Design, Sizing and Evaluation of a Photovoltaic Aeration System

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Abstract— Aquaculture as one of the major sectors sustaining the global food demand is facing issues on addressing global warming. With the fast-growing global population, the challenge to sustain the world's fish per capita consumption equates to emerging problem in energy scarcity. This issue serves as a driving force on integrating renewable energy systems to fish food production. The sun that can offer ubiquitous source of clean, infinite and free source of energy can be an answer to minimize electric consumption, thus lowering burning of fossil fuels. This paper presents the synergy of fish production and photovoltaic technology and its potential both on lowering the energy cost and carbon emissions of aquaculture operations. This also tends to analyze and summarize the performance characteristics of a Photovoltaic (PV) aeration system in terms of the efficiency of PV array and inverter as well as the influence of temperature, time of day, and solar radiation to its performance**.**

Keywords—Photovoltaic, solar radiation, carbon emission reduction, dissolved oxygen (DO), energy savings.

I. Introduction

The inevitable increase of global population is leading to an ambitious way of maintaining the per capita consumption of aquatic foods. In the past decades world food fish production has expanded by almost 12 times which make it very evident that large chunk of fish food supply will have to come from aquaculture [1].

Considering the developments in aquaculture industry, various DO introducing device were invented and adopted by many fish farming ventures. These innovations tend to suffice the oxygen in the water when natural aeration cannot be possible. These artificial aeration devices required some sort of energy source to keep on operating. Further, these devices cannot be deployed in remote areas where power lines are unavailable [2].

The pursuit of maintaining ideal DO levels have contributed to the high production cost. The considerable increase may be attributable to the advanced equipment necessary to supply sufficient amount of oxygen to prevent stress, cessation of growth and mortality of the cultured organism. Proper management of energy resources in aquaculture is one of the fundamental issues arising today. The utilization of electricity has come to a responsibility to ensure that the energy is used efficiently with the minimum impact to the environment. Carbon emissions generated by electrical generation is becoming one of the major concerns as it may be destructive to the environment especially in a large scale basis.

The synergy of the aeration system and renewable energy system can change how the aquaculture sector is becoming. The aim of developing oxygen introducing device utilizing solar energy will generate a great impact in world's fish farming sector.

II. Materials and Methods

The method of the study was subdivided into four phases namely: system design and sizing; site assessment, system assembly and installation; system deployment and operation; and system performance analysis.

A. System Design and Sizing

The system design comprised the determination of the purpose of the system, place of deployment, duration or length of operation and needed components for the system.

Sizing, on the other hand plays a very important part on identifying the correct sizing factors such as the number of solar panels, batteries and efficiency of power inverter where the performance of the PV system is very dependent [3]. The following are the sizing factors with corresponding formulae used in the experiment:

- Daily load requirement

$$AC\ load = \frac{LPR}{LVR} \qquad (1)$$

$$DC\ load = AC\ load \times \frac{LVR}{BSV} \div ICE \qquad (2)$$

$$LR = DC\ load \times total\ hour\ of\ presence\ of\ solar\ radiation \qquad (3)$$

$$LR = DC\ load \times total\ hour\ of\ absence\ of\ solar\ radiation \qquad (4)$$

- Storage capacity of the battery

$$BC = TDL \times DA \times DF \qquad (5)$$

Where:

AC: Alternating Current	LVR: Load Voltage Requirement
DC: Direct Current	LPR: Load Power Requirement
LR: Load Requirement	BSV: Battery System Voltage
BC: Battery Capacity	TDL: Total Daily Load
DA: Days of Autonomy	DF: Design Factor
ICE: Inverter's Conversion Efficiency	

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B. Site Assessment, System Assembly and Installation

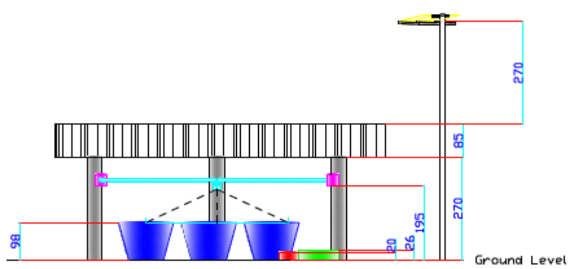
Site assessment was crucial to determine if the site has the proper area for the mounting of the PV array and whether it could operate efficiently even without shading especially at critical times.

Site assessment determined the most appropriate spot for the mounting of the array at the installation site, the mounting method of the array that can be adopted, exact placement of the main and subcomponents and the performance of the PV array in the whole system. Figure 1 shows the detailed drawing of the system.

The system was installed at the outdoor aquaculture facility of the Freshwater Aquaculture Center (FAC), Central Luzon State University (CLSU), Science City of Muñoz, Nueva Ecija, Philippines.

- *Array Tilt and Angular Orientation*

The PV array was placed in the same direction and angular orientations regardless of the sun's position in the sky. The optimal position for a fixed system is facing south and oriented at the same angle in degrees as the latitude of the location [4]. Therefore, the angular orientation of the PV array was facing south tilted with an angle of 15.70°.



Legend: Solar Panel, Battery Bank, PVC pipe, Control Box, Air blower, Fiberglass Tank

Fig. 1. Detailed drawing of the PV aeration system

C. System Deployment and Operation

The demonstration of the system was carried out by comparing the designed system with the conventional aeration system. Generally, operation of both the control and experimental systems was operated under the same conditions such as the number of fish tanks to be aerated, number of air nozzles, species, number and size of fish to be cultured and capacity of tank.

Each system was operated for 24 hours daily for two months. The same operational procedures such as the stocking, sampling, feeding, water quality management and monitoring were observed for both the experimental and control systems.

The method of evaluating the power output from the PV aeration system was based from the reading from the charge controller, while reading from a sub meter was the basis of energy demand of the conventional system (control). Reading was done every hour and the last reading in the afternoon was the base value to determine the consumption of the load during nighttime.

D. System Performance Analysis

System performance of the PV and conventional aeration system was evaluated through their performance characteristics in terms of the power output of the PV array, power inverter and PV array efficiency, operational capacity, carbon emission reduction and cost of generated electricity.

- PV Array Efficiency

The efficiency of the photovoltaic array was measured to determine its ability to convert the available solar radiation into usable energy for the load consumption. The determination of the efficiency is important in order to know if the array was able to supply sufficient amount of DC power for the operation of the system. The maximum efficiency of the array was determined using the formula:

$$\eta max = \frac{Pmax}{E_{S,Y}^{SW} * Ac} \tag{6}$$

Where:
ηmax = maximum efficiency
Pmax = maximum power output
$E_{S,Y}^{SW}$ = incident radiation flux
Ac = area of collector

- Power Inverter Efficiency

Power inverter converts the DC electricity produced and stored by the PV array to AC electricity for the consumption of the load. All power inverters are inherent to power conversion losses which means that the input power is always less than the output power. The power inverter's efficiency was determined by comparing the input power to its output power. This is essential to determine the exact power input and how much power is wasted during the conversion process. The efficiency was calculated using the formula:

$$\eta = \frac{Pout}{Pin} \tag{7}$$

where:
η = power inverter's efficiency
P_{out} = output power
P_{in} = average DC power input

The efficiency of the inverter also reflects the certain percentage of wasted power that was converted to heat energy during heat dissipation by triggering an exhaust fan. Wasted power and input power on the other hand were calculated by the formulae:

$$Pwaste = \frac{\eta}{Pout} \tag{8}$$

$$Pin = Pout + Pwaste \tag{9}$$

where:
η = power inverter's efficiency
P_{out} = output power
P_{waste} = average DC power input

- Carbon Emission Reduction

A Conversion factor calculator – editable spreadsheet using Defra's conversion factors (2013) was used to convert electricity consumed in kWh to kg of carbon dioxide

On the other hand, the total avoided carbon dioxide emission was computed using the formula:

$$Avoided\ CO2\ =\ GE\ x\ CO2AF \tag{10}$$

Where: GE=Generated Electricity (kWh)
CO2AF: Avoidance Factor (kg/kWh)

A 0.44548 CO_2 avoidance factor (Defra's energy conversion factors, 2013) was used for the computation.

- Economic Analysis

A simple cost analysis was performed to determine the cost of producing energy by the system and the cost of operating the aerator in hourly basis.

III. Results And Discussion

The performance of the PV aeration system was determined in terms of its daily power output in relation to the time of the day, temperature and solar radiation.

Figures 2-4 shows the graphical representation of total daily power output of the PV array with respect to the average daily solar radiation for the months of December, January and February. The output efficiency of the PV array was influenced by solar radiation at the plane of the PV array and shading of clouds that directly affected sunlight intensity. The average daily power output generated by the PV array was 1,110.40 W, 1,131.87 W and 1,219.20 W for the months of December, January and February, respectively.

The lower power output with higher solar radiation and vice versa can be attributed to long duration of cloud shading and lower temperature with clear sky, respectively. Temperature was also a major factor that influenced the power output of the PV array. This was consistent on previous studies on analysis of PV cell performance [5], [6] which revealed that temperature acted like a negative factor affecting solar cell performance. Solar cells give their full performance on cold and sunny days rather on hot and sunny weather.

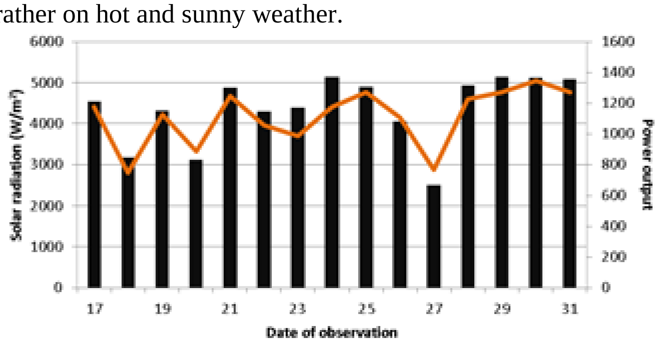


Fig. 2. Raw data from system operation with 15-day observation of total power output of PV array vs. solar radiation for the month of December.

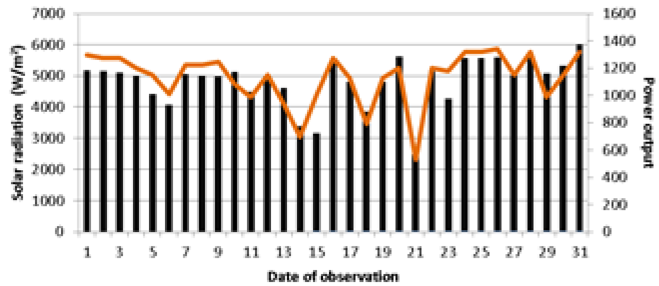


Fig. 3. Raw data from system operation with 31-day observation of total power output of PV array vs. solar radiation for the month of January.

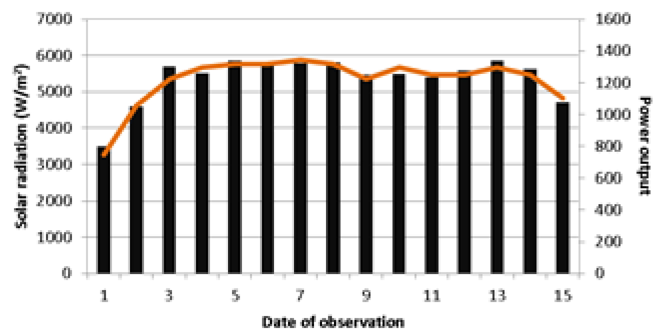


Fig. 4. Raw data from system operation with 15-day observation of total power output of PV array vs. solar radiation for the month of February.

The PV array had the highest generation during 1100 to 1200 h with an average power output of 194.925 (±26.84W) and 194.286 W (±42.70W), respectively. The high generation was attributable to the fact that during those times the available solar radiation had increased drastically with 694.40±154.42 W/m² and 709.85±180.76 W/m² for 1100 and 1200 h, respectively (Figure 5). Solar radiation on horizontal surface varies from one time to another due to the inclination angle of solar radiation [7]. At early morning solar radiation has a low angle and rays penetrate at the thick atmosphere layers. Abundant solar radiation was at noon where the sun is at the highest angle above the horizon, thus it encounters minimum thickness of the atmosphere.

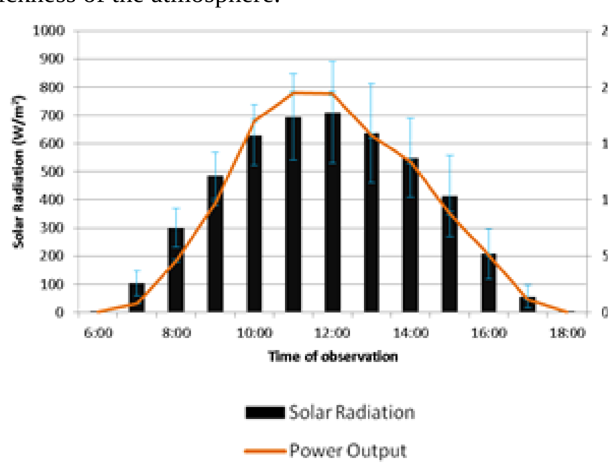


Fig. 5. Average power output with respect to solar radiation by time.

Figure 6 shows the relationship of the available solar radiation on the output of the array. The equation of the line suggested that the available solar radiation explains 91.15% of the variance in the power output of the array. The equation also suggests that for every 1.00% increase in solar radiation there is a 0.24% increase in the output of the array.

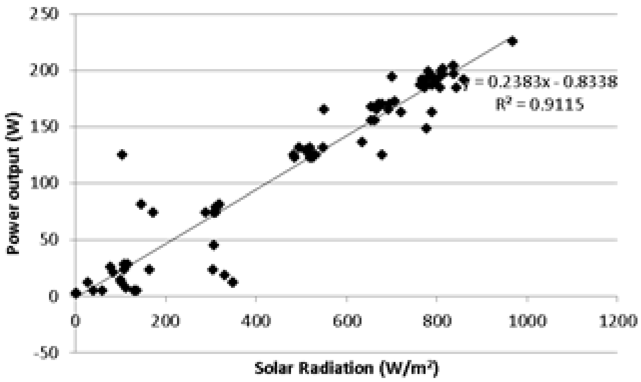


Fig. 6. Relationship between the power output of the array as response variable vs. the solar radiation as the predictor variable

Photovoltaic Array Efficiency

Figure 7 shows the efficiency of PV array for the months of December, January and February. The graph is not linear because the raw data were taken in natural environment where the solar intensity as well as the temperature were inconsistent.

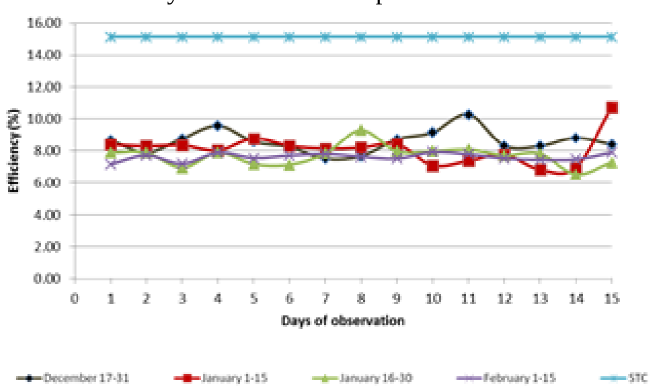


Fig. 7. Average PV array efficiency per day for the months of December, January and February

The result suggested that efficiency of the PV array was dependent on the daily available solar radiation, temperature and shading. From the observed data, Day 15 from the month of January had the highest efficiency with 10.73% which was only 4.42% below the maximum efficiency of the panel under the standard test condition (STC). The high efficiency level was due to low average temperature during that specific day with only 25.52 °C. This is comparable on a study on calculation of power efficiency of installed PV solar panels at different temperatures that basically compared the ability of the installed solar panels to convert usable energy at various times of the day from different months of observation. The efficiency of the installed PV solar panels was plotted against various times of the day and showed that the efficiency of solar cells increased with increasing solar intensity [6].

In addition, a study on analysis of PV solar cell performance with changing irradiance and temperature found out that increasing temperature leads to marginal changes in current but major changes in voltage. The temperature acted like a negative factor affecting solar cell performance, implying that, solar cells give their full performance on cold and sunny days rather than during hot and sunny weather [5].

The overall efficiency level of the PV array was lower than the manufacturer's rated conversion efficiency of 15.15% (Figure 7), this was due to mixing of two dissimilar modules wired in series. Most experienced installers observed that in two dissimilar modules that are wired in series, the voltage is still additive, but the current is only slightly greater than the current produced by the panel with the lowest current output in the series string. Therefore, there was a large difference in the output of the modules. Poor performance can be the consequence of a bad sizing or matching between the power production and the load [8]. For the designed system, the mismatched was between the rated voltage of the charge controller and the maximum power voltage of the individual panels. The initial 18.5 V modules wired in series was not able to charge the batteries because it did not meet the rated voltage of the charge controller. The only option was to mix dissimilar modules which resulted in decreased maximum power current output of 12.165 A instead of 24.33 A.

The daily PV array efficiencies were 8.60%, 7.62% and 7.91% for the 15-day observation for the months of December and February and the 31-day observation for the month of January, respectively. The overall daily average efficiency of the array was 8.0% which was 7.15% lower than the panel's rated efficiency. This means that the PV array had the ability to convert 8.0% total daily available solar radiation into usable energy.

The lower efficiency was basically due to inconsistencies of daily solar radiation and temperature compared to the rated efficiency that was tested under STC of 1000 W/m^2 incident radiation flux under 25°C. In a related study on analysis of performance of a grid-connected PV system, the mean value of the power of the modules was 9.40% lower than the rated maximum power stated by the manufacturer [9]. This is also comparable with the findings on the performance analysis of grid-connected PV system in Egypt with only 4.22% [10].

Temperature had also considerable effect on the efficiency of PV system. Efficiency increases rapidly with increasing solar radiation and decreases with the influence of a cloudy sky [7].

Power Inverter Efficiency

The efficiency of the power inverter was calculated to determine how much was the actual energy input as well as the wasted power during the conversion process. The input power was always greater than the output power. This was attributable to the fact that the inverter had some means of cooling process in times with high temperatures. The specific inverter that was used in the study has a charge thermal protection feature which automatically started a thermal exhaust fan when the temperature of its radiator exceeds 50°C. This cooling means has a sort of extra power requirement, therefore converting the potential usable energy to heat energy.

The linear representation of the inverter's efficiency throughout the day is shown in Figure 8. The highest conversion efficiency was during mid day with 92.59%. The lowest efficiency was observed during 1600 h. Ideally, the conversion efficiency starts to increase in times with greater available solar radiation while it starts to decline in times with declining solar radiation. The lowest conversion efficiency was observed from 1400 to 1600 h. The average temperatures during the 1400, 1500 and 1600 h were 29.69±1.15 °C, 29.74±1.73 °C and 28.30 ±1.15 °C, respectively. This means that the inverter had triggered its exhaust fan most of these times and this cooling means had resulted in wasted power, converting some of the drawn power to heat energy.

Even though the inverter had low converting efficiency this was still comparable to the study in the analysis on the performance of grid-connected PV system which uses a single phase Sunny Boy SB 3800 inverter that reported an average efficiency of 94.55% compared to its maximum efficiency rating of 95.6% [10].

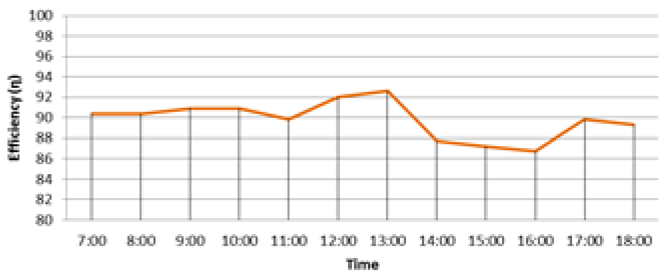


Fig. 8. Power inverter's efficiency fluctuation throughout the day.

Growth Performance

The average weight gain of the fish reared in tanks aerated by conventional system (11.78±0.715 g) was not significantly different from the weight gain of the fish reared in tanks aerated by PV system (11.38±1.574 g) (Table 1).

The mean final specific growth rate (SGR) in conventional system (5.13%/day) was slightly higher than in PV system (5.07%/day). However, the SGR in both aeration systems showed no significant difference (Table 1). The SGR of the fish from both systems was high during the first sampling period and declined as the rearing progressed. In general, low SGR was observed from both systems. This was due to low temperature of the water observed from both system with mean temperature of 26.29±0.062 °C in the conventional system and 25.86±0.211 °C in the PV system.

The mean survival rate on PV system (57.53±8.05%) was lower than in conventional system (62.35±1.49%). However, no significant difference was detected.

TABLE 1. MEAN WEIGHT, LENGTH AND SURVIVAL OF NILE TILAPIA FINGERLINGS REARED USING TWO DIFFERENT AERATION SYSTEMS.

Treatment	Mean Weight	Mean SGR	Mean Survival Rate
Conventional (Control)	11.78[a] (±0.715)	5.13[a] (±0.221)	62.35[a] (±1.495)
PV aeration system	11.38[a] (±1.574)	5.07[a] (±0.331)	57.53[a] (±8.053)

Values inside the parenthesis are standard deviation. Means within a column having the same letter are not significantly different at 5% probability level by T-test

Carbon Emission Reduction

The energy generated by the PV system does not only signifies the monetary savings it can offer. In an environmental viewpoint, the clean energy it produces has a great environmental impact. The generated kWh of energy represents the carbon emission the system had avoided.

The total emission reduction of the PV system was 35.19 $kgCO_2$. The Philippine has annual average emission of 139 $MtCO_2$ which represents a global share 0.31% [11]. Therefore the two-month operation of the PV aeration system had avoided 0.025% of the .potential annual carbon emission of the country and has contributed to the reduction of emission in the sector of agriculture by 0.20%.

Economic Analysis of the System

The capital investment for the PV aeration system was considered as the initial capital outlay of the operation. The total depreciation cost per year of the system was PhP 14,103.71. The cost of operating the aerator alone was PhP 3.69 per hour.

The computed cost of generated energy of the system was PhP 30.79 per kW. The price of the energy from using the system was 67.52% higher than the price of energy from conventional system. In economies of price, mass production of electricity had resulted to a cheaper price compared to independent generation which was the case of this study.

Renewable energy will not instantaneously address the energy problems of the sector, but implementing this kind of system on the aquaculture sector could give a positive window for a greener way of producing fish food [12]. Furthermore, the application of such technology can be cost-effective in remote locations as the price of fuel on such areas is too expensive and electric supply is unavailable.

IV. CONCLUSION

The following conclusions were drawn based on the results of the experiment: (1) The daily power output of the PV array was directly influenced by temperature, solar radiation, cloud shading and time of the day; (2) Solar radiation explains 91.10% of the variance in the power output of the PV array; (3) Growth in terms of mean final weight and specific growth rate of the tilapia reared under conventional and PV aeration system was not significantly different; (4) The avoided carbon emission using the PV aeration system was 35.19 kg CO_2 which corresponds to potential contributive reduction to average annual emission of the country's agriculture sector; (5) The cost of operating the aerator was PhP 3.69 per hour; (6) The cost of generated energy of the system was PhP 30.79 per kW which was 67.52% higher than the cost of conventional electricity. However, with the use of the system, the utilization of coal-based electricity can be avoided, thereby reducing the carbon emission in the atmosphere. Further, with higher diesel price and lower cost of PV panel in the future, the payback period will be reduced significantly, thus making it more attractive in the future.

Based on the stated conclusions, the following recommendations are considered: (1) Design of a movable array mounting pole to direct the array where the sun's inclination angle is, thus maximizing output of the array; (2) Deployment of the system in grow-out production of tilapia to have a higher revenue, thus maximum economic feasibility potential of the system can be viewed; (3) Research on the emission reports of the electricity distributing company to determine that exact emission reduction of the system where it has been deployed; and (4) Investigation on possible cost reduction of the system by reducing the number of batteries which covers more than 50% of the total system cost.

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