Design, Operation, and Analysis of a Floating Water Fountain System Using Renewable Energy Technology

Hans Chapman, Eduardo Gomez, Nilesh Joshi, and Sanjeev Adhikari

Abstract

Engineering and technological applications of renewable energy installations, such as photovoltaic (solar) energy, are making important contributions toward the development of environmentally friendly products and processes for a more sustainable future. This article presents the design, assembly, and operation of a solar powered floating fountain system for analysis of aeration in stagnant water. The goal was to increase the level of dissolved oxygen in a body of water by harnessing solar energy for submerged aeration. The system is composed of six solar panels, a kit of batteries, a linear current booster, pressurized water tank, two pumps, an air compressor, and a float. The design factors for dissolved oxygen (DO) measurements were determined from depth of water, time of the day, location of fountain, and status of fountain (on or off). A Split Plot design was used to investigate the performance of the fountain, based on the changes in levels of DO in the pond. Statistical analysis showed a 120% gain in DO concentration during a 20-day period with significant destratification of the pond. This applied research will be of interest to engineers and technologists in various areas, including environmental development, green construction, and aquatic and energy conservation.

Keywords: Renewable Energy Technology, Solar Powered Fountain, Aeration, Dissolved Oxygen.

Introduction

Photovoltaic (PV) renewable energy systems offer new alternatives for consumers and businesses as to how power can be provided. PV systems react to light by transforming part of the radiant energy into electricity. PV cells require no fuel to operate, produce no pollution, require little maintenance, and are modular. These attributes permit a wide range of solar - electric applications (Markvart, 1999; Marshall & Dimova-Malinovska, 2002; Dunlap, 2010). Other advantages of PV systems include: unlimited input solar energy, reliable power output, flexibility in assembly, and easy installation (Boyd, 1997; Butler & Sinton, 2004).

Pumps are useful devices for the operation of water fountains. Fountains are installed on water bodies, like ponds, streams, and lakes, to prevent destratification of the water (Michaud & Noel, 1991; Lynch & Commer, 1994). Water pumping is one of the most competitive areas for PV power. PV pumping systems pump most water during the sunniest, hottest days of summers. PV pumping systems have, as a minimum, a PV array, a motor, and a pump. In addition to water pumping, PV systems can also be useful for aeration of water bodies.

Natural stream purification processes require adequate dissolved oxygen levels in order to provide for aerobic life forms. When pollution enters a body of water, plant and algae die and sink to the bottom, resulting in an overload of organic sludge. A lower form of life in lakes and ponds die and this debris eventually rots. Oxygen solubility has been shown to increase with decreasing temperature, salinity and pressure (Wieland & Kühl, 2006). When dissolved oxygen (DO) is at saturation level, the number of oxygen molecules leaving the water surface equals the number entering (no net movement) (Michaud & Noel, 1991). Below DO saturation, there is a net movement of oxygen from atmosphere to water. The greater the difference between the oxygen pressures in the water and the atmosphere, the larger the movement of oxygen from the atmosphere to the water.

System Design

The solar powered water fountain (SPOWF) was designed to enhance dissolved oxygen levels in a test pond at Innovation Park, Tallahassee, Florida. The three primary components for producing electricity using solar power are: solar panels, a charge controller, and batteries. Solar panels charge the batteries, and the charge regulator or linear current booster (LCB) ensures proper charging of the battery. The system was designed in two main parts (the fountain and the aerator). The water fountain adds oxygen to the water body by exposing the water to the external air. The aerator provides air bubbles into the body of

Table 1. Loads and Their Electrical Ratings for the Fountain

Description	Volts	Amps	Watts	Amp –hour /day
Submersible pump	24	4	96	48
Surface pump	24	6	144	72

water by using an air supply line from an air compressor. A different electrical circuit was designed for each part. The required solar panels and batteries were placed onshore and the loads were located offshore. The loads of the fountain include a submersible pump, a surface pump, and the air compressor.

Design of the Fountain

The fountain design consists of (i) solar array, (ii) deep cycle batteries, (iii) pumps, and (iv) pressure tank. The loads for the fountain are shown in Table 1.

The number of solar modules in parallel required was 3. It was also determined that 2 modules in series were required for the 24 Volts battery, making a total of 6 batteries.

Deep-cycle Batteries

The capacity of the deep-cycle batteries used for a total of 432 Amp-hours (assuming 3 days in the week without sun and a correction factor of 1.2) was determined to be 4 batteries in series.

Pumps and Pressure Tank

Two pumps were chosen:

- A positive displacement 3-chamber diaphragm submersible pump with a total vertical lift of 70 meters, a flow rate of 8.6×10^{-4} m^3/s, and a maximum pressure of 6.9×10^5 N/m^2.
- A surface pump with a vertical lift of 9.1 meters, a flow rate of 3.3×10^{-5} m^3/s, and a maximum pressure of 3.1×10^5 N/m^2.

Figure 1 is a schematic diagram of the fountain showing how the panels, batteries, actuator, and pumps are connected. Considering the pressure and flow rate of the pumps, a 0.13 m3 tank was chosen. Additionally, a "cut-in 2.1×10^5 N/m^2 / cut-out 3.4×10^5 N/m^2" pressure switch and a pressure gauge were attached to the tank.

Design of the aerator

The aerator is comprised of one item each from the following: 7.2 Amps solar panel, 6- Amp air compressor, 6.1 m #12 AWG wire, 15 Amps charge regulator, 12 Volts battery, and a plastic case. A 0.13 m diameter, 1.68 m long PVC pipe was chosen, and a 90˚ elbow was glued at the top of the pipe to transport the air bubbles from the bottom to the surface of the lake. Four radial holes were drilled six inches from the end of the pipe to hold the air stones in place, using plastic fittings. The air stones were interconnected to a 9.5×10^{-3} m flexible hose. The hose was connected to the air compressor located on top of the fountain as shown in Figure 2. The PVC pipe was then strapped with two 0.91 m x 0.04 m aluminum flat bars. One side was welded to the SPOWF aluminum structure, and the other side bolted to the pipe as showed in Figure 2.

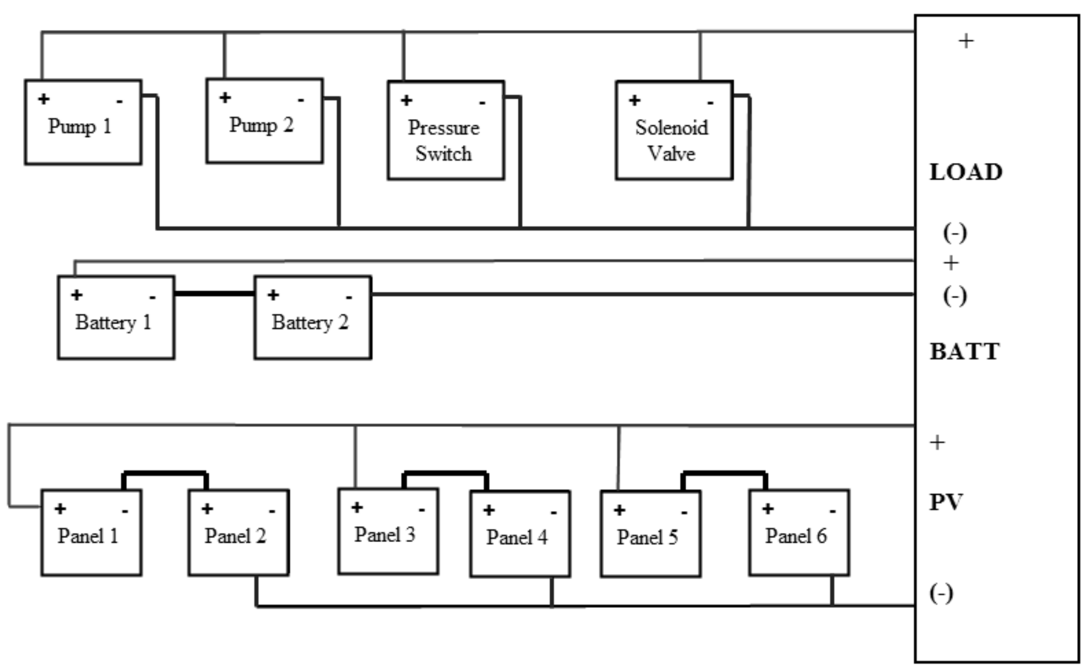


Figure 1. Schematic Diagram Showing the Arrangement of Pumps, Batteries, and Solar Panels in the Fountain Design

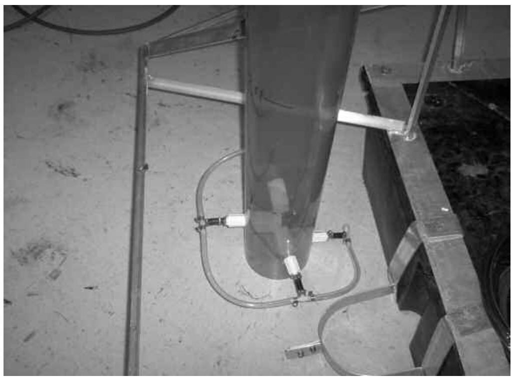


Figure 2. Photos of the Solar-powered Water Fountain (SPOWF) ***[Top]: SPOWF unit under construction, showing the aeration system (vertical tube), blue water tank, aluminum frame, base float, and electrical wiring for connecting the panels, batteries, and actuator. [Middle]: Close-up view of the bottom part of the aerator, revealing arrangement of air stones. [Bottom]: Fully assembled SPOWF unit***

System Operation

When the SPOWF system is turned on, both pumps constantly pump water into the tank through the one-way valve. As the water flows into the tank, the pressure in the tank increases steadily to 3.44 x 10^5 N/m^2. At this critical pressure, water is jetted of the fountain through the nozzles. The flow stops when the pressure drops below 2.1 x 10^5 N/m^2, and the pressure switch shuts off to rebuild the pressure in the tank. This sequence is continued as long as there is enough current flow to power the loads (Braimah, 2004; Gomez, 2006).

The purpose of running both the fountain and aerator together was to maximize the daily water circulation. The voltage output of the PV panels is often too low to run the pumps under these conditions. To offset this limitation, it was necessary to operate an energy booster with the system. The linear current booster (LCB) works by enhancing the output current from two batteries, especially under low light conditions, cloudy days, and early morning or late evening.

System Analysis

Cause-and-effect diagram

A cause-and effect diagram was developed for the SPOWF system as shown in Figure 3. From this diagram, the factors were classified as design factors, factors held-constant, and nuisance factors. The design factors were: depth of the water, time of the day, location of the fountain, and the status of the fountain i.e., ON or OFF. The factors held-constant were variables that could modify the response, but for the purpose of this experiment, these factors were not of interest, so they were held at their specific level. Some of them were: filters, fountain, solar panels, and pumps. Nuisance factors, on the other hand may have a large effect that must be accounted for. The nuisance factors considered in this experiment were: barometric pressure, temperature of the water, cloudiness, and air temperature.

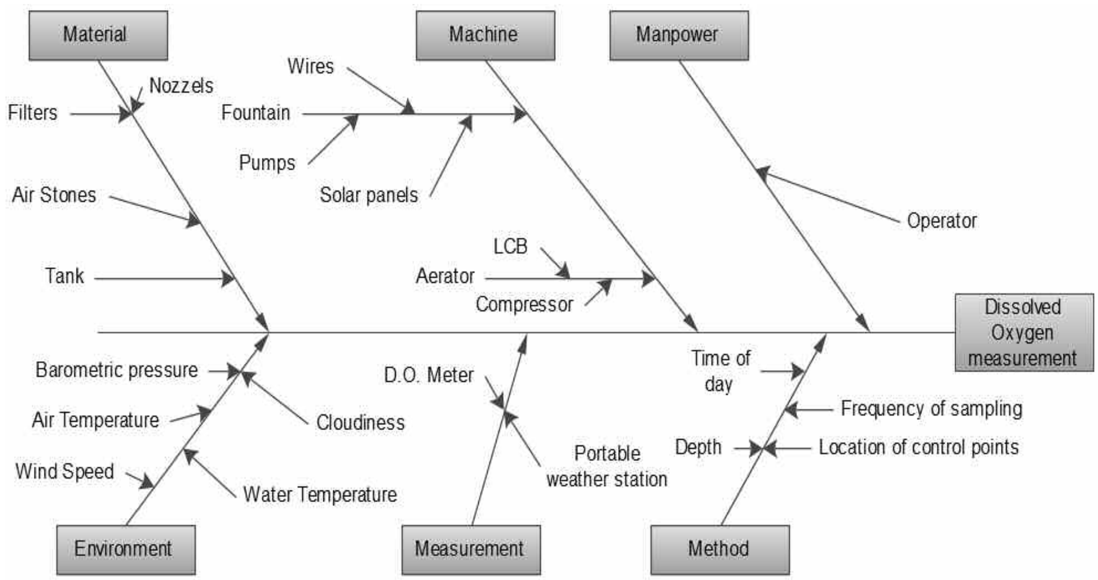
Dissolved oxygen measurement

The dissolved oxygen meter provided the reading of the concentration of dissolved oxygen as well as the depth and temperature of the water. Measurements were done every day at 7:00 AM and 1:00 PM during 20 consecutive days in October and November. Table 2 shows the data set after measurements were taken.

Estimated general linear relation for final model

The final estimated model equation in terms of coded units with all the statistically significant terms was determined for two scenarios, i.e., "Fountain Off" and "Fountain On" as indicated below:

Figure 3. Cause-and-effect Diagram for the Solar-powered Floating Fountain



Fountain OFF

DO = 4.63 **-** 0.5244 (Location) + 0.3569 (time of day) (7)

Fountain ON

DO = 6.0455 – 1.0238 (Location) + 0.7138 (time of day) (8)

Interactions between "fountain with location" and "fountain with time of day" are evident in the differing coefficient estimates for location and time of day for "fountain off" vs. "fountain on", respectively. A response surface analysis (Simpson, Kowalsky, & Landman, 2004) was performed and the results are shown in Figure 4.

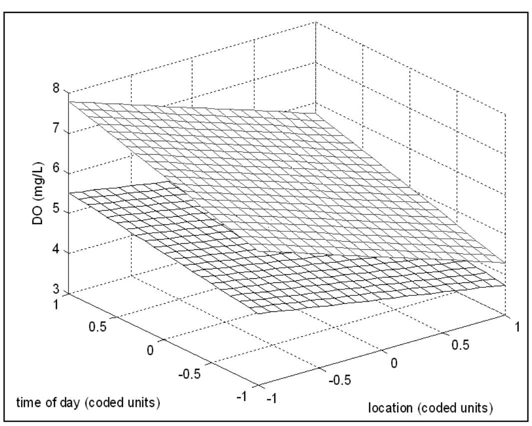


Figure 4. Response Surface for Dissolved Oxygen (DO) as a Function of Location and Time of Day, When Fountain is ON (top) and Fountain is OFF (bottom)

In order to accurately predict DO as a function of location and time of day, a transformation from natural to coded units (Myers & Montgomery, 2002; Montgomery, 2005) should be made prior to applying the model as shown in Eqs. 7 and 8, respectively.

In general,

$$\text{Coded units} = \frac{NU - [Min + Max]/2}{[Max - Min]/2} \qquad (9)$$

Where, *NU* is the value in natural units

Min is the (-1) value of the factor in natural units

Max is the (+1) value of the factor in natural units.

Table 3 shows an example for calculating DO at a location, 3.7 m away from the fountain at 9:00 AM.

Final model charts

The first datum for the fourth subplot was collected again, after 12 days, with the fountain in the OFF status. It was observed that the aeration effect due to the floating fountain had disappeared. Consequently, the measured DO levels were at the original values as shown in Figure 5. This new information is valuable because it can be inferred that the experiment was time independent.

Table 2. Data Set Collected Indicating Factors and Response (*dissolved oxygen measurement*)

Day	Depth of water (meters)	Time of day (hours)	Location (meters)	Status of Fountain (On / Off)	Air Temp (°K)	Water Temp (°K)	Cloudiness (0 or 1)	Wind speed (m/s)	DO (mg/L)
1	0.3	13	1.52	Off	291	293	0	2.24	4.5
2	1.52	13	7.62	Off	291	291	1	0.45	4.7
3	0.3	7	7.62	Off	280	293	1	0	4.8
4	0.91	10	4.57	Off	291	292	0	1.34	4.6
5	1.52	7	1.52	Off	279	291	0	0.89	4.5
6	1.52	7	1.52	On	279	291	0	0.45	6.4
7	0.3	7	7.62	On	282	291	1	1.34	7.1
8	0.3	13	1.52	On	301	298	0	0.89	6.1
9	0.91	10	4.57	On	292	295	0	1.34	9.8
10	1.52	13	7.62	On	295	291	0	0.89	7.6
11	1.52	13	7.62	On	297	292	1	0.45	10
12	1.52	7	1.52	On	283	294	1	1.34	6.4
13	0.91	10	4.57	On	295	295	0	0.89	6.3
14	0.3	13	1.52	On	299	296	1	0.45	7.1
15	0.3	7	7.62	On	284	299	0	0.45	7.8
16	0.3	13	1.52	Off	300	302	1	1.34	4.6
17	0.91	10	4.57	Off	295	299	0	1.34	4.7
18	0.3	7	7.62	Off	285	299	1	1.79	4.6
19	1.52	7	1.52	Off	282	293	1	2.24	4.8
20	1.52	13	7.62	Off	295	296	1	2.24	4.5

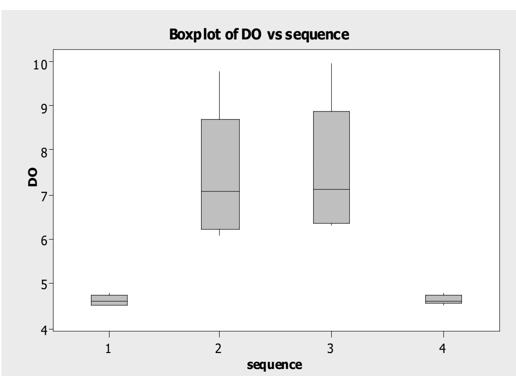


Figure 5. Box Plot of DO Concentration Showing Time Independent Effect

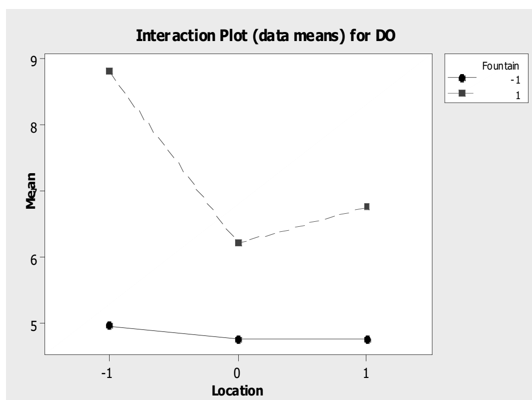


Figure 6. Interaction Between Fountain and Location Set Up at Two Levels

Table 3. Natural to Coded Units Transformation for Dissolved Oxygen Measurement, 3.7 m Away from the Fountain at 9.00 AM

Natural Units		Coded Units		DO (mg / L)	
Location	Time of Day	Location	Time of Day	ON	OFF
3.7 m	9:00 AM	-0.30	-0.33	6.1147	4.66

The interaction between the fountain and its location is shown in Figure 6. When the aeration system was in the OFF status, the DO concentration was observed to be 4.95 mg / L at 5 feet away from the fountain. At the same location when the aeration system was in the ON status, the value for DO was 8.8 mg / L. At the high level of location (7.6 m away from the fountain), the results were similar. When the fountain was OFF, the DO was 4.75 mg/ L and when the fountain was ON, the DO reached 6.75 mg/L. Note that there was a difference for the center point between fountain OFF and ON. The DO changed from 4.75 to 6.2 mg /L respectively.

Figure 7 shows the interaction between fountain and time of day. There was an increase in DO at different times of day whether the fountain was ON or OFF. However, the magnitude of the increase depended on the fountain status. When the fountain was ON, the DO value increased from 7.06 mg /L at 7:00 am to 8.49 mg / L at 1:00 pm. When the fountain was OFF, the DO value changed from 4.75 mg / L to 4.85 mg / L. As with the interaction between fountain status and location, the center point responded differently when the fountain was ON compared to OFF mode. The accepted minimum level of dissolved oxygen required for aquatic species is 6 mg/L (Hondzo & Steinberger, 2002). Results indicated that the floating fountain achieved the minimum desired level of dissolved oxygen.

Cost Analysis of the Floating Fountain

Table 4 lists the materials, labor and maintenance cost for the floating water fountain system. All cost items have been rounded to the nearest $50. Small-scale solar PV installations require minimum yearly maintenance, if any. Thus, a lifetime maintenance cost of $1,000 is included.

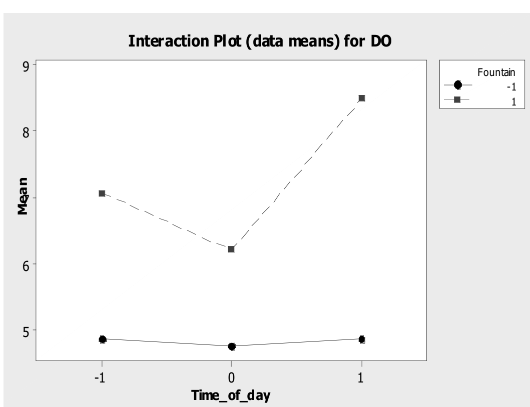


Figure 7. Interaction Between DO and Time of Day When the Fountain is ON and OFF

Total Cost = Materials Cost + Labor Cost + Maintenance Cost
= $6,600.00 (4)

On the other hand, assuming that the fountain is powered entirely by utility grid electricity, the total estimated amount of Kw used during operation of the Floating Fountain is as follows:

Fountain:
(24 V x 8.4 Amp) x 24 hours = 4.8 kw-hr/day (5)

Aerator:
(12 V x 6.4 Amp) x 24 hours = 1.8 kw-hr/day (6)

The Total usage is 6.4 kw-hr/day.

Thus, the estimated annual output in kw-hr/year is equivalent to 2340 kw-hr/year

If the cost of electricity (utility)
= $ 0.2175 / kw-hr (for Tallahassee, FL)
= approximately $500 / year

(*assuming no inflation and no increase in electricity tariffs*)

The use of grid electricity will require all the materials listed in Table 4, with the exception of the PV modules and batteries.

Table 4. Materials, Labor and Maintenance Cost of the Floating Fountain

Description	Cost ($)	Subtotal ($)
Materials		**5,000.00**
Modules	3,000.00	
Pumps	300.00	
Structure	500.00	
Tank	300.00	
Plumbing	100.00	
Compressor	200.00	
Batteries	200.00	
Hoses and fittings	150.00	
Linear current booster	150.00	
Wiring	100.00	
Labor	600.00	**600.00**
Maintenance	1,000.00	**1,000.00**
Total		**6,600.00**

Since the cost of solar PV modules and batteries is $3,200, the above analysis yields a payback period of 3,200 / 500 = 6.4 years, which is economically profitable, considering that the useful life of photovoltaic modules is 20 – 30 years. There is also the added environmental benefit of using solar energy.

Conclusion

Solar-powered appliances present unique advantages over traditional devices. The Solar-Powered Water Fountain (SPOWF) system manufactured and tested in this work achieved its main function, i.e., aeration of a selected water body with the aid of the aerator and fountain. Consequently, the dissolved oxygen (DO) concentration was increased significantly from a low level of 4.5 mg/L to a high of 9.95 mg/L, an increase of about 120%. Statistical analysis of the data (DO measurements) was conducted using a Split Plot Design. This mathematical model described a linear relationship between the primary operating factors, location of the aerator and time of the day, and the output, DO.

Economic analysis conducted using a payback period approach, by comparing the solar generated power with the utility grid electricity, yielded a payback period of 6.4 years. Considering that photovoltaic systems have a useful life of between 20 to 30 years, this payback period is profitable both economically and environmentally, considering the enormous benefits of the aerator / fountain unit to aquatic life.

The SPOWF system has immense potential commercialization opportunities. Possible consumer markets include environmental, building and construction, parks and gardens, private homes, estate developers, aquatic, and energy conservation.

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