3.4: Project Milestone Part 2

3.2 Setup and Selection of Equipment

A small-scale prototype aquaponic setup has been constructed to limit the scope of experiment. To reduce cost and time of construction, a pre-cut, off the shelf kit is being used. A 3-layer system has been chosen; layer 1 to layer 3 from the top as in Figure 3.5, with PVC pipe and 108 holes instead of tray for better control of study. Besides, this design fits typical size of apartment or condominium balcony width hence it is considered very suitable for this study. The total dimension after assembly is around 100 cm (L) × 45 cm (W) × 100 cm (H). A plastic container with dimension of 60 cm (L) × 40 cm (W) × 32 cm (H) is placed at the bottom of the setup. Plumbing has been connected from the pump to the inlet of the setup and another outlet pipe is connected back to the container. 10 juvenile sized gold fishes were added to the container due to their low in initial cost, yet still able to produce high waste to fertilize the plants. Before adding the fishes, water in the system was cycled for 2 weeks with filter media at the bottom of container to kick-start nitrification process. Within the two weeks, fishes were gradually added. They have been fed twice daily. The setup is oriented at North direction due to constraint of the location and space.

A PV system of 150 W PV module and 12 V, 55 AH battery has been installed as in Figure 3.7, to give power to the system based on calculation eqn. (1) to eqn. (7), described in literature review Section 2.3.2. PV panel is tilt-mounted on pole around 3 m height with 10° pitch to face south, based on observation on sun trajectory and general practice in Kuala Lumpur, Malaysia, also as verified by study by (Elhab, B.R., et al., 2012). This is to simplify the experiment to simulate fixed mounting on roof. Generally, the battery is sized to back up the system for 1 day with the described operation during worst case scenario; raining/gloomy whole day. Care has been taken in sizing the battery to maintain low DoD to maximize battery lifetime. Figure 3.9 shows the single line diagram to better visualize the setup. The full calculations are presented in Sections 3.2.1. The main specifications of main components are attached in Appendix.

The equipment in this setup consists of a submersible pump of 6 W capable of delivering 1.5 m head, 4.4 W air pump and 4 numbers of 10 W LED lighting, 2 lighting per tier for tier 2 and tier 3. All equipment selected is rated 12 V. Corrugated plastic sheets are fixed between tier 2 and 3 to purposely lower the natural lighting level of the two tiers for the sake of experiment. The submersible pump has been run for collective 12 hours in 1 hour interval daily, whenever the pump stops the air pump will run aerate the water. This is controlled with a timer-controlled relay. On the other hand, lighting has been turned on for 4 hours daily from 11am to 2 pm to compensate for loss of light in tier 2 and tier 3. It is also controlled by using timer. All devices; battery charger, timers, meters are mounted in a control panel as in Figure 3.8. Total consumption of the load is taken by a digital power meter at the end of the experiment.

Plants have been grown on the setup and to estimate the yield of the system at the end of this experiment. Butterhead lettuces have been grown in this experiment due to the relatively short time they take to grow to maturity, which is around 45 days according to seed company’s instructions. Seeds were let to germinate on wet paper towel in a small container for a day. The lettuce sprouts were transplanted to and grown on each layer of the planter. 30 lettuces were grown on each layer. The plants are fertilized with 35 ml liquid fertilizer added into water to supplement the nutrients missing from fish waste during every 20 % water change. The amount is reduced by half as per manufacturer instruction due to the additional fertilizers from fish waste.

Figure 3.5: Aquaponic Setup (Actual)

Figure 3.6: Germination and sprouts transplant process

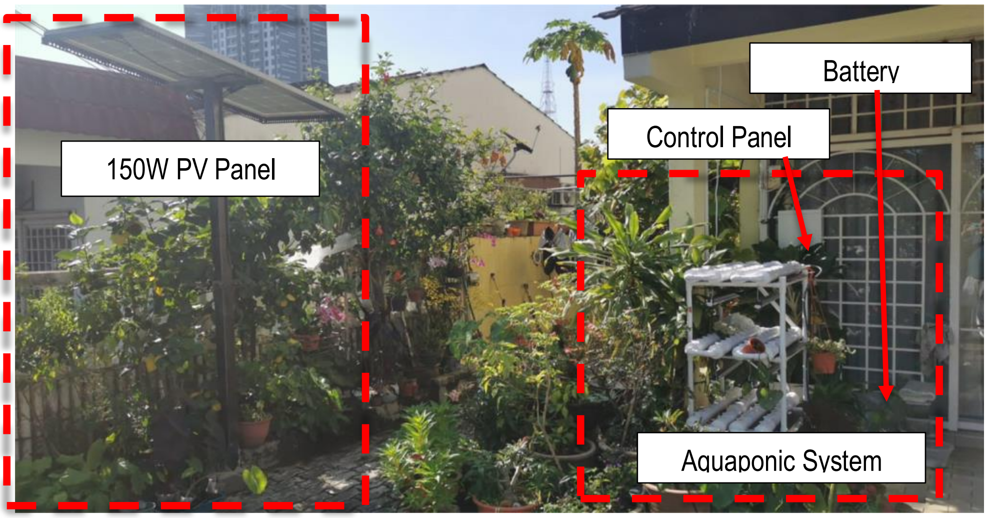


Figure 3.7: PV Aquaponic System

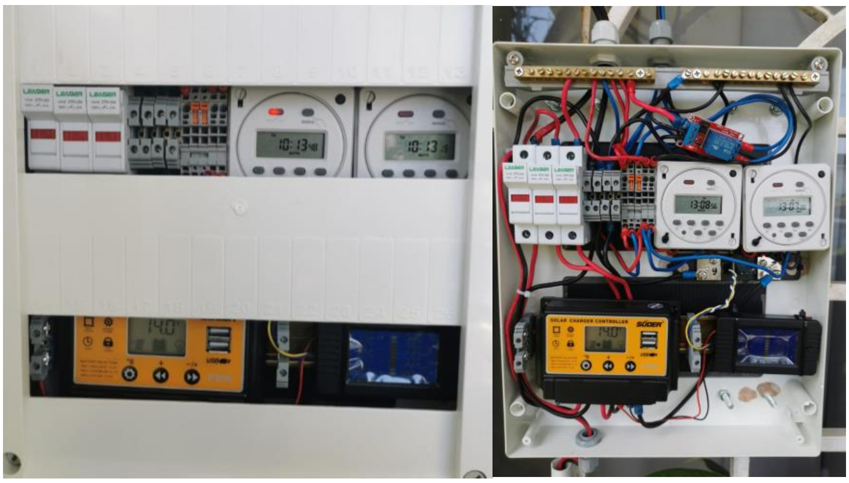


Figure 3.8: Control Panel

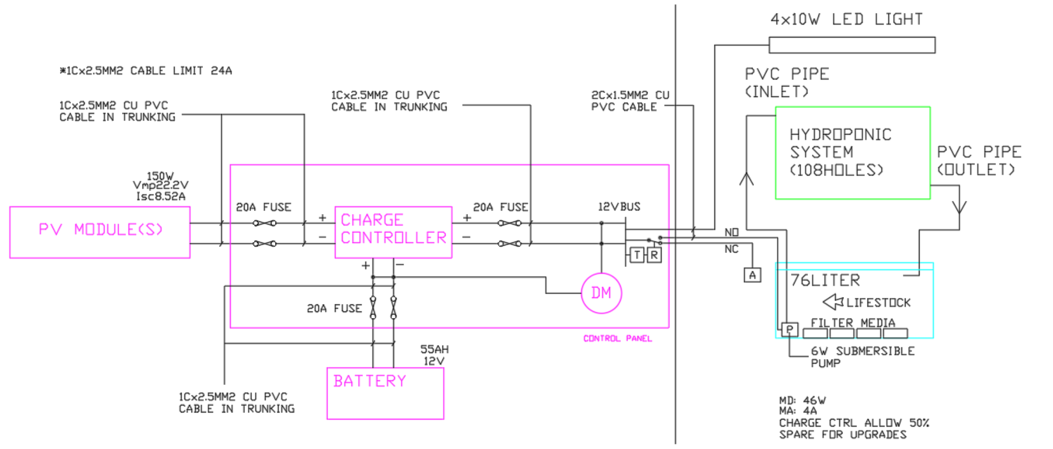


Figure 3.9: Single line diagram

For comparison purpose, a soil-based planter in Figure 3.10 was setup in order to establish basic base data for comparison purpose. A tray of 45 cm × 50 cm was filled and levelled evenly with a bag of mixed soil of 10 kg. Planting tray was used for better control of the experiment as it was easier to protect against the elements. 30 sprouts of the butterhead lettuce were planted around 2 to 3 inches apart. The lettuce sprouts were planted on the aquaponic system and the soil-based planter on the same day for sake of achieving consistency in the experiment in term of weather, ambience temperature, humidity etc. 1200 ml of tap water has been used to water the planted lettuce on daily basis. 42 grams of chemical fertilizer has been used to fertilize the vegetables grown on soil over the experiment period, measured according to the manufacturer's instructions.

Figure 3.10: Soil-based planter (Reference)

3.2.1 PV System Sizing Calculations

Table 3.1: Power Consumption & Design Parameters

A. Maximum Demand Estimation & Consumption Calculation							
Item	Major Equipment	Qty (set)	Rated Power Watt, (W)	Demand Watt, (W)	Usage Hrs	Wh/day	Remark
i	Submersible Pump	1	6.00	6.00	12	72	12 hours running, 12 hours stop hourly interval per day
ii	Mini Air Pump	1	4.40	4.40	12	52.8	Continue to maintain air exchange when pump is off.
iii	Lighting	4	10.0	40.00	4	160	4 hours minimum to compensate loss of light at shaded area.
						284.8	

A1	Total Energy Demand per day, Wh	284.80
A2	Total Amp-Hour per day	23.73
A3	Battery Bus Voltage, V	12.00

Major devices in this system as shown in Table 3.1 consist of a submersible pump for water circulation which will be run for 12 hours, a mini air pump of 4.4 W which will be run for 12 hours and 4 × 10 W LED light which will be turned on 4 hours a day. Daily power consumption was identified to be 284.80 Wh per day, equivalent to 36.63 AH, the bus voltage of the system is 12 V all the selected equipment/devices are 12 V.

Table 3.2: Battery Sizing Calculation

B. Battery Sizing				
Item	**Description**	**Unit**	**Qty**	**Remark**
1	Days Required	day(s)	1	
2a	Allowable depth of discharge	%	80	
2b	DC Charger Efficiency	%	90	
2c	Battery Round Trip Efficiency	%	90	
3	Required Battery Capacity	AH	36.63	A3 × B1 / B2
4	Selection Battery Capacities	AH	55	user input
5	Selected Battery Voltage	V	12	user input
6	Batteries in Parallel	no(s)	1	B.3 / B.4, (rounded)
7	Batteries in Series	no(s)	1	Bus Voltage / Selected Battery Voltage, (rounded)

Table 3.2 shows the battery sizing calculation for the system after identifying the daily consumption. Eqn. (8) to eqn. (10) used is described in Section 2.3.2 and Section 2.3.5, where the capacity needed for the battery is calculated to include losses and day(s) of backup; 1 day in this case. Selection of battery is based on market available capacities, in this case 55 AH, 12 V battery is selected. Meaning when PV system is disconnected or during very gloomy day, the fully charged battery can run the system for whole day and 36.63 AH, 67.0 % of the battery will be discharged to achieve this. The average daily DoD can be seen in Table 3.3 where 35% of DoD is calculated which is acceptable considering the battery used is a deep cycle battery.

Table 3.3: Average Daily DoD of Battery

Item	**Description**	**Unit**	**Qty**	**Remark**
1	Total pieces of battery	no(s)	1	
2	Total AH	AH	55.00	
3	Total Battery kWh	kWh	0.660	
4	Average daily depth of discharge	%	35%	0.80 × AH required / Actual AH, 35% of system power is supply by battery while the rest is fully by PV (peak).

Table 3.4: PV Panel Sizing

C. PV Sizing				
Item	**Description**	**Unit**	**Qty**	**Remark**
1	Total Energy Demand per day	Wh/day	285	From Above (A1)
2a	Battery Round Trip Efficiency	%	90	
2b	Charger Efficiency	%	90	
2c	PV Module Performance Ratio	%	83	*Note: Different from PV efficiency
2d	PV Module Performance to temperature	%	80	Assume 80%
3	Required Array Output per day	Wh	529.53	
4a	Selected PV Vmp @ STC	V	22.20	Selected 150W PV Module. Vmp & Imp as advertised
4b	Selected PV Imp @ STC	A	8.52	"
6	Guaranteed Power output from Selected PV Module	W	102	Vmp × Imp × Eff; refer catalogue/spec. (4a × 4b × 2a × 2b × 2c)
7	Peak sun hours for design	hrs	4	For fixed panels in Malaysia
8	Energy output per module per day	Wh	407	C6 × C7
10	Pieces of module required	piece	1.30	C3 / C8
11	Number of Strings in parellel	number	1.00	Bus voltage or output voltage / 4a × 2c (to be rounded up)
12	Total PV module required	piece	2.00	Rounded up

From eqn. (1) to eqn. (7) described in Section 2.3.2, the output required from the PV is 469.26 Wh taking consideration of losses. 150 W panel is selected to generate the required power. The PSH in Malaysia is usually 4 hours and after considering the losses occurs on the PV module, the PV module is only able to generate a calculated of 407 Wh per day. By calculation 2 numbers of 150 W PV panel will be required. However, practically, the chances of full day without sun in Malaysia is very small, hence only 1 no. 150 W panel is installed as it can supply majority of the needed power, and the battery capacity is larger than required hence back up of the system in worst case scenario is still achievable. The calculated values are shown in Table 3.4.

3.3 Measurements, Data Collection & Observations

3.3.1 Optical Measurement on Quality

The optical properties of vegetables and yield is measured to determine the quality and effectiveness of planting method. Height and span of the plants were measured and average out during transplant of sprout to serve as base data. Final total weight of crops from both soil-based planting and aquaponic method is measured to compare the yield. Comparison was conducted during the end of the experiment to differentiate the results of different planting method. Table 3.5 shows the collected data. The new sprouts were measured with average span and height of respectively 0.75 cm and 0.5 cm. The weight is set to be 0 gram (due to very small value) to ease the study can calculations.

Table 3.5: Optical Measurement

Item	Description	Sprout				Mature /Harvest			
		Qty	Ave. Span (cm)	Ave. Height (cm)	Weight (g)	*Ave. Span (cm)	*Ave. Height (cm)	Total Weight (g)	Colour
1	Baseline	22	0.75	0.5	0	20	21	**703	Vibrant Green
2	Layer 1	30	0.75	0.5	0	14	16	900	Light Green
3	Layer 2	30	0.75	0.5	0	11	14	846	Light Green
4	Layer 3	30	0.75	0.5	0	13	15	787	Light Green

Note:

* The measurement is for average for single plant.

** Weighted for 22 plants only. Others perished during experiment.

It is worth to note that the first soil-based planter failed due to constant rain. Crops were damaged because of rain drops and roots were rotted due to water saturated soil. There were also lack of sunlight for plant growth during rainy season. Therefore, the subsequent planter was covered with mesh and moved to shelter during rain for the sake of obtaining experiment data. Weed were also observed to grow in the planter. The mesh also served as protection against animals like cats, birds etc. and pest insects. Data collected after 45 days are shown in Table 3.5. 22 plants in the reference planter were measured, 30 plants on each layer; total of 90 plants on the aquaponic system were measured. The measured values for average span and height of the plants in layer 2, and layer 3 are larger than of layer 1. However, the total weight of plants in layer 1 is higher. All plants in the 3 layers are visually lighter in colour. Generally, the plants in the reference planter are better in term of span and height, however the total plants weight is less than total plants weight in the aquaponic system.

Figure 3.11 shows the plants measured in the reference planter, whereas measured plants on aquaponic is shown in Figure 3.12.

Figure 3.11: Results (Reference)

Figure 3.12: Results (PV

3.3.2 Photosynthetically Active Radiation (PAR) Measurements

PAR value of the three layers of aquaponic setup were measured. The values are as tabulated in Table 3.6. Under direct sun, the PAR obviously is plentiful, measured around 3000 µmol/ m^2/ s and DLI is more than 100 mol/ m^2/ day. In comparison, for the shaded aquaponic system, layer 1 is measured with 150 µmol/m^2/s and 6.5 mol/ m^2/ day, layer 2 with 19 µmol/m^2/s and 0.8 mol/ m^2/ day, layer 3 with 16 µmol/ m^2/ s and 0.7 mol/ m^2/ day. With the assist of 2 × 10W LED light at layer 2 and layer 3, they are both measured with 110 µmol/ m^2/ s and 4.8 mol/ m^2/ day, and 104 µmol/ m^2/ s and 4.5 mol/ m^2/ day.

Table 3.6: PPFD and DLI Values

Item	Description	Measurement location	Time	PAR (PPFD - µmol/m^2/s)	DLI mol/m^2/d (12hr)
1	Direct Sun	Exterior	12 pm	3073	>100
2	Indirect Sun	Aq-Layer 1	12 pm	150	6.5
3	Indirect Sun	Aq-Layer 2	12 pm	19	0.8
4	Indirect Sun	Aq-Layer 3	12 pm	16	0.7
5	Indirect Sun+LED	Aq-Layer 2	12 pm	110	4.8
6	Indirect Sun+LED	Aq-Layer 3	12 pm	104	4.5

3.3.3 Electrical Consumption

Actual electrical consumption (kWh) from the day of transplant was being collected from the digital meter until the end of experiment to verify the estimated consumption. From calculation, the system should consume around 284.8 W daily and 12.8 kWh for 45 days.

The actual consumption recorded from power meter is as shown in Table 3.7. The actual electrical consumption is actually around 4.5%, higher than the calculated consumption. This may be due to the rated power of the equipment is different in actual, or affected due to ambient temperature with higher losses. Therefore, the total consumption for 45 days is 13.39 kWh or 8.9 kWh per month or 108 kWh annually.

Table 3.7: Actual Electrical Consumption

Item	Description	Ave. Power, W	Operation Hour	Consumption, Wh
1	LED Lighting	41.02	4	164.08
2	Air Pump only	4.62	12	55.44
3	Sub. Pump only	6.51	12	78.12
			Total Wh/Day	297.64

3.3.4 Operation and Maintenance Cost

Table 3.8 and Table 3.9 show the operation and maintenance cost for both PV aquaponic and aquaponic without PV panel.

Table 3.8: PV Aquaponic Operation & Maintenance Cost

Item	Description	Unit	Qty	Monthly Rate (RM)	Monthly Amount (RM)	Remark
1	Liquid Fertilizer	ml	70	0.065	4.55	35 ml per water change for 70L tank
2	Fish food	ls	1	6.00	6.00	500 g pack a month
3	Water	m3	0.028	0.57	0.016	14 liter (20%) per change, twice monthly
				Total	10.60	

Table 3.9: Aquaponic Operation & Maintenance Cost

Item	Description	Unit	Qty	Monthly Rate (RM)	Monthly Amount (RM)	Remark
1	Liquid Fertilizer	ml	70	0.065	4.55	35 ml per water change for 70L tank
2	Fish food	ls	1	6.00	6.00	500 g pack a month
3	Water	m3	0.028	0.57	0.016	14 liter (20%) per change, twice monthly
4	Electricity	kWh	8.9	0.218	1.94	
				Total	12.51	

Liquid fertilizer is added with each water change with reduced amount to make up for missing nutrients from fish waste. Which is around 70 ml, or around RM 5 a month. A 600 grams pack of fish food pellet can last for 3 months, which translate to RM 6 in a month. Water supply used in the system is around 28 liters or ~RM 0.02 in a month, mainly from water changes. Lastly, it shows that the difference in electricity used is RM 12.38 monthly and RM 153.96 yearly.

CHAPTER 4.0

RESULTS AND ANALYSIS

4.1 Physical Appearance

The physical appearance in general helps to identify the quality of crops. From data collected and observation it appears that the crops grown on soil grows in size consistently while it is less consistent in the shaded aquaponic system. The crops grown on soil is greener in colour than those in aquaponic. This may be due to the system is shaded and inconsistent in fertilizer flow in the water.

The total weight of harvest in aquaponic is actually 22.00 %, 17.00 %, and 11 % more for layer 1, layer 2, and layer 3 respectively as compared to the baseline. This is because only 22 plants survive in the reference planter whereas all 30 plants survived on the aquaponic system. This shows that the mortality rate of soil planting/ conventional planting is higher due to affects from the elements. However, the individual weight of plant is actually smaller compared to baseline is -6.25 %, -11.87 %, and -18.03 % for layer 1, layer 2, and layer 3 respectively. The average weight gain also are slower than baseline. Data are summarized in Table 4.1.

It is observed that the span and height values of plants in layer 2 and layer 3 on aquaponic are actually higher than that of layer 1. This is due to the lack of lighting comparatively, which cause the elongation of plants, trying to reach for better lighting. Although the span and height in layer 1 is lesser than those in layer 2 and layer 3, they are more compact, with more leaves and overall heavier, therefore higher in quality. Also, it would appear that the quality of crops in layer 1 is more consistent and better than layer 2 and layer 3. The mentioned differences are not significant. Therefore, the lighting installed to supplement the crops in layer 2 and layer 3 actually does helped in the growth of the crops to a certain degree.

All plants failed to reach the expected maturity in 45 days as mentioned in seed packager’s instructions. This might be due to factors such as temperature, humidity, soil quality and lighting as it has been raining quite extensively during the course of the experiment which was the main reason that caused some plants in the baseline planter to perish. According to (Gilmour, 2023) lettuce can take up to 30 days to 70 days and subject to factors mentioned. However due to time constraint and timing, the experiment could not be extended. It is anticipated that the growth of plants will be faster during sunny seasons.

Table 4.1: Physical Analysis

Item	Descrip.	Average Value					
		Qty	**Growth in Span (cm/day)**	**Growth in Height (cm/day)**	**Average Weight (g)**	**Average Weight Gain (g/day)**	**Difference in Weight (%)**
1	Baseline	22	0.45	0.45	32.00	0.71	-
2	Layer 1	30	0.29	0.34	30.00	0.66	7.00
3	Layer 2	30	0.23	0.30	28.20	0.62	12.67
4	Layer 3	30	0.27	0.32	26.23	0.58	18.30

4.2 Lighting Levels

Table 4.2: Baseline for Aquaponic Lighting (GrowPackage, 2021)

Item	Description	PPFD - μmol/m^2/s	DLI mol/m^2/d (12hr)
1	Microgreens	>150	>6
2	Leafy Vegetables	>150	>6
3	Flowering Vegetables	>200	>9

Table 4.3: PAR and DLI Values Analysis

Item	Description	Measurement location	Time	PPFD - μmol/m^2/s	DLI mol/m^2/d (12hr)	Compared to Layer 1
1	Direct Sun	Exterior	12pm	3073	>100	-
2	**Indirect Sun**	**Aq-Layer 1**	**12pm**	**150**	**6.5**	**-**
3	Indirect Sun	Aq-Layer 2	12pm	19	0.8	-
4	Indirect Sun	Aq-Layer 3	12pm	16	0.7	-
5	**Indirect Sun+LED**	**Aq-Layer 2**	**12pm**	**110**	**4.8**	**-26.67%**
6	**Indirect Sun+LED**	**Aq-Layer 3**	**12pm**	**104**	**4.5**	**-30.67%**

Based on the results of the physical/optical measurement and PAR values measured. Summarized comparison was made with the recommended lighting data from GrowPackage as shown in Table 4.2. Based on the guideline, it would appear that the lighting for layer 2 and layer 3 was lacking as shown in Table 4.3. For layer 2 and layer 3; item 5 and item 6 the lighting even with added LED are 27 % and 31 % lesser than the minimum baseline as in layer 1. Therefore, this explains why the crops are less ideal and leaves elongated as compared to those at layer 1. All 3 layers can be used to grow vegetables however it may take longer for them to grow to mature. To improve the quality of crops, the design or construction of the aquaponic planters may need to be reviewed.

4.3 System Cost, Maintenance, Net Present Value (NPV) and Levelized Cost of Energy (LCOE)

4.3.1 System Cost

The component-list and cost for the system is tabulated in Table 4.4 and Table 4.5. The Total System Cost is **RM 1,782**.

Table 4.4: PV System Component-list

Item	Description	Unit	Qty	Rate (RM)	Amount (RM)
1	Battery 55 AH, 12 V	piece	1	461	461
2	PV 150 W, 22.2 V, 8A	piece	1	402	402
3	30 A PWM Charge Controller	set	1	64	64
4	20 A Fuse Holder	set	3	20	59
5	20 A Fuse	set	3	10	29
6	PV Mounting Brackets	lot	2	29	59
7	PV Cable Connectors	sets	1	10	10
8	Digital Power Meter	set	1	63	63
9	Panel & Other Accessories	set	1	150	150
10	2 × 1C 2.5 mm^2 PVC PV Cabling	m	12	5.8	70
11	Mounting Accessories	ls	1	25	25
12	Timer	set	2	22	44
				Total	1,435

Note: Price as of December 2022.

Table 4.5: Aquaponic System component-list

Item	Description	Unit	Qty	Rate (RM)	Amount (RM)
1	PVC Planter Rack	set	1	175	175
2	Filter media	bags	2	16	32
3	Fishes	number	10	4	40
4	Container	number	1	30	30
5	Lighting 10 W	set	4	10	40
6	DC Pump 8 W	set	1	20	20
7	Air Pump 4.4 W	set	1	10	10
				Total	347

Note: Price as of December 2022.

4.3.2 Maintenance Cost

From Section 3.3.4 the maintenance costs are rounded and summarized as Table 4.6. The system saves RM 2 in a month and **RM 24 a year**.

Table 4.6: Summary of Maintenance Cost

Item	Description	Amount per Month (RM)	Amount per Year (RM)
1	Aquaponic System	13	156
2	PV Aquaponic System	11	132
3	Difference / Saving	2	24
4	Difference / Saving (%)	15 %	

4.3.3 Harvest Pay-Offs

Assuming general leafy vegetables take maximum duration 70 days to get to maturity under ideal weather condition, which is a safe assumption, as it takes generally around that duration or less, for typical tropical-suited leafy vegetables to reach maturity, such as:

<u>Maturity period for various leafy vegetables</u>

Lettuce: 40 to 70 days, Spinach: 37 to 45 days, Kailan (Kale): 55 to 75 days, Bok Choi: 45 to 60 days.

For comparison purpose, it is generalized by assuming that the vegetables grown are harvested in rotation method, where 30 stems of vegetables can be harvested from layer 1 of the system after 70 days and subsequent 30 stems after 15 days from layer 2 and so on until layer 3, therefore 90 stems of vegetables can be harvested in 100 days. Hence, in average 27 of vegetables can be harvested in a month. Assuming each plant reaches maturity around 100 grams. In term of monetary, it will be **RM 70.2 per month** according to market rates; average of RM 0.026 per gram from local hypermarket. Which calculates to **RM 842.4 a year**.

<u>Price of various organic vegetables</u>
Kailan = 0.022 per gram, Butterhead = 0.034 per gram, Spinach = 0.023 per gram, Bok Choi = 0.023 per gram (Jaya Grocer, 2023)
*Price valid at the time of this report

However, the actual results from the experiment did not achieve the baseline. According to the growth rate, it would likely require 180 days for the crops to reach maturity. Therefore only 15 stems of vegetables can be harvested in a month. Therefore, average of **RM 39 per month of return** is calculated or **RM 468 a year**.

4.3.4 Net Present Value (NPV)

According to calculated values from previous sections. NPV is calculated with:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \qquad (11)$$

Where, Co is the initial investment value, Ct is the annual cash flow, r is the discounted value, T is years of analysis

Initial Investment = RM 1,782

Initial Investment for recommended system = RM 2,000

Annual Cash Flows = Return from Harvest - Yearly Maintenance Cost

Discounted Rate = Assumed 6%

*Note: It is assumed major system maintenance is not necessary assuming typical PV panel lifespan is about 25 years.

Table 4.7: Summary of Net Present Values and Breakeven Period

.Items	Description	Years of Analysis	Annual Cash Flow, Ct	NPV
1	Ref 1: Grid Powered Aquaponic with Baseline/Target Yield	3	686	49
2	Ref 2: Solar Powered Aquaponic with Baseline/Target Yield	3	710	109
3	Grid Powered Aquaponic with Actual Results	8	312	147
4	Solar Powered Aquaponic with Actual Results	7	336	88
5	Recommended Solar Powered Aquaponic System with Target Yield	4	710	434

From Table 4.7, it is observed that there is minor difference in NPV whether if the system is grid powered or solar powered. The results in Item 1 and Item 2 compared to Item 3 and Item 4 respectively indicates that the time difference to breakeven is 1 year earlier, if PV is integrated. It also shows that the yield of crops grown is important to decrease the breakeven time to 3 years.

However, due to the result of the experiment, it is recommended to enhance the system to a 300 W PV system with additional lighting up total to 80 W, making total consumption to 160 kWh annually. The enhancement will assist in producing the yield within the expected time. The early investment is increased to RM 2,000 and the breakeven period is about 4 years as shown in Item 5 the Table 4.7. Calculation of the system can be referred to at the next section.

4.3.5 Recommended PV Aquaponic System with Target Yield

As briefly mentioned in previous section, analysis and data collected in Table 4.3. The main issue affecting the system appears to be the lack of lighting especially at layer 2 and 3 of the setup. Therefore, by doubling the Wattage of the lighting, it is possible to increase the PAR level to close to minimum of 150 µmol /m^2 /s for all layers thus hasten the growth of all vegetables of the two layers which are lacking behind in growth, ideally improving the yield quantity and shorten the yield period according to the expected maturity period.

Table 4.8: Revised Maximum Demand and Electrical Consumption Calculation

A. Maximum Demand Estimation & Consumption Calculation							
Item	Major Equipment	Qty (pc)	Rated Power Watt, (W)	Demand Watt, (W)	Usage Hrs	Wh/day	Remark
i	Submersible Pump	1	6.00	6.00	12	72	12 hours running, 12 hours stop hourly interval per day
ii	Mini Air Pump	1	4.40	4.40	12	52.8	Continue to maintain air exchange when pump is off.
iii	Lighting	4	10.0	80.00	8	320	4 hours minimum to compensate loss of light at shaded area.
						444.8	

A1	Total Energy Demand per day, Wh	284.80
A2	Total Amp-Hour per day	37.07
A3	Battery Bus Voltage, V	12.00

The daily demand is calculated in Table 4.8 with revised electrical consumption of 444.8 Wh daily or 13.3 kWh monthly or 160 kWh annually.

Table 4.9: Revised Battery Sizing Calculation

B. Battery Sizing				
Item	**Description**	**Unit**	**Qty**	**Remark**
1	Days Required	day(s)	1	
2a	Allowable depth of discharge	%	80	
2b	DC Charger Efficiency	%	90	
2c	Battery Round Trip Efficiency	%	90	
3	Required Battery Capacity	AH	57.20	A3 × B1 / B2
4	Selection Battery Capacities	AH	55	user input
5	Selected Battery Voltage	V	12	user input
6	Batteries in Parallel	set	2	B.3 / B.4, (rounded)
7	Batteries in Series	set	1	Bus Voltage / Selected Battery Voltage, (rounded)

The calculation based on Table 4.9 shows that 2 batteries are required. However as discussed previously, it is impractical to assume total black out from the sun and 100% reliant on the battery considering Malaysia climate, therefore the battery is not upgraded.

Table 4.10: Revised Average DoD per day

Item	Description	Unit	Qty	Remark
1	Total pieces of batteries	set	1	
2	Total AH	AH	55.00	
3	Total Battery kWh	kWh	0.660	
4	Average daily depth of discharge	%	54%	0.80 × AH required / Actual AH, 54% of system power is supply by battery while the rest is fully by PV (peak).

In Table 4.10 the average daily DoD now is 54% which is still acceptable. This means more electrical power is required from the PV panel(s) to charge up the battery. Thus, the calculation is shown in Table 4.11.

Table 4.11: Revised PV Panel Sizing Calculation

C. PV Sizing				
Item	**Description**	**Unit**	**Qty**	**Remark**
1	Total Energy Demand per day	Wh/day	285	From Above (A1)
2a	Battery Round Trip Efficiency	%	90	
2b	Charger Efficiency	%	90	
2c	PV Module Performance Ratio	%	83	*Note: Different from PV efficiency
2d	PV Module Performance to temperature	%	80	Assume 80%
3	Required Array Output per day	Wh	827	
4a	Selected PV Vmp @ STC	V	22.20	Selected 150W PV Module. Vmp & Imp as advertised
4b	Selected PV Imp @ STC	A	8.52	"
6	Guaranteed Power output from Selected PV Module	W	102	Vmp × Imp × Eff; refer catalogue/spec. (4a × 4b × 2a × 2b × 2c)
7	Peak sun hours for design	hrs	4	For fixed panels in Malaysia

8	Energy output per module per day	Wh	407	C6 × C7
10	Pieces of module required	pc	2.03	C3 / C8
11	Number of Strings in parallel	number	1.00	Bus voltage or output voltage / 4a × 2c (to be rounded up)
12	Total PV module required	pc	3.00	Rounded up

In Table 4.11, 3 numbers of 150 W PV panels are calculated from the rounded-up value however the required panels required are slightly over 2, so 2 numbers of PV panels are used considering the minor difference. Alternatively, 1 number of 300 W PV panel can be used.

4.3.6 Levelized Cost of Energy (LCOE)

The LCOE is calculated by eqn. (12) where the numerator is the NPV of the system lifespan as in eqn. (11) and denominator total generated power during the period. A_k is the annual cash flow for years of analysis k, I_o is the initial investment, M_k is the energy generated in years k, i_r is the discounted rate.

$$LCOE = \frac{I_0 + \sum_{k=1}^{n} \frac{A_k}{(1+i_r)^k}}{\sum_{k=1}^{n} \frac{M_{k,el}}{(1+i_r)^k}} \quad \text{---(12)}$$

Assuming the discounted rate i_r is 6%. the amount calculated for 25 years NPV, power generated and LCOE for the cases below are:

Table 4.12: Summary of LCOE Calculated

Items	Description	Years of Analysis	System Cost, (RM)	Yield (RM)	Annual Cash Flow, Ct (RM)	Energy fr. PV (kWh/yr)	LCOE (RM/kWh)
1	Solar Powered Aquaponic with Baseline/Target Yield	25	1,782	842	710	108	5.29

2	Solar Powered Aquaponic with Exp. Results	25	1,782	468	336	108	1.82
3	Recommended Solar Powered Aquaponic System with Target Yield	25	2,000	842	710	108	3.46

The calculated LCOE the first case shows the best results with highest return per kWh generated from the PV system, follows by the recommended system in item 3. Even when the system producing half of the expected yield, it could still produce RM 1.82 per kWh as in item 2. They are higher compared to TNB domestic tariff rate of RM 0.218 – RM 0.571.

As mentioned in problem statement, there is no record of similar studies. Therefore, the LCOE calculated here can be used as reference or comparison for future studies or enhancement on similar installations or applications.

CHAPTER 5.0

DISCUSSION & CONCLUSION

From the results of the study and experiment, it appears that the small-scaled PV Aquaponic System as domestic self-sustaining system to assist in food security is plausible. The experimental model was only able to produce 55 % of the expected yield, it is likely due to the effects of the unprecedented weather with gloomy and rainy days or due unsuitable climate for the selected vegetable. This is deduced from the crops grown in the reference planter. The difference in average weight of individual plant size as compared to an aquaponic system is small. In fact, based on the data, if continuously affected by bad weather, the yield from the reference planter will be much worse than that on aquaponic system. This demonstrated the advantage and purpose of the system. Therefore, it is deduced that the system should work as expected under better weather condition, selection of suitable plants and minor upgrades. Based estimated calculation based on the data and improved theoretical model, the system is able to produce RM 842 worth of vegetables annually.

Initial cost of the system is calculated to be less than RM 2,000.00 and maintenance cost yearly is RM 132.00 annually. Compared to a grid-connected system, the energy saving aspect is not significant this is because only little equipment is used in the system and the electrical load of the system is small. Unlike commercial hydroponic/aquaponic farming that required more and bigger capacity pumps, high power lighting and other equipment. Consideration into the operation and load profile is essential to reduce the daily consumption of the system. 3 to 4 years of breakeven period based on NPV calculated was calculated according to the upgraded system based on data and theoretical model. The LCOE calculated indicates that for every kWh generation from the system the owner actually gaining RM 3.46. Comparatively the residential tariff rate of local electricity provider TNB is RM 0.218/ kWh, if the system is connected to the grid. The key to decrease the breakeven period and increase the LCOE value is to reduce the cost of the system and increase the yield.

In terms of pros and cons, besides those mentioned in the literature review, due to the relatively low-cost, small-scaled system compared to commercial setup, it is suitable and affordable for individuals or families that wish to invest into the system for long-term cost saving, self-sufficient and to able to enjoy self-grown organic vegetables. The grown vegetables can be self-consumed or sold. For general estimation purpose, the system with similar design needs 0.11 W of PV capacity for every gram of vegetable produced. The largest weakness of the system is that it is restricted to the orientation of the setup and the planter design. As indicated by study from (Sengodan, 2022), North-South orientation may not receive adequate sun light for proper plant growth. East-west orientation would be most ideal for the system. Even so, as seen in the experiment, the plants grown do not lack behind very much compared to the plants grown as control; planter placed on flat ground without obstruction from sun light. The difference is considered acceptable especially on layer 1 of the aquaponic setup, which receive most of the sunlight. Landed houses owners with yard may have better options as to where to place the setup, however it is worst for apartment or condominium owners which is limited mostly to the balcony. Hence, options of plants are limited and selection of plants is important. Another problem faced by condominium and apartment owners is that there are limited space options to mount any PV panels except on the roof top. Therefore, it is very difficult to implement in existing high-rise building. For retrofitting buildings and new buildings, solar panels can be installed at the roof top to provide power to the systems.

It is reported that there are increasingly more high-rise building including residential building being fitting with PV panels (Bellini, 2021). Developers in support of government policy for clean energy and sustainability usually include sustainability into building design with the help of green building certification requirements tools such as Green Building Index (GBI) certification tool as a guideline. These certifications are based on scoring system, and the points are not all equally weighted in term of cost effort. Due to the initial cost to implement renewable energy like solar panel, and budget constraint in residential projects, the installation is usually being avoided to allocate cost to score other points that are easier to score and less expensive. Naturally, some developers may only willing to install minimum provision to score points related to green technology including PV panels as last resort to gain enough points to gain the green certification. Or when they have no choice as the installation is required by development order by local council.

As means of encouragement to score these points, developers may propose and try to score additional innovation point by investing a little more into provisional infrastructure cabling and proper space planning for provisional space to allow future solar panel installation requested by residence, to allow installation of aquaponic system by residence or other self-consumption purpose. It is economically impractical to have developer to bare full cost for the system, due to high initial cost. Alternatively, developers can design herb gardens or vegetation garden at roof top with aquaponics as common facility and slightly increase capacity of PV system to power the system. Herb gardens and vegetation gardens build on roof top have more advantage than installation at balconies because exposure to sunlight is much better. With careful design and planning as suggested above, developer can potentially increase the worth of the points scored in the green certification. In addition, developer also may discuss and explore with manufacturers or supplier on the use of Grade B solar panels instead of Grade A solar panels to reduce the cost of the system since there seem to have no significant difference in performance and life expectancy between the two grades.

From the above discussion, it is concluded that the objectives of this study have been achieved. Nevertheless, some aspects in the experiment are recommended to be taken into consideration to streamline future studies. First, it is recommended to upgrade the system with additional lighting with PV system capacity to 300 W, as in Section 4.3.4 to improve the system to better sustain plant growth during bad weather and accelerate growth in general. Secondly, because the current study used only one type of crop in the experiment, it is recommended to expand the experiment by including different leafy vegetables and/or different categories such as microgreens, and flowering vegetables, and extend the experimental period longer, for more conclusive information. Proper plants selections can be recommended as not all plants are resilient to high temperatures and sun ray (Sengodan, 2022). Thirdly, plants also should be selected based on their respected minimum PAR level and planted depending on PAR levels measures at the respective planters. This way, extra lighting can likely be avoided because from the evaluation we can see that the major load in the system actually comes from lightings. Using the experimental setup as example, layer 1 can be planted with leafy vegetables, layer 2 and layer 3 can be planted with microgreens, this may hasten and increase the yield from harvest while maintaining the system cost without upgrades. Those North-South oriented setup can grow microgreens instead of large leafy vegetables or fruits. Fifth different farmable fish or prawns for small-scale aquaponic system can be explored in future study to maximize the system's potential.

Sixth, because the system is intent to be used by homeowners, labour cost was not included in calculation of breakeven period and LCOE. For larger system or when the system is being used for commercial purpose it is recommended to include labour cost as more time and effort is being invest into the installation and maintenance. Seventh, the system consists of different aspect from engineering and agriculture, it is recommended for joint studies from respected disciplines for future related studies, including experts in lighting, electrical, agriculture and/or perhaps chemistry to fully optimist the system and provide a more comprehensive study. Lastly, it is suggested to conduct similar studies during period with better weathers according to Malaysia climate rainfall data. In Kuala Lumpur as per Figure 5.1 it is around June to August of the year. Because the climate may affect the experimental results. Due to lack of time and resources in current experiment the orientation and tilt angle of the PV panel were based on general practice. It is recommended to better optimist the PV panel output with best orientation and pitch angle based on onsite solar irradiation with the use of irradiation meter. Additional electrical power meter can be installed after the PV panel(s) to measure the electrical power profile and total electrical power converted from solar energy, in order to determine the full load capacity of the system.

Kuala Lumpur - Average precipitation			
Month	**Millimeters**	**Inches**	**Days**
January	170	6.7	11
February	165	6.5	12
March	240	9.4	14
April	260	10.2	16
May	205	8.1	13
June	125	4.9	9
July	125	4.9	10
August	155	6.1	11
September	195	7.7	13
October	255	10	16
November	290	11.4	18
December	245	9.6	15
Year	2425	95.5	158

Figure 5.1: Climate in Kuala Lumpur (Climates To Travel, n.d.)

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Appendix A

1. Battery Controller

SUOER ST-S1230 SOLAR PANEL CONTROLLER WITH DUAL PORT 12V/24V 30A MPPT/PWM AUTO PARAMETER, ADJUSTABLE

1) Description:

- 12v/24v 20A controller / 12v/24v 30A controller
- It can automatically recognize 12V or 24V, Lead acid and Gel battery.
- Maximum Solar Watt for 30A: 12V 300 - 450W; 24V 300 - 450W
- Maximum Solar Watt for 20A: 12V 200 - 350W; 24V 200 - 350W
- USB Output: 5V3A 3) Features:
- Build-in industrial micro controller.
- Big LCD display with adjustable parameter. - Fully 4-stage PWM charge management. - Build-in short-circuit protection, open-circuit protection, reverse protection, over-load protection. - Dual mosfet Reverse current protection ,low heat production.

2) Product Specification: *Model : ST-S1230

- System Voltage : 12V/24V
- Max input voltage : <50V - Rated current : 30A
- MN External 12V Battery : 300-450W / 18V
- External 24V Battery : 300-450W / 36V
- External Battery : 12V/24V 100-150Ah
- Battery type : Li-iron phosphate battery 4 series 3.2V = 12.8V
- Charging voltage 14.6V

- Low voltage cut-off voltage : 10V
- Low power recovery voltage : 12V - USB output : 5V/2A

3) Package Information:
- Nett Weight : 130 g +-
- Gross Weight : 155 g +-
- Size / Weight : 125*86*34 mm / 200 g

2. PV Panel

SW180M-36

Monocrystalline 36 Cells 150W-180W

Mono Solar Panel Features

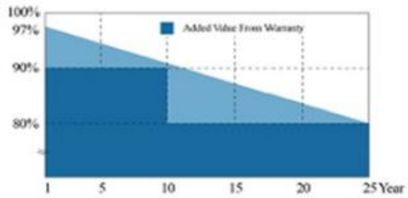
- Widely using of the most popular and mature type of modules for solar system
- High power output and highest conversion efficien-cy of 18.08%
- Anti-reflective and anti-soiling surface reduces power loss from dirt and dust
- Outstanding Performance in low-light irradiance en-vironments
- Excellent mechanical load resistance: Certified to withstand high wind loads (2400Pa) and Snow loads(5400Pa)
- Positive power tolerance: 0~+5W

Warranty

- 12 years for product defects in materials & workmanship
- 10 years for 90% of warranted minimum power output
- 25 years for 80% of warranted minimum power output
- 25 years liner warranty

Reliable Quality

- Positive power tolerance: 0~+5W
- 100% EL Double-inspection ensures modules are defects free
- Modules Binned by Current to improve system performance
- Potential induced Degradation (PID) Resistant



Electrical Parameters

Module	SW150M-36 ~ SW180M-36			
Encapsulation	Class/Eva/Cell/Eva/Backsheet			
Maximum Power Pmax (W)	150	160	170	180
Maximum Power Voltage (Vmp/V)	18.50	18.70	18.85	18.95
Maximum Power Current (Imp/A)	8.11	8.56	9.02	9.50
Open Circuit Voltage (Voc/V)	22.20	22.44	22.62	22.74
Short Circuit Current (Isc/A)	8.52	8.98	9.47	9.98
Cell Efficiency(%)	17.78	18.30	18.68	19.18
Module Efficiency (%)	15.07	16.06	17.06	18.08
Power Tolerance (W)	0 ~ +5W			
Temperature Coefficient of Isc (αIsc)	+0.059%/℃			
Temperature Coefficient of Voc (βVoc)	-0.330%/℃			
Temperature Coefficient of Pmax (γPmp)	-0.410%/℃			
STC	Irradiance 1000W/㎡, Cell Temperature 25℃, Air Mass 1.5			

3. 12V DC Battery

M-B ULTRA 6V &12V RANGE

AGM

The new improved technology gained from years of experience of manufacturing Sealed VRLA batteries PLUS the introduction of new design high capacity plates makes the M-B ULTRA ideally suitable for DC standby applications requiring long and reliable back-up DC supply, as well as for high discharge current for short periods. Moreover the new thicker plates are designed specifically to provide a longer lifespan and also improved cycling abilities making this battery suitable for various applications including telecommunications standby.

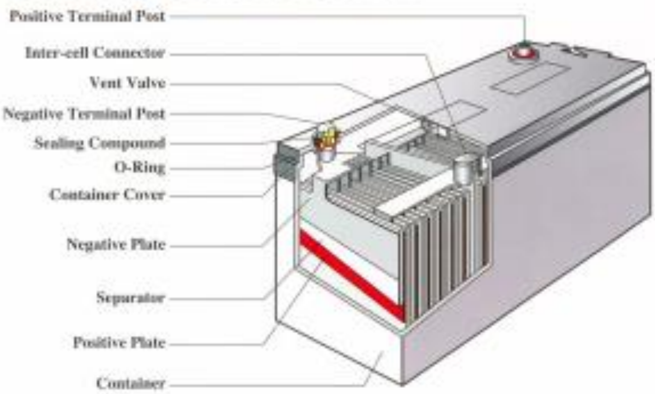
Standby Applications Include:

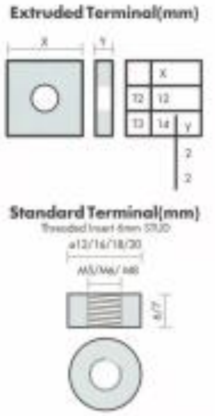
UPS / Instrumentation Control
Telecommunication / PA / PABX System
Emergency Lighting / Solar
Fire Alarms / Intercom
Engine Starting / Signalling (Railway)
Switch Tripping and Closing / Portable Power Packs

Features

- Long Life Design
- Copper Insert Terminal
- ABS Container
- Fully Sealed Construction
- High Energy Density
- ≥ 95% Gas Recombination Efficiency
- Space Saving. No Special Room Required
- Ease of Handling
- Unrestricted Transportation

Battery Construction





Terminals: M6/M8 Threaded Inserts

Capacity Test

A Capacity Test is recommended for the string of batteries to be performed annually or if the Internal Resistance is 50% greater than the base line value. This will verify the actual performance and capacity which should achieve greater than 80% of the battery capacity.

* Flame Retardant Container to UL 94 FV '0' is available on request.

MSB ULTRA 6V & 12V RANGE

AGM TECHNOLOGY

Technical Description

Positive Plates	Grid Plates
Negative Plates	Grid Plates
Separator	Absorbed Glass Mat(AGM)
Terminals	Copper Inserts, Extruded Lead, Electrolyte Tight
Type of Connection	Screwed (bolt-in & bolt-on) Connection
Cell Container	ABS
Design Life	Up to 12 Years, Maintenance Free
Float Charge	2.23 – 2.25 VPC @ 20°C
Boost Charge	2.35 VPC @ 20°C for Maximum of 3 Hours
Standards	Comply fully to IEC 896-2, equi. BS 6290 Pt. 4
Self Discharge	MSB series batteries may be stored for up to 6 months at 20°C and then a freshening charge is required. For higher temperatures the time internal will be shorter.

Specifications

MS12V Ultra

MODEL	VOLTAGE	CAPACITY @ 10hr	DIMENSIONS(mm)				Approx WEIGHT (kg)	Approx Int. Res.	Ter./hole size
			LENGTH(L)	WIDTH(W)	HEIGHT(H1)	OVERALL HEIGHT(H2)			
MS12-18 Ultra	12	18	181.5±2	78±2	167.5±2	167.5±2	5.4	16mΩ	T2
MS12-26 Ultra	12	26	166.5±2	175±2	125±2	126±2	7.8	14mΩ	T3
MS12-33 Ultra	12	33	195±2	130±2	164±2	180±2	10.5	13mΩ	M5/12
MS12-40 Ultra	12	40	197±2	166±2	170±2	170±2	12.2	10mΩ	M6/16
MS12-55 Ultra	12	55	229±2	138±2	205±2	226±2	16.5	7.5mΩ	M6/16
MS12-65 Ultra	12	65	348±3	167±2	178±2	178±2	19.2	7.3mΩ	M6/16
MS12-80 Ultra	12	80	348±3	167±2	178±2	178±2	22.3	6.6mΩ	M6/16
MS12-100 Ultra	12	100	333±2	173±2	210±2	220±2	28.0	5.0mΩ	M8/20
MS12-110 Ultra	12	110	333±3	173±2	210±2	220±2	30.4	4.9mΩ	M8/20
MS12-125 Ultra	12	125	410±2	177±2	211±2	230±2	35.0	4.0mΩ	M8/20
MS12-150 Ultra	12	150	345±2	173±2	280±2	280±2	40.0	3.5mΩ	M8/20
MS12-165 Ultra	12	165	485±2	171±1	242±2	242±2	43.0	3.5mΩ	M8/20
MS12-200 Ultra	12	200	535±3	205±2	215±2	222±2	53.0	3.4mΩ	M8/20
MS12-230 Ultra	12	230	522±3	240±2	220±2	225±2	61.5	2.7mΩ	M8/20
MS12-260 Ultra	12	260	513±3	270±2	220±2	230±2	73.0	2.7mΩ	M8/20

Layout

MS12V Ultra