Energy Analysis and Solar Photovoltaic System Sizing for a Sub-Wet Bulb Evaporative Cooling System in Tropical Climate

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Abstract: This study presents the design of a solar photovoltaic (PV) power system designed from the first principle to power a 1 kW Sub-Wet Bulb Evaporative Cooling (SWEC) system for building comfort applications in Owerri, Nigeria. A cooling load of a pilot office space was estimated following ASHRAE standards, yielding a design cooling load of 0.978 kW (approximately 0.3 tons of refrigeration) at 8-hour daily operation. This load informed the sizing of SWEC components at a heat exchanger area of 1.4 m² and a total electrical load of 303 W comprising fan, pump, and data logger/ control system. The solar photovoltaic (PV) power system sizing were carried out considering system losses, depth of discharge, 8-hour noontime sunlight of Owerri, Nigeria. The results show that a 400 W solar array with a battery bank of 303 Ah at 12 V, configured as two 150 Ah batteries in parallel effectively powered the system, at an energy yield of over 7% more than the power needed to power the cooling system. The result demonstrated the viability of solar-powered evaporative cooling system for sustainable building applications.

Keywords: *Sub-Wet Bulb Evaporative Cooling, Solar Photovoltaic System, Cooling Load Estimation, Sustainable Cooling.*

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I. INTRODUCTION

The need for space cooling is growing steadily at the rate of 3.3% anually [1] and this has led to a surge in building energy consumption from conventional air-conditioning systems. Vapor compression systems are energy-intensive, consuming 20 – 30% of total building energy [2] and contribute significantly to greenhouse gas emissions [3;4]. Hence, alternative cooling technologies that could be powered by renewable energy sources are gaining global attention [5]. Evaporative cooling systems, particularly Sub–Wet Bulb Evaporative Cooling (SWEC) which by utilizes the principles of heat and mass transfer [6; 7], offer a low-energy space cooling alternative suitable for tropical climates when integrated with solar photovoltaic (PV) system. SWEC system offers a sustainable solution, especially in regions with high insolation such as Owerri, Nigeria. Photovoltaic (PV) system are widely accepted globally, as green energy source with great advantage owing to their simpler mechanism. PV panels converts energy from the sun to electrical power, using semiconductor materials [8].

In this study, a solar PV system will be designed to power a Sub-wet bulb evaporative cooler specifically designed based on the comfort cooling need of an office space. The design execution will be based on estimated cooling load of the space, ventilation rate, and component sizing [9;10]. The integration of solar energy aligns with global renewable energy transition goals and offers practical solutions for office applications with daytime cooling demand.

The research objectives include cooling load estimation for a pilot office space in Owerri, Nigeria, component sizing of the SWEC system based on established design principles, and design of the solar PV array and battery bank requirements for autonomous operation.

II. LITERATURE REVIEW

Previous studies have established methods for cooling load estimation and evaporative cooler design. Ibe and Anyanwu [11] emphasized systematic cooling load evaluation prior to Heating, Ventilation and Air-Conditioning

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system design. The American Society of Heating, Refrigerating and Air-Conditioning Engineers provides standardized procedures for calculating sensible and latent heat gains in buildings [9;10].

Sibanda [12] integrated a solar PV system with an indirect evaporative cooling system for preservation of vegetables in South Africa.The research discussed considerations in evaporative cooling system's PV Solar power design, adopting a 50% depth of discharge for system that runs for 24-hours each day.

Anarbaev, Zakhidov, & Mukhtarov [13] reported the study of a 200 W solar powered evaporative cooling systems under the Ubekistan climatic condition. They reported lower energy consumption by the system. Battery sizing methodologies for renewable systems were discussed by Linden [14], highlighting the balance between depth of discharge and battery lifespan.

However, limited literature integrates detailed SWEC cooling load estimation with complete solar PV sizing for small-scale comfort applications. This study bridges that gap by presenting an integrated design approach.

III. METHODOLOGY

The design of a solar power system for the purpose of powering a SWEC system for comfort cooling application in building is thus presented in this section. The design of the solar power system will be based on the cooling load which is the cooling required to be provided by the SWEC system per time to meet the design comfort requirement of the space. The cooling load determines the ventilation rate and the water requirement as well as size of the heat exchanging area of the SWEC system. The ventilation rate is a function of the fan rating and size while the water requirement and the total heat area is a function of pump parameters [15]. Hence, the solar power system configuration will be estimated from the sum of energy required by the components of the cooling machine which include; the fan, pump, data logger/ control system. Therefore, the electrical load determines the size and capacity of the solar power system with safety factor.

- *Cooling Load Estimation*

The development of an efficient cooling system for comfort application, is a function of proper cooling demand estimation [11]. The proposed system is meant to meet the cooling demand of the room by handling the heat load per time [6].

The heat load are broadly classified as Transmission heat gains, internal heat gains and outside heat gains respectively. The heat load was calculated in line with ASHRAE [9;10] and also using standard equations in literature as shown in Table 1

Table 1 Estimation of Cooling Load of the SWEC System

Heat gain Equation	Sources	Sensible (KW)	Latent (KW)	Total (KW)
Transmission Heat Gains $Q = U \times A \times CLTD$ (1) U =Thermal transmittance (W/m^{2}K); A = wall surface Area (m^2) $CLTD$ = Cooling load temperature difference	Walls	0.162		0.162
	Roof	0.048		0.048
	Floor	Nil		0
$Q_{g1} = U \times A \times (T_{i-d} - T_{r-d})$ (2) $Q_{g2} = A * MSHG * SC * SLF$ (3) Q_{g1}= Heat transmission due to temperature difference (KW) Q_{g2}= Heat transmission due to direct /scattered radiation (KW) T_{r-d} =Room dry bulb temperature [°C]. T_{i-d}= ambient air dry bulb temperature [°C] $MSHG$= Maximum solar heat gain (W/m^2) SC = Shading coefficient ; SLF = Storage load factor [11].	Glazing	0.5		0.5

Internal Heat Gains				
$Q_{occupancy} = \frac{Q}{360 \times n}$ (4) Q = Sensible heat + latent heat by occupant(s) in (kj/hr) n = number of hours of work	Occupancy	0.067	0.056	0.123
$Q_{lighting}$ = Power of rating of bulbs	Lighting	0.005		0.005
Power of rating of Equipment(s)	Equipment	0.003		0.003
Outside Air Load				
$Q_{vs} = mC_P \times (T_{i-d} - T_{r-d})(KW)$; (5) $Q_{vl} = mL \times (W_i - W_P)\ (KW)$ (6) Q_{vs} = ventilation sensible heat gain Q_{vl} = ventilation latent heat gain m = mass of inlet air (kg/s) C_P =heat capacity of inlet air (KJ/KgK) W_i= moisture content of ambient air (kg/kg of dry air) W_P = moisture content of room air (kg/kg of dry air) L = latent heat of vapourization [9;10]	Ventilation	Nil	Nil	0
$Q_{Is} = m_I C_P \times (T_{i-d} - T_{r-d})(KW)$; (7) $Q_{Il} = m_I L \times (W_i - W_P)\ (KW)$ (8) Q_{Is} ; Q_{Il} = infiltration sensible and latent heat gains respectively m_I = mass of outside air that infiltrated (kg/s)	Infiltration	0.041	0.0071	0.0481
Total		0.785KW	0.0631KW	0.889KW

Therefore, applying Safety factor, we have;

$$Design\ load\ (Cooling) = Estimated\ load \times 10\%\ safety\ factor \quad (9)$$

$$Design\ load\ (Cooling) = 0.889 \times 1.1 = 0.978KW$$

➢ *Determination of Required Air Quantity*

The SWEC Air-cooler uses a fan to draw hot ambient air channel into the heat-exchanger of the system, thus creating an evaporative cooling effect when the air comes in contact with wetted pad in the indirect heat-exchanger. According to ASHRAE [9]; Bellaney [16] for tropical air-conditioning, the quantity of airflow required to satisfy the room cooling load; V (m^3/s), is determined using eqns 10;

$$V = \frac{RSH}{\rho C_P\ (T_{r-d} - T_{P-d})} \quad (10)$$

Where,

RSH = Room sensible heat (KW), evaluated as $0.864KW$ at total load of 0.978kw
ρ = density of product air ≈1.0 kg/m^3
C_P = specific heat of humid air ≈ 1.025 Kj/KgK (neglected)

Designing for a dry-bulb temperature difference of 10°C, between ambient and inside the room, gives;

$$V = \frac{0.978}{1 \times 1.025 \times 10} = 0.0954\,m^3/s \cong 0.1\,m^3/s$$

Hence, fan sizing is shown in Table 2.

➢ *Pump Sizing*

The quantity of cooling needed to satisfy the cooling load of the space is dependent on the accurate sizing of the evaporating heat exchanging area of the SWEC system, which will then determine the pump rating.

Where V = 0.1 m^3/s, we have;

$$0.1 \times 35.315ft^3 \times \frac{60}{minute} = 211.9CFM \quad (11)$$

Designing for a multi-plate evaporative cooler, effective surface area is calculated. Refer to eqn 12 [17], given as

$$A_{evap} = \frac{CFM}{Cooling\ capac\ ity\ per\ ft^2\ of\ pad} \quad (12)$$

Applying a locally sourced wetting pad of poorly weaved cotton cloth (cooling capacity per ft^2 of pad is unknown), eqn 13 [18] gives the evaporating area of the heat and mass exchanger;

$$V = A_F \times v \times Conversion\ factor \quad (13)$$

Where;

V =Air flow rate in m^3/s
A_F =Face Area (m^2)
v = Recommended face Air velocity, from literature Sibanda, 2019)

The recommended rate of water application in SWEC system for a high cooling efficiency is in the range of 4 to 4.76L/min.m^2 [7,19].

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Hence, for $1.4m^2$ cooling area, total water flow rate, Q_T; is given by eqn 14 as

$$Q_T = A_T \times W_{AR} \quad (14)$$

Where,

W_{AR} = Rate of water application = 4.0 L/min.m²

$$Q_T = 1.4m^2 \times \frac{4L}{min.m^2} = 5.6\ litres\ per\ minute$$

Therefore, the pump sizing is shown in Table 2

Table 2 Sizing of the Electrical Components of the Sub Wet Bulb Evaporative Cooling System

Design Parameters	**Design Equations**	**Corresponding values**
	Sizing of pump	
Total Dynamic Head (TDH) for pump	$TDH = Static\ head + Friction\ loss + Additional\ losses$ (15)	0.7m
Pump power requirement	$P = \frac{\rho \times g \times TDH \times Q_T}{3600 \times \eta}$ (16)	100 watts
Voltage		DC 12v
Flow rate		≈ 8L/min
	Sizing of Fan:	
Head drop	$\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + Z_2 + h_L$ (17)	500pa
Fan power		200 watts
Volume flow rate		$0.1\, m^3/s$
Power for control system / datalogger		3watts

Where P = power rating of pump, ρ = density of water (kg.m-³), g = acceleration due to gravity (kg.m. s-²), TDH =Total dynamic head, Q_T = flow rate (m³/hr), η = pump efficiency = 0.85, P_1 *and* P_2 = static pressures at inlet and exit, v_1 *and* v_2 = The fluid velocities at inlet and outlet; Z_1 *and* Z_2 = Elevations; $Z_1 - Z_2 = 0$ (for horizontal configuration), h_L = total head loss.

Figure 1 shows the layout of the Sub-wet bulb evaporative cooling system and the solar PV system.

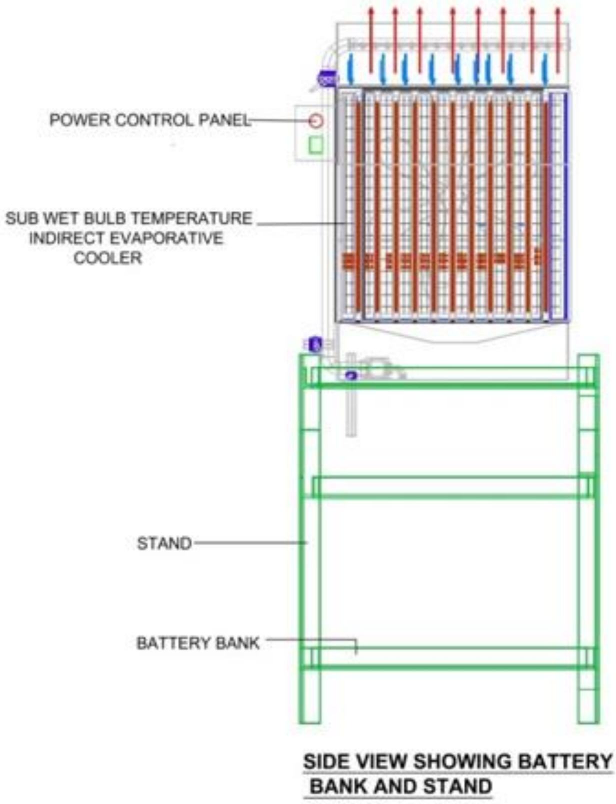

Fig 1 Front View Showing Battery Bank

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➢ *Sizing of the Solar Power Unit of the SWEC system*

- *Sizing of Panel and Battery*

The size of solar photovoltaic system designed as renewable energy source to power the SWEC system depends on the amount of power required by the electrical components of the SWEC system . Other variables to be considered include the number of hours of operation of the components and sunshine hours. These will determine the size of battery and panel to be selected for the solar PV system.

This system is designed to operate for 8-hours daily (9am-5pm) as it is an office room. The components and their electrical load rating are; Pump (100W), Axial fan (200W) and Datalogger with 4-unit of. 5-K thermocouple / control unit (3W).

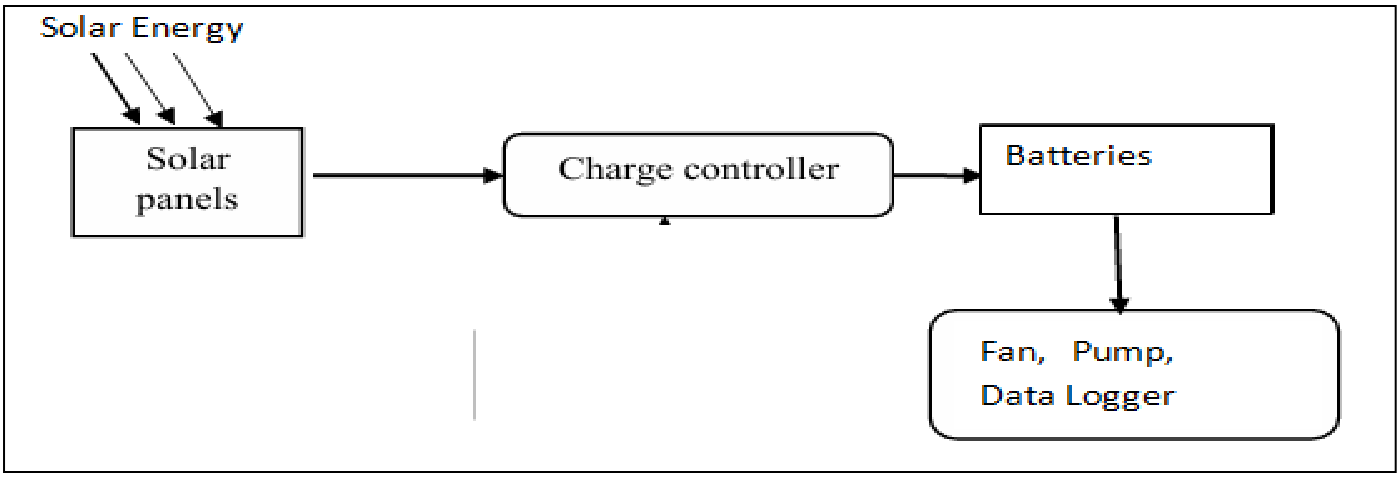

Fig 2 Schematic Diagram of the Solar Energy Process Flow

The total connected load to the solar PV unit is 303 watts, therefore daily watt-hour rating of the SWEC system is given as;

$$\text{Daily Rating} = \text{Power Consumption} \times \text{Hours of Operation} \times \text{Loss factor} \quad (18)$$

Where Loss Factor = 1.2 owing to natural losses in the system [14; 15].

Therefore, $\text{Daily (wh)} = 303 \times 8 \times 1.2 = 2908.8\ \text{Wh}$

$$\text{Hourly power generation} = \frac{\text{Daily Rating}}{\text{Sunshine hours}} \quad (19)$$

However, to balance shelf life and cost of buying batteries respectively, the present design, selected a depth of discharge of 80% [14]. This is feasible using modern Lithium deep cycle batteries (LiFePO4)

Therefore,

$$80\%\ \text{depth of discharge of the battery} = \frac{2908.8\ \text{Wh}}{0.8} = 3636\text{wh}$$

Converting to Amp-hours (Ah),

$$\text{Battery bank size} = \frac{\text{Total battery capacity (wh)}}{\text{System voltage (v)}} \quad (20)$$

$$\text{Battery bank size} = \frac{3636}{12} = 303Ah$$

Therefore,

based on the AH of battery Available in the Market, this solar PV module will require a minimum of $303Ah$ battery bank capacity to deliver the required $0.278\ tons$ of cooling. The present design selected a 2-unit of 150AH of batteries for the PV unit.

- *Sizing of Solar Array Based on Owerri Insolation data*

Ndukwe [20] puts the monthly mean hourly insolation of Okigwe near Owerri at 1011.85W/m^2 and 8 hours of noontime sunlight, while Mong et al. [21] reported 900 W/m^2 for Owerri. Both reports suggest the region's solar resource.

$$\text{Required Solar Array power (W)} = \frac{\text{Daily Energy Need (wh)}}{\text{Peak Sun Hours (h)}} \quad (21)$$

$$= \frac{2908.8}{8} = 364W$$

Further accounting for losses in wiring and charge controller, a solar panel array rated 400W will be ideal for the design.

- *Sizing the Charge Controller*

Standard practice suggests oversizing charge controller by 25% in order for the system to handle surges, when panel produced more than the rated current.

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Evaluating the Solar Array current, we have

$$\text{Solar Array Current (A)} = \frac{\text{Solar Array power (W)}}{\text{Solar Array Voltage (V)}} \quad (22)$$

$$= \frac{364W}{12\text{V}} = 30.3\text{A}$$

Applying the safety factor, we have,

$$\text{Solar Array Current (A)} = 30.3\text{A} * 1.25 = 38.0\text{A}$$

Therefore, a 12V, 40-50Ampare MPPT charge controller is a great choice and readily available in the market for this design.

Note that the system does not require an inverter since the appliances to be powered are all Direct Current systems.

IV. RESULTS AND DISCUSSION

A solar PV system was successfully integrated with SWEC system of 1kw refrigeration and DC power requirement of 303W with the electrical load distribution of components shown if figure 3, indicating that fan accounts for the highest energy consumption, which is consistent with airflow requirements reported in literature [15]. The cooling system was adequately powered by a PV system of battery capacity of 303 Ah at 80% depth of discharge [14], a solar array of 400 W with a charge controller of 12v. 40 – 50 A rating. The power generated when tested was at an energy yield of over 7% more than the power needed to power the cooling system. The system design aligns with regional solar insolation values reported by Ndukwe [20] and Mong et al. [21], confirming feasibility.

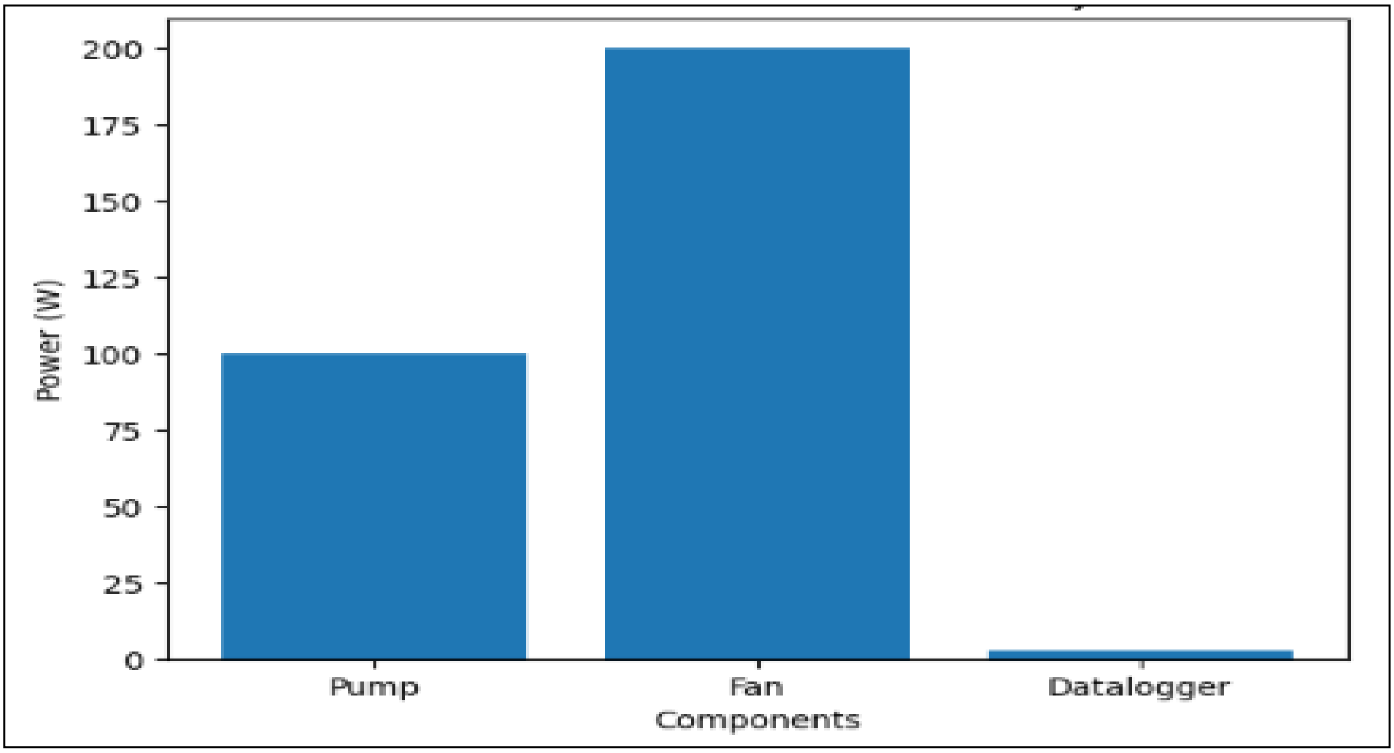

Fig 3 Electrical Load Distribution of Sub We Bulb Evaporative System

The result aligns with reports in literature [14;15] and other solar engineering standard.

V. CONCLUSION

The findings demonstrated that the integration of solar PV systems on SWEC technology is technically viable, energy-efficient, and environmentally sustainable. The approach provides a promising pathway for reducing the huge stress on electrical grid and operational costs in small buildings, caused by conventional air-conditioning system, particularly in regions with high solar potential as Owerri, Nigeria.

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