Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 8, Issue 2, page 207-222
eISSN : 2747-173X

Submitted : September 18, 2025
Accepted : November 8, 2025
Online : November 28, 2025
DOI : 10.19184/cerimre.v8i2.5

Design and Deployment of an Uninterruptable Power Supply Utilizing a Solar PV System for Tilapia Aquaculture Farm in Sabah, Malaysia

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Abstract. *Continuous power supply is essential for maintaining operational stability of indoor aquaculture farms to protect their mortality. This paper examines the feasibility and performance of a 0.83 kWp stand-alone solar PV system for providing an uninterrupted power supply to a 185.8 m² indoor tilapia farm located in Sabah, Malaysia (latitude: 6.03º N, longitude: 116.30ºE). Concerning these aspects, the system was designed specifically to operate critical equipment aerators and water pump within about five hours every week during grid power interruptions. The site was evaluated through the Global Solar Atlas showing an average global horizontal irradiation of 4.74 kWh/m²/day. Using on-site load analysis, the demand was found to be 1,750 Wh/week. The system consists of two 415 Wp PV modules connected in series, a 2.4 kWh lithium-ion battery, and a 2.4 kW inverter/charger scaled up to meet the demand while considering system losses. In addition, the virtual simulation of the system confirmed the average daily energy production to be about 2.95 kWh, which exceeds the demand by approximately 69%, hence allowing operation within the scheduled grid power outage. This research work highlights the technical feasibility along operational benefits resulting from small-scale PV deployment at aquaculture in tropical region, offering a scalable framework for improving energy reliability and sustainability in rural environments.*

Keywords: PV System, Aquaculture, Renewable Energy, Solar Energy

Introduction

Access to electrical energy is fundamentally crucial for population growth, urbanization, and expanding human activities. Currently, the world population stands at 8 billion with projection of 9.7 billion by 2050 [1], [2]. According to the statistics, 5% increase in 2021 was observed relative to prior years with annual growth. To fulfil demand, 83% energy produced by fossil fuels and 63% of that used for electricity generation [3]–[5]. This trend raises concerns about long-term resource sustainability as the depletion rate is consistent with global energy consumption. Studies have highlighted that easily accessible oil could be significantly depleted within this century at current consumption rates [5], [6]. In response to these challenges, the trend for adopting renewable energy is increasing. As of now, green energy sources account for approximately 30% of global generation [7], with country level contributions varying significantly. For instance, Pakistan generates 2.4% [8], India 38% [9] and Malaysia produce 22% of its overall electricity generation [10].

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Demographically, Malaysia comprises of 30.3 million people, and with the current oil consumption rate, approximately 14 years of oil left without net exports [11]. Similar to most other nations, Malaysia accommodate 88.4% of its total energy demand by fossil fuels, and about 83% is in form of electricity [12]. In addition to that 20% from renewable sources (i.e., solar energy and hydropower) [10]. Malaysia divided into two main region, West Malaysia and East Malaysia. While approximation of 99.5% of the rural communities in West Malaysia benefited by the generated power from renewable sources. In comparable, the high percentage of coverage was not applicable in East Malaysia (Sabah and Sarawak) [13]. The majority of the rural communities in Sabah utilized high operation petrol or diesel engines to generate electricity and do daily tasks [14].

Solar photovoltaic (PV) system offers promising solution with Sabah's geographic location and abundant solar resource. Malaysia, which is an equatorial country, receives an average of 4 to 8 hours of irradiance daily [15]. According to several studies in Malaysia, Sabah has the highest potential for renewable energy. It is the only state having feasible geothermal and wind energy generating potential aside from the success story of clean energy generation as witnessed in Kudat and now expanding to Kunak [16], [17]. [18] stated that the solar radiation was highest in February–April and lowest in December. At the capital city of Sabah, which is Kota Kinabalu, it received about 182 W/m^2, or 1,590 kWh/m^2, of solar radiation annually. Furthermore, researcher found that in March and April, the direct average solar irradiance at the in Kota Belud District of Sabah, was over 4 kWh/m^2. Peak solar production occurs between 10:00 and 14:00, however usable solar radiation may be captured as early as 08:00 to 15:00 [19]. These research shows that Sabah has a significant solar PV system potential.

Scarcity and unavailability of electricity can affect both human activities and economic growth across multiple sectors on a global scale [20]. For instance, In the food industry, electricity is used at all stages from running the machinery to transporting processed food to the markets. Aquaculture is a key part of the food industry and second largest contributor to Sabah's economy after tourism industry [21], [22]. Hence, reliable energy is essential for sustainable aquaculture because fish farms depend on steady power to run aerators, pumps, and water systems that keep oxygen levels stable and prevent fish mortality. The reliance on energy-intensive water pumps, often powered by fossil fuels, increases production costs and environmental pollution [23]. These highlights the importance of clean and 24-hour electricity for industry but in remote or off-grid areas of Sabah are without access to the national power grid, diesel generators are often used to power mechanical aeration systems. According to the third agriculture policy of Sabah, power interruption and expensive diesel fuel is one of key issues to the food sector's growth in Sabah. Inconsistent electricity supply has hampered processing facilities, fisheries complexes, and other industrial facilities. Power outages raise production costs and lower the product quality, hence causing delays in import and export [21].

This study focused on an indoor tilapia aquaculture farm in Sabah that experiences frequent power interruptions, causing operational losses. Hence, reliable energy backup systems are essential to prevent fish mortality and sustain farm productivity. An operational indoor aquaculture farm requires instruments such as water pumps, aeration, light, and small machinery [24]. However, limited research has examined specifically the design and deployment of stand-alone photovoltaic systems for aquaculture operations in Sabah under local climatic and operational conditions. To address the identified gap, this study proposed and evaluated a stand-alone solar photovoltaic (PV) system configured to operate as an Uninterruptable Power Supply (UPS) for an

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indoor tilapia aquaculture facility in Sabah. The system is designed to mitigate frequent power interruptions that compromise fish mortality and disrupt farm operations. The research focuses on site-specific system sizing utilizing Global Solar Atlas data to maintain energy balance between supply and demand. Furthermore, the study aims to demonstrate the technical feasibility of system by aligning the availability of renewable energy with the requirements of aquaculture.

Theoretical Background

This theoretical background covers the basic principles of stand-alone (PV) systems used as UPS. It includes solar radiation, photovoltaic energy conversion, battery storage, inverter and charge controller operation. This background is crucial for designing, sizing, and ensuring reliable operation of the PV UPS for the application.

Solar Radiation and Photovoltaic Energy Conversion

Solar radiation reaching the Earth's surface is comprised of direct, diffuse, and reflected radiation. For horizontal surfaces, the total solar input is termed as the Global Horizontal Irradiance, which is described as the amount of direct and diffuse radiation projected onto a horizontal plane [25]. It does not include reflected radiation unless the study involves tilted or non-horizontal surfaces, where the ground-reflected components are considerable [26]. Sabah, located at latitude 6.03º N, receives an average of 4.7 kWh/m^2 of daily solar irradiation as shown in **Table 1**, which is ideal for PV energy conversion with very minimal tilt adjustments. Study showed that optimal tilt-angle in tropical conditions avoids excessive panel heating. In contrast, incorrect tilt results in higher operating temperatures, and increased semiconductor resistance diminishes the photovoltaic efficiency [27]. The photovoltaic effect allows the direct conversion of sunlight to electricity when photons excite electrons within a semiconductor material, generating an electric current [28], [29].

Battery Energy Storage Theory

Energy generated by PV arrays can be stored in batteries for continuous power supply in case of grid outage. Batteries store and release energy through electrochemical reactions. The usable energy depends upon the state of charge (SOC), depth of discharge (DOD), and battery efficiencies [30]. In photovoltaic systems, batteries help provide backup during grid outages or low solar irradiance periods to ensure uninterruptible operations. There are several energy storage batteries available but Lithium iron phosphate ($LiFePO_4$) batteries are used due to high energy density, long cycle life, and stability, suitable for PV applications [31]. This principle represents a basis of the present research on optimization of battery sizing, load management, and reliable system performance.

Photovoltaic Energy Conversion Principle

Photovoltaic (PV) systems generate direct current (DC) and battery store as DC, whereas most loads and the electrical grid operate on alternating current (AC). The inverter is responsible for converting DC from the PV array or battery into AC electricity suitable for consumption [32]. In addition to that, the charge controller regulates the flow of current between the PV modules and the battery to prevent overcharging and over-discharging. which can reduce battery life, and deep discharge, which can cause permanent damage. Charge controllers also ensure the battery is charged efficiently and safely according to its specifications [33].

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Materials and Methods

This study adopted a site-specific design methodology to develop a (PV) system for an aquaculture facility. The design strategy approach included the assessment of the availability of solar energy, estimation of energy requirements, and configuration of the PV system with an appropriate number of modules, battery, and inverter/charger to satisfy operational needs.

On-Site Data Collection for the Design of PV System

The site was visited to check technical feasibility and gather a preliminary information on load requirement which is crucial for system design. Through on-site observation, potential structural for PV module placement were identified ensuring minimal shading require tilt angle. Global Solar Atlas (GSA) website was utilized to determine solar irradiance data as shown in **Table 1**. The solar irradiance data varied by location, and it is crucial to obtain at coordinates of study prior to design.

Table 1. GSA data illustrate tilt angle at which maximum solar energy can harness along with available and specific power output [34]

Data	Value
Specific photovoltaic power output	3.748 kWh/kWp Per day
Direct normal irradiation	3.299 kWh/m^2 Per day
Global horizontal irradiation	4.740 kWh/m^2 Per day
Diffuse horizontal irradiation	2.306 kWh/m^2 Per day
Global tilted irradiation at optimum angle	4.747 kWh/m^2 Per day
Optimum tilt PV module	6/180º
Air temperature	26.6 ºC
Terrain elevation	250 m

GSA highlighted that the site experiences favorable solar conditions throughout the year. The average global horizontal irradiation (GHI) is 4.74 kWh/m^2 per day, and the global tilted irradiation at the optimum tilt is 4.75 kWh/m^2 per day, indicating that the location is near the equator where the sun is almost overhead and the difference between horizontal and tilted surfaces is minimal. The optimum tilt angle for (PV) modules is 6º facing south (180º azimuth), which corresponds closely to the local latitude. The average ambient temperature was suggested 26.6 ºC and elevation of 250 m above sea level which represent typical tropical lowland conditions. These parameters indicated that the specific PV power output is will be 3.748 kWh/kWp per day for each kilowatt of installed PV capacity. This information provides the base values for system sizing and expected performance.

On-Site Load Analysis for the Design of PV System

The research area consists of multiple electrical components including lighting, empty sockets, a water pump, and aerators. A preliminary load analysis was conducted to identify which components should be considered in the system design. Load analysis confirmed that the facility experiences approximately five hours of power interruption per week. Accordingly, the system was designed to support that power outage hours in order to maintain operation of aerators and water pump. The power Information of required instruments and frequency of usage was gathered

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and tabulated in **Table 2** for load analysis. Equation (1) was used to calculate energy demand required by farm.

Table 2. Load Type, their wattage, and quantity of appliances

Type of Instrument	Power rating (W)	Quantity	Hour use per week
Aerator	100	2	5
Water Pump	1000	1	0.75

$$E_{demand} = \left[\left(P_{aerator} \times t\right) + \left(P_{water\ pump} \times t\right)\right] = \left[(200 \times 5) + (1000 \times 0.75)\right] = 1750\ Wh \quad (1)$$

PV System Design

The components in the PV system design were determined based on the steps (1 – 4).

Step 1. Sizing of rooftop solar PV modules:

The specification of the reference PV modules is shown in **Table 3**. The power supplied by the PV module was calculated based on equation (2), while the number of PV module was determined based on equation (3). To ensure the PV array meets actual energy demand, typical system losses such as temperature effects, dust, wiring resistance, inverter inefficiency, and charge losses were considered prior to system design. Therefore, a DC/AC ratio of 1.20 was applied to account for these losses, effectively adding a 20% buffer above the theoretical demand [35]. The power from PV module is the total energy required divided by the global horizontal irradiation or average sun hour at the site.

$$P_{module} = (E_{demand}/t_{sun}) \times 1.20 = (1750/4.740) \times 1.20 = 443.037\ Watt \quad (2)$$

$$N_{module} = P_{module}/P_{rated} = 443.037/415 \approx 2\ modules \quad (3)$$

Table 3. Specification of reference PV module

PV Module Specification	
Model	**BSM415M-72OPH**
Max Power (P_{max}) [W]	415
Open Circuit Voltage (V_{oc}) [V]	49.8
Short Circuit Current (I_{sc}) [A]	10.66
Max Power Voltage (V_{mp}) [V]	41.1
Max Power Current (I_{mp}) [A]	10.11

Step 2. Sizing of the inverter/charger:

An inverter was required for the conversion of the direct power to alternating current. The selection of the inverter/charge controller was done according to equation (4) and (5) in order to match the

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voltage of the PV module and the solar PV system. If the power rating of the inverter is less than the entire power of the electrical load, the system will be overloaded. Thus, the power rating of the inverter should be 20 to 30 percent more than the power of the appliances [35]. Therefore, a small buffer of 20% for surge or transient loads for additional power margin added. It is crucial of sizing a power supply, allowing it to handle temporary spikes in demand without failing for devices like motors. Motor draws a much higher initial current during startup than during continuous operation. Hence, equation (6) was used to determine the inverter rating. Specification of the reference inverter/charger was mentioned in **Table 4**. A charge controller was essential to control the PV array charge into the batteries bank, prevent overcharging, and reverse the current flow. The system voltage is 24V and PV module specification, Short Circuit Current (□□□) is 10.66 A and Open Circuit Voltage (Voc) is 49.8 V. Two modules in series were installed at location. Therefore, it will produce 99.6 V and reference inverter maximum can handle 102 V and 100 A.

Table 4. Specification of reference inverter/charger

PIP2424MSE1 Inverter/Charger	
Inverter Mode:	
Model Name	PIP2424MSE1
Rated Power	3000 VA/2400 W
DC Input	24 VDC, 100 A
AC Output	230 VAC,50/60 Hz, 13 A, 1 ϕ
Solar Charger Mode	
Rated Power	1000 W
System Voltage	24 VDC
Operating Voltage Range	30-80 VDC
Max. Solar Voltage (V_{oc})	102 VDC

$$I_{max} = I_{sc} \times N_{module} = 10.66 \times 1 = 10.66\, Ampere \quad (4)$$

$$V_{max} = V_{oc} \times N_{module}(in\ series) = 49.8 \times 2 = 99.6\, Volt \quad (5)$$

$$P_{inverter} = P_{Appliances} \times 1.20 = 1200 \times 1.20 = 1440\, Watt \quad (6)$$

Step 3. Sizing of the battery:

Energy generated by the solar panel will be stored in battery pack. The capacity was determined using equations (7), (8), (9), and (10). The chemistry of the solar battery was $LiFePO_4$ and the specification was mentioned in **Table 5**. The minimum battery capacity required was 97.22 Ah to store 2100 Wh of energy, and approximately 1 pc of the reference battery was enough to store this capacity.

$$C_{demand} = \left(E_{demand}/V_{system} \times DOD\right) \times t_{sol} = (2100/24 \times 0.90) \times 1 = 97.22\, Ah \quad (7)$$

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$$N_{batteries\ (series)} = V_{system}/V_{battery} = 24/24 = 1\ pc \quad (8)$$

$$N_{batteries\ (parallel)} = C_{demand}/C_{battery} = 97.22/100 = 1\ pc \quad (9)$$

$$N_{total\ batteries} = N_{batteries\ (series)} \times N_{batteries\ (parallel)} = 1 \times 1 = 1\ pc \quad (10)$$

Table 5. Specification of reference battery

Battery Specification	
Type	Lithium-ion
Capacity	100 Ah
DOD	90%
Voltage	24 V

Step 4. Balancing of system:

Balance of system (BOS) were typically consisting of cable size, switches, and surge protection devices (i.e., fuse, breaker). The BOS function is to ensure the solar PV system continues to function reliably and safely. BOS prevents the system from damage as much as possible during overload and voltage. The equation (11–15) is used to calculate the cross-sectional area of the cable, fuse and breaker size that can carry this current, voltage and power protectively.

Sizing of DC cable:

$$A_{cable} = \left[\left(2 \times p_{copper\ wire} \times L_{dc\ cable} \times I_{max}\right)/\left(\left(V_{drop} \times V_{max}\right)/V_{max}\right)\right] = \left[(2 \times 1/56 \times 1 \times 10.11)/((0.02 \times 99.6)/99.6)\right] = 18.05\ mm^2 \quad (11)$$

Sizing of fuse for PV modules:

$$I_{trip} = 1.5 \times I_{sc} < I_{trip} < 2 \times I_{sc} = 1.5 \times 10.66 < I_{trip} < 2 \times 10.66 = 15.99\ A < I_{trip} < 21.32\ A \quad (12)$$

$$V_{pmax\ min} = 2 \times V_{oc} \times N_{module\ (in\ series)} = 2 \times 49.8 \times 2 = 199.2\ V \quad (13)$$

Sizing of DC breaker:

$$V_{rated\ (main\ switch)} \geq 1.3 \times I_{sc} \geq 1.3 \times 10.66 = 13.86\ V \quad (14)$$

$$I_{rated\ (main\ switch)} \geq 1.2 \times V_{oc} \geq 1.2 \times 49.8 = 59.76\ A \quad (15)$$

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The Balance of System (BOS) components were sized to ensure safe, reliable, and continuous operation of the PV system. Based on design calculations, the minimum required ratings were 18 mm² cable size, 59 A DC breaker at 14 V, and a maximum array voltage ($V_{pmax\,min}$) of 199.2 V. The calculated array voltage represents the highest voltage the PV string can reach under cold, clear-sky conditions and determines the voltage withstand rating for all DC protection devices. These ratings safeguard the system from overcurrent, voltage drop, and short-circuit risks that could cause overheating or component failure. The calculated values represent the minimum requirements but actual components were used with higher ratings depending on market availability and standard to further enhance system safety and durability [36], [37].

Results and Discussion

The tilapia aquaculture farm is located across Sabah district including Kota Kinabalu, Tuaran and Ranau. The distance from the surrounding area is 47 km, 23 km, and 84 km respectively. The farm in Sabah, Malaysia lies between the latitude of 06.03º N, and longitude of 116.30º E, where it received significant amount of solar irradiation each year. At the facility, the global horizontal irradiation data was recorded about 4.75 kWh/m^2 with 6º of optimum tilt PV module facing south. In addition, there were different areas noticed to position the components. one of them was finalized which is quite near to load with strong structure, and far from tree shades. As shown in **Figure 1** most of the site area is surrounded by trees. Trees can block solar radiation and create the shedding effect on modules which will affect the overall electricity generation efficiency. To be more precise, a 3D model of the aquaculture farm was shown in **Figure 2**. This model was designed using the PV SOL software to depict the potential of chosen area, highlighting the placement of the PV modules with minimal shading.

The information gathered on-site indicated that the aquaculture farm experiences power interruptions for approximately five hours per week. To ensure continuous and safe operation during these outages, the solar PV system was designed using Equations (1)– (15) and tabulated in **Table 6**. The actual energy requirement of the farm was calculated to be 1,750 Wh, and after accounting for inverter/charger, cable, and temperature losses, the adjusted requirement increased to 2,100 Wh. Based on the reference components, a system consisting of two PV modules connected in series, one inverter/charger to convert DC to AC and regulate battery charging, and one lithium-ion battery to store energy was found sufficient to meet the energy demand. In contrast, system can generate more than the requirement. For instance, power interruptions in the study area occur on average 5 hours per week, equivalent to approximately 0.714 hours per day, with an energy demand during interruption of 0.26 kWh/day. The system has a total capacity of 0.83 kWp, capable of generating approximately 2.9 kWh per day, which exceeds the overall farm's energy demand by nearly about 69%. Moreover, considering daily average interruption usage (0.26 kWh/day), the PV system produces over 10 times the demand. This excess energy produced by system ensures uninterrupted operation of aeration and water circulation systems during grid outages, prevent fish from dying and uphold operational continuity.

The system was configured with a smart inverter/charger equipped with MPPT (maximum power point tracking) and battery-management functions. During daylight hours, the PV array directly supplies the instantaneous AC load through the inverter, while the MPPT controller maximizes PV energy harvest. Any PV energy not immediately consumed by the load is directed by the inverter/charger to charge the battery bank. During grid outages or after sunset, the inverter supplies the AC loads from the battery. If the battery drops below a certain threshold and there is

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insufficient PV energy, the load is supplied by the grid, and the inverter charges the battery from AC/grid. This ensures that the battery is always near full capacity, ready for the next outage. In this configuration the calculated PV daily production (≈2.95 kWh/day) first meets the farm demand (2.1 kWh/day adjusted for losses) and the remaining surplus (≈0.85 kWh/day) is available to recharge the battery.

Figure 1. Shows the project site, illustrating the proximity of greenery that may affect solar exposure

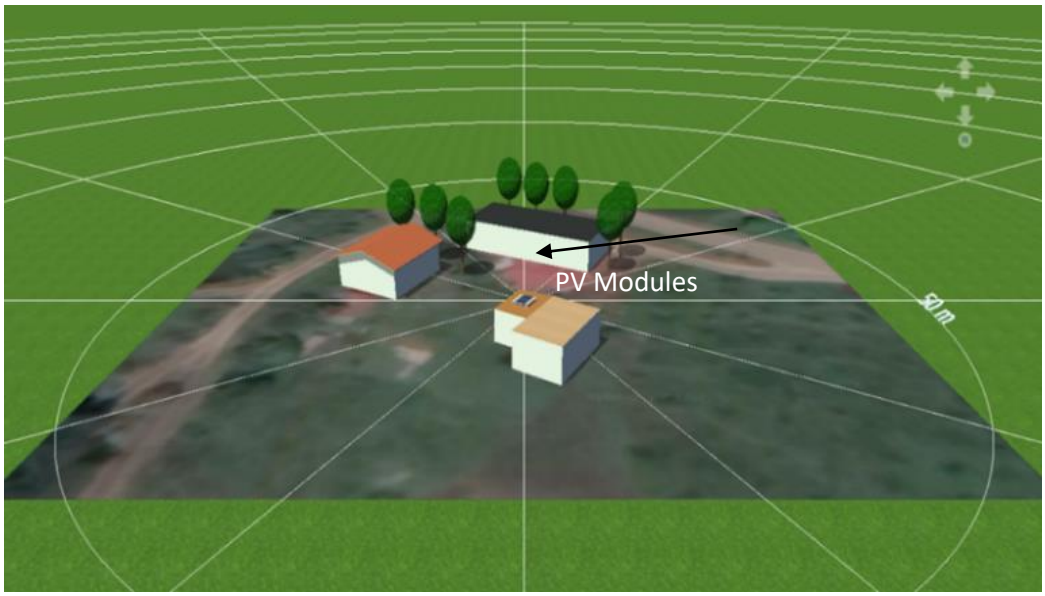

Figure 2. Illustrate the 3d model of study area

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Table 6. System components and requirement

System components and requirement	Value
Energy Demand	1750 Wh
Energy Required	2100 Wh
Number of Modules Required	2
Number of batteries required	1

Furthermore, a system was simulated utilizing GSA at site coordinated to evaluate the solar energy potential. A detailed performance report was generated based on the selected system configuration such as a 0.83 kWp PV system south-facing with tilt angle of 6º. **Figure 3** illustrates a direct correlation between direct normal irradiation (DNI) and photovoltaic (PV) output power, with higher irradiation levels resulting in increased energy yield.

	Month											
Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0	0	0	0	0	0	0	0	0	0	0	0
1 - 2	0	0	0	0	0	0	0	0	0	0	0	0
2 - 3	0	0	0	0	0	0	0	0	0	0	0	0
3 - 4	0	0	0	0	0	0	0	0	0	0	0	0
4 - 5	0	0	0	0	0	0	0	0	0	0	0	0
5 - 6	0	0	0	0	0	0	0	0	0	0	0	0
6 - 7	0	0	0	0	62	49	0	0	42	88	103	42
7 - 8	218	261	316	355	335	277	245	249	233	269	310	275
8 - 9	317	401	453	480	455	366	328	358	333	366	403	366
9 - 10	397	497	546	582	546	439	409	447	408	432	458	450
10 - 11	427	520	543	589	555	459	443	485	421	433	452	457
11 - 12	393	475	504	524	508	423	426	456	395	380	380	387
12 - 13	315	401	407	394	392	354	370	380	326	299	283	302
13 - 14	249	330	336	330	284	276	300	331	268	219	200	226
14 - 15	188	272	281	268	209	216	244	260	199	165	146	160
15 - 16	151	243	233	222	160	170	204	191	149	129	118	143
16 - 17	125	194	173	150	117	125	136	130	102	90	74	85
17 - 18	25	40	72	61	68	66	73	66	20	0	0	0
18 - 19	0	0	0	0	0	0	0	0	0	0	0	0
19 - 20	0	0	0	0	0	0	0	0	0	0	0	0
20 - 21	0	0	0	0	0	0	0	0	0	0	0	0
21 - 22	0	0	0	0	0	0	0	0	0	0	0	0
22 - 23	0	0	0	0	0	0	0	0	0	0	0	0
23 - 24	0	0	0	0	0	0	0	0	0	0	0	0

(a)

	Month											
Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0	0	0	0	0	0	0	0	0	0	0	0
1 - 2	0	0	0	0	0	0	0	0	0	0	0	0
2 - 3	0	0	0	0	0	0	0	0	0	0	0	0
3 - 4	0	0	0	0	0	0	0	0	0	0	0	0
4 - 5	0	0	0	0	0	0	0	0	0	0	0	0
5 - 6	0	0	0	0	0	0	0	0	0	0	0	0
6 - 7	2	2	5	12	21	18	10	11	19	28	26	9
7 - 8	84	90	114	138	134	116	103	111	126	141	143	113
8 - 9	206	233	266	285	269	236	219	240	252	269	275	238
9 - 10	315	358	394	410	382	338	323	356	360	374	375	349
10 - 11	385	437	463	481	447	403	394	431	426	427	427	409
11 - 12	403	457	485	490	458	418	422	451	440	427	416	408
12 - 13	375	429	445	438	411	386	399	420	404	376	365	367
13 - 14	324	380	389	383	329	326	343	377	348	306	288	307
14 - 15	253	312	323	308	250	260	278	299	274	235	216	235
15 - 16	178	241	239	221	171	182	203	209	185	156	144	167
16 - 17	106	151	143	123	95	104	115	115	98	77	70	84
17 - 18	26	42	48	40	33	37	43	40	23	13	10	14
18 - 19	0	2	2	0	0	1	2	1	0	0	0	0
19 - 20	0	0	0	0	0	0	0	0	0	0	0	0
20 - 21	0	0	0	0	0	0	0	0	0	0	0	0
21 - 22	0	0	0	0	0	0	0	0	0	0	0	0
22 - 23	0	0	0	0	0	0	0	0	0	0	0	0
23 - 24	0	0	0	0	0	0	0	0	0	0	0	0

(b)

Figure 3. Direct normal irradiation and PV power output of monthly hourly average profile: a) direct normal irradiation (Wh/m^2) b) PV power output (Wh)

The predicted mean of monthly hourly PV output alongside DNI data reveals fluctuations month-to-month and seasonal patterns in solar energy availability at the study location. Throughout the year, the system demonstrates sustained performance in peak energy generation between 10:00-12:00, confirmation of strong mid-day solar exposure or peak hours. The significant output was observed in April and May 490 and 458Wh respectively, with a favorable tilt and improved solar irradiance during these months. Similarly, DNI shows same trend during concurrent period, with April and May approaching 589 and 555 kWh/m^2 sequentially. The PV system captured estimated 82–83% of the available DNI during peak months. Furthermore, the data indicates that energy consumption is not feasible during the early hours of day from 00:00–07:00 and after the late afternoon from 17:00–24:00, stressing the system's reliance on the grid energy or a battery storage during these periods. The monthly performance was determined based on the aggregated hourly data for each calendar month. It indicates March, April and May are the (PV) outputs month with 3.33, 3.32 and 3.12 kWh in the stated sequence, attributed to favorable solar conditions. In contrast, the remaining nine months demonstrate comparatively lower average outputs, ranging between 2.65 – 2.95 kWh.

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eISSN : 2747-173X

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DOI : 10.19184/cerimre.v8i2.5

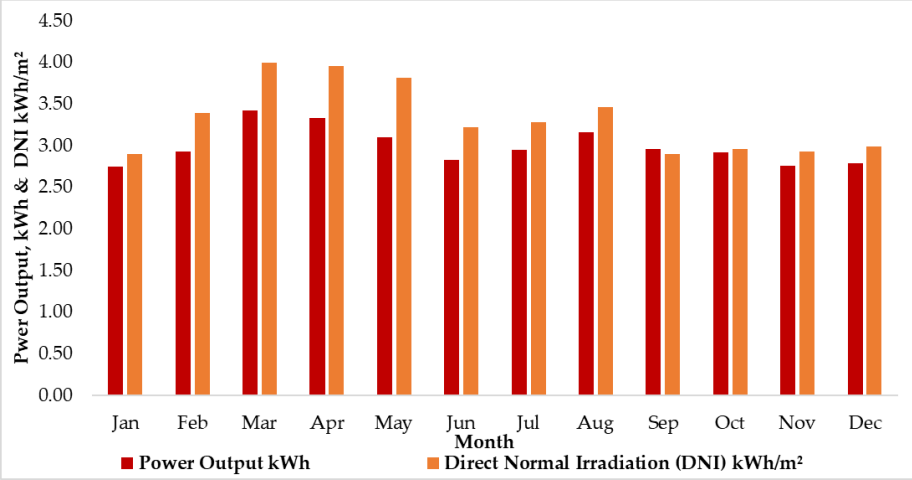

Figure 4. Direct normal irradiation and photovoltaic power output of average daily profile

Moreover, using monthly average values the comparative analysis of DNI and PV output shown in **Figure 4,** exhibits a clear seasonal Influence. The trend reveals that both parameters corelated and showing synchronized fluctuations throughout the year. The highest power output is recorded in March with 3.43 kWh, closely aligned with the peak DNI value of 3.99 kWh/m^2 followed by April, August and May, indicating optimal solar harvesting months. June and July are low performance between peak yield months with power outputs of 2.83 kWh and 2.95 kWh respectively, corresponding to DNI values of 3.22 and 3.22 kWh/m^2. From September to February, the trend indicating stable system performance with average of 2.8wh compare to DNI value of 3.0 kWh/m^2. The fluctuation and seasonal patterns observed in this study closely align with data previously reported for Kota Kinabalu. studies have consistently identified that Kota Kinabalu receives an estimated 2.9 kWh/m^2 of solar energy annually, with a daily average of 4.4 kWh/m^2. March and April consistently exhibit peak irradiance and minimal rainfall, making them the most favourable months for solar harvesting. In contrast, January and December show the lowest solar radiation, Corresponding with high rainfall. During the Southwest Monsoon (May–September), solar radiation remains relatively stable despite variable precipitation, while the Northeast Monsoon (November–March) brings reduced irradiance [18], [38]. These documented trends corroborate the present study's findings highlight the importance of localized climatic analysis particularly the high photovoltaic output observed in March and April, and underscore the importance of localized climatic analysis in optimizing solar PV system performance.

The comparative analysis of DNI and predicted output power highlights the strong correlation between solar irradiance and photovoltaic performance, while minor deviations may reflect temperature effects, system losses, or operational variability. Furthermore, the system was predicted to yield a total PV power of 1.09 MWh per year or around 2.990 kWh per day. The minor deviation between the theoretical output (2.95 kWh/day) and the Global Solar Atlas estimate (2.990 kWh/day) highlights the reliability of the design assumptions and confirms both the suitability of the site and the accuracy of the system sizing approach. In addition, a similar study was conducted for tourism centre at Kota Belud, Sabah. Study reported a daily DNI of 3.164 kWh/m^2 and 8.72 kWh/day power from a 2.5 kWp system, validated using Global Solar Atlas and ESCoBox tools. Present and reported study produced equal energy approximately 3.49 kWh/kWp/day per unit of installed capacity. Both studies demonstrating solar resource availability

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and the technical feasibility of PV systems in rural area of Sabah under comparable climatic conditions [19]. Hence, a solar PV system was deployed at the aquaculture farm in Sabah as shown in **Figure 5**. Furthermore, a schematic diagram of the stand-alone UPS PV system shown in **Figure 6**, illustrating its main components and interconnections.

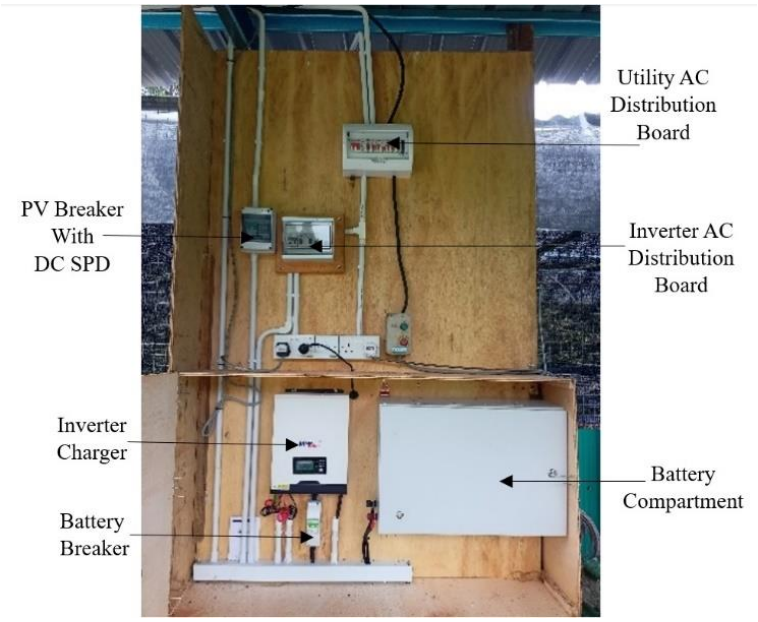

Figure 5. Installed solar PV system components at the aquaculture farm, illustrating the final deployment configuration at the study site

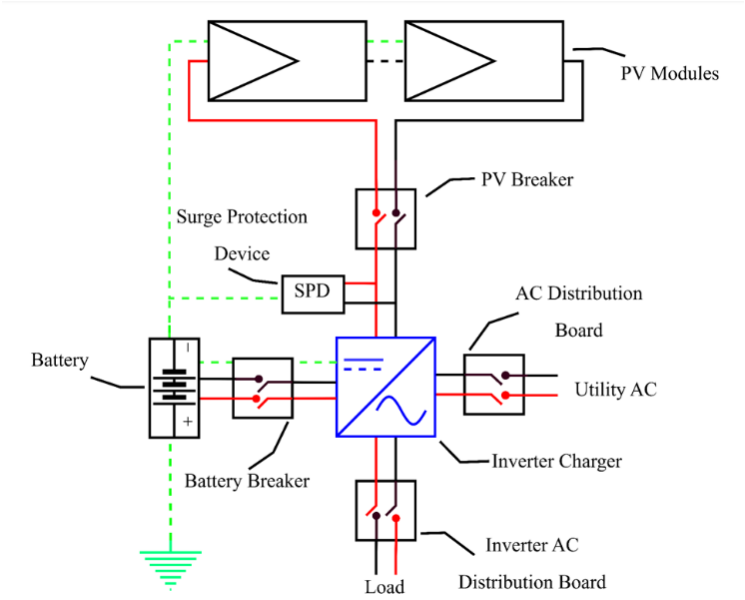

Figure 6. Schematic diagram of stand-alone solar PV system

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Conclusions

A stand-alone solar photovoltaic system was designed and configured as an Uninterruptable Power Supply for a tilapia aquaculture farm in Sabah (east region of Malaysia). Considering the requirements, 0.83 kWp system was designed to generate 2.95 kWh energy per day. The generated amount of energy exceeded the total energy demand of 1.75 kWh used by required load by 69%, and over 10 times the energy required for backup of 0.26 kWh per day during outages. It highlights the comprehensive availability of backup energy. Moreover, the configuration validated using Global Solar Atlas data. The theoretical performance comparably matched the Global Solar Atlas prediction of 2.99 kWh per day, which confirmed the accuracy of the predicted yield and articulated the system's technical feasibility for rural aquaculture. Although the system was designed and validated using simulation tools, future work will focus on assessing its real-world performance includes actual energy output, operational reliability, and economic viability. These insights are critical for confirming the practicality and long-term sustainability of solar PV integration in rural aquaculture environment. This study provides a practical framework for implementing solar energy system into aquaculture located in Sabah, with extended scope across Malaysia and other tropical regions.

ACKNOWLEDGEMENTS
The authors acknowledge Universiti Malaysia Sabah for the research support provided.

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