Hybrid renewable/grid power systems, an essential for base transceiver station penetration in Rural Nigeria

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ABSTRACT

The energy crisis in Nigeria has continued to impede the rapid expansion of the telecommunication industry, whose operating expenditure is galloping due to over-dependence on diesel generators as an alternative source of power to its base transceiver station (BTS). This fossil-fuel power source has also increased the industry's carbon footprint. As a solution to these problems, the objective of this work is to provide a sustainable and quality hybrid DC power supply system for BTS that would increase access to information and communication technology or ICT infrastructure. This involves the integration of solar & wind energy with the grid. The sizing of the hybrid sub-systems was designed & simulated using MATLAB Simulink to test for functionality. A prototype of the design system was then implemented with the results showing an average power output that guarantees 21 hours/day of supply. By installing this hybrid system of 1.3 kW, approximately 2.55 kg of diesel (C10H20) would be un-utilized by one BTS, thereby preventing 3.6 kg of CO_2 from been emitted to the atmosphere daily. Extrapolating these values shows 930.75 kg of diesel can be saved and reduce 1314 kg of CO_2 emission within a year. Hence eliminating the need for diesel-backup generator for a grid connected or non-grid BTS sited in rural areas.

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1. INTRODUCTION

Today, several issues are related to energy demands such as industrial growth, food security, transport, social dynamics, and quality of life. In Nigeria, the expected techno-social-economic growths are impeded by the meagre average 3,600 MW/day (out of the 12,522 MW installed capacity) of the national grid power. The information and communication technology (ICT) sector consumes roughly 3% of the world's electricity, resulting in an estimated 2% of global CO_2 emissions. Of this number (3% of world electricity), Network radios contribute to about 9% of the industry's overall energy consumption [1]. And within the network radios, 10% of the energy is attributed to users of terminals, with the remaining 90% coming from telecommunication base transceiver stations. It is estimated that the industry's energy demand will increase to 1,700 TWh (8.5%) of world electricity by 2030. According to [1], an estimated 11,692 base transceiver stations (BTS) in Nigeria are connected to the national grid, with 9%, 10%, and 81% of these stations (estimated 11,692) experiencing up to 6, 6–12, and over 12hours grid power outage/day respectively [2]. The Nigerian Communications Commission (NCC) at a forum in December 2019, disclosed that as a power contingency plan, the industry expends about N260 billion yearly on diesel for powering the over 50,000 diesel-backup generators across the country. While this plan has been able to serve the industry up till now, there is a problem of sustainability arising from the continuous high cost of diesel, the cost of servicing these diesel-backup generators, and paying the 11 power utility companies for power consumed by grid-connected BTS and changes in the macroeconomic indices in Nigeria [3]. These has resulted in the industry's slow network expansion program and poor quality of service across the country, as operators push to increase their yearly average revenue per user [4]. It has become imperative to find new solutions to meet the telecommunication industry energy needs and thus make the industry "greener". As a solution to these problems, the objective of this research study is to provide a clean and sustainable alternative hybrid DC power supply system for BTS that would increase access to ICT infrastructure [5].

With the advent and rapid deployment of renewable energy solutions around the globe, this seemingly eternal power problem facing the industry can be surmounted through the design & implementation of a low-cost hybrid solar-wind-grid power supply system [6]. The choice of the two renewable energy sources (solar and wind) hinges on the fact that they are readily available energy sources across the country almost throughout the year at a sufficient quantity to generate the needed electricity. In Nigeria, the average monthly solar radiation stands at 5.8 kWh/m^2 per day, accompanied by an average of 6-7 hours of daily sunshine [7]. The coastal region experiences an annual average wind speed of around 2 m/s, while the far northern region experiences an average wind speed of 4 m/s [8]. But due to the intermittent nature of the individual renewable energy sources (solar, wind), neither can generate constant or reliable electricity [9], [10]. According to [11], a typical size of rural areas in south-south Nigeria where this project was implemented, the result of this research would offer a competitive advantage with quality network service delivery, lower service-based tariff due to lower cost of energy and an improved techno-socio-economic life of the people being served [12]. This paper is divided into four sections, vis-a-viz the introduction; methodology; results/discussions of results; and conclusion.

2. DESIGN AND DEVELOPMENT

2.1. Load analysis

The load summary of the BTS is shown in Table 1. Total power rating of installed equipment and appliances are:

$$(20)\ W + (300)\ W + (4 \times 7)\ W + (500)\ W + (12 \times 5)\ W = 908\ W$$

Applying a diversity factor of 0.7 in (1), the average power consumption or total individual peak consumption in watts is [13].

$$Diversty\ factor(f_D) = \frac{Total\ individual\ peak\ load}{Aggregated\ max.load} \quad (1)$$

$$0.7 = \frac{Total\ individual\ peak\ load}{908\ W}$$

$$Total\ individual\ Peak\ Load = 0.7 \times 908\ W = 635.6\ W$$

The total estimated daily energy demand of a basic BTS from Table 1 is calculation thus:

$$24(20 + 300 + 21 + 500)\ Wh + (60 \times 8)\ Wh = 20.66\ 4\ kWh/day$$

Table 1. Basic BTS appliances and equipment

Equipment	Power rating	Hours of service	Average daily consumption
Communication equipment	24 W,48 V	24h/24	0.48 kWh
Heat extractor	30 W	24h/24	7.20 kWh
Seven lighting lamps	4 W*7	24h/24	0.50 kWh
TX/RX RF (FMTX Model T213SJ, DRS 3200 QPSK receiver	500 W	24h/24	12.00 kWh
5 security lamps 220 V, 50 Hz	12 W*5	8h/24	0.48 kWh
Total	908 W		20.66 kWh

2.2. Solar photovoltaic (PV) system

The sun serves as the primary and abundant energy source crucial for sustaining life on Earth. It is projected that the global solar electricity capacity will reach 3000 GW by 2050. In Nigeria, considering a device conversion efficiency of 5%, the technical potential of solar energy amounts to roughly 416.7 GWh in a year. The solar panel is used to convert solar radiation to electrical energy. The average solar irradiation against months for Benin city, Nigeria where the experience is conducted is as shown in Table 2. The total power in watts of a PV module that can be placed in the selected available area is calculated using the formula of (2).

$$Area\ of\ module\ \times Power\ density\ of\ module = watt(estimated\ power) \quad (2)$$

The (3) and (4), the top of the BTS control room was used in positioning the PV modules applying in (1) and taking the losses (30%) in the PV system into consideration [14].

$$Energy\ required\ \times Loss = 20.664\ kWh\ \times 1.3 = 26.863\ kWh \quad (3)$$

$$Panel\ generating\ factor(GF_p) = Solar\ irradiation\ of\ the\ area\ \times Total\ correction\ factor\ of\ the\ solar\ panel \quad (4)$$

Table 2. Average solar irradiation against months for Benin-city [15]

S/N	Months	Solar irradiation (kWh/m2/day)
1	January	5.37
2	February	5.43
3	March	5.28
4	April	4.99
5	May	4.67
6	June	4.16
7	July	3.51
8	August	3.51
9	September	3.77
10	October	4.33
11	November	4.94
12	December	5.19
Total		55.15
Average		4.60

According to Sudarsan and Sreenivasan [15], to calculate the correction factor for a single solar PV module, the following are considered: i) 15% for temperature above 25 °C; ii) 5% for losses due to sunlight not striking the panel straight on (caused by glass having increasing reflectance at lower angles of incidence); iii) 5% allowance for dirt; and iv) 10% allowance for the panel being below specification and for ageing.

For this design, a maximum power point tracker (MPPT) is used, therefore there will be no need to consider losses due to not receiving maximum power. Thus, the total correction factor based on the above considerations is calculated by:

$$CF_p = 0.85 \times 0.95 \times 0.95 \times 0.9 = 0.69$$

$$Panel\ generating\ factor\ (GF_p) = 4.596 \times 0.69 = 3.17$$

$$Watt\ peak\ rating\ of\ the\ panel\ (W_p) = \frac{26.863\ kWh}{3.17} = 8.474\ kW$$

The number of PV modules required depends on the total energy demand of the load (the BTS in this project).

$$Total\ energy\ to\ be\ delivered\ by\ the\ modules = 26.863\ kWh$$

$$Watt\ rating\ of\ the\ modules\ to\ be\ used = 260\ watts$$

However, considering the efficiency of the panels at 40%.

$$0.4 \times 260\ watts = 104\ watts$$

The modules will have an 8hr window (period of the day when there’s useful sunlight or daylight) to generate the part of the energy required by the BTS equipment, therefore, to obtain the exact power to be generated by the modules in (5), the following applies.

$$\frac{26.863\ kWh}{8\ h} = 3.358\ kW$$

$$Number\ of\ Panels(N_p) = \frac{Power\ required\ to\ be\ generated\ (watts)}{Watt\ Rating\ of\ PV\ modules \times efficiency} = \frac{3.358\ kW}{104\ W} = 32.2 \approx 32 PV\ modules \quad (5)$$

The calculations summarized in Table 3 show the minimum number of PV panels that can be applied in this design. If more PV modules are installed, the system will perform better, and battery life will be improved.

Table 3. Solar PV energy delivered to the BTS load

Items	Rating
Number of panels	32
Watt rating of each panel	260 W
Solar irradiation of the area	4.60
Total energy required by BTS equipment	20.66 kWh
Total energy to be delivered by modules	26.86 kWh

2.3. Wind turbine system

Wind energy is derived from the utilization of wind kinetic energy. It is estimated that roughly an average of 10 TW of mechanical power is continuously present in the earth's wind. The orientation of the shaft and rotational axis determines the classification of the wind turbine. A wind turbine that features a horizontally oriented shaft parallel to the ground is referred to as a horizontal axis wind turbine (HAWT). The HAWT is widely adopted in modern wind turbine designs due to its advantageous characteristics such as a high tip speed ratio, high lift-drag ratio, and high efficiency ranging from 50% to 60% [16].

A vertical axis wind turbine (VAWT) has its shaft normal to the ground. Although VAWT is aesthetically pleasing with no need for a yaw system, it is attributed to a low tip speed ratio and difficult to control its rotor speed. In the wind turbine, the kinetic energy of the wind is initially converted into mechanical energy within the rotor. Subsequently, the mechanical power is further transformed into electric power by the internal electric generator of the turbine [17]. The kinetic energy per second i.e., power of an air mass flowing through an area A(m^2) with a velocity V(m/s) and density of air (ρ) is expressed as in (6).

$$Power_{wind} = \frac{1}{2}\rho A V^3 \quad (6)$$

Table 4. P-300 technical specifications for wind turbine

Items	Description	Items	Description
Model	Hycinth	Cut in speed	2 m/s
Orientation	10	Rated speed	6.29/10 m/s
Rating	300 W/25 A/12 V/24/48 V	Protection	Aluminum oxide
Rotor type	3 blades	Controller type	MPPT
Rotor diameter	1140 mm	Weight	6 kg

The following were considered to meet the technical requirements in Table 4, they are: i) Average wind speed, V_m in Benin city is $17\ km/h = 4.726\ m/s$; ii) A generator (car alternator) rating of 300 W was used; iii) A power coefficient of 0.40 was used. This is because the theoretical maximum of 0.593 [18] cannot be attained in practice; and iv) A tip speed ratio of five. This falls within the suitable tip speed ratio range for generators. Based on these considerations, the turbine parameters were computed as:

- Rotor swept area

The rotor swept area A expressed in (7) can be determined thus [19]:

$$A = \pi \frac{D^2}{4} \quad (7)$$

where $D = diameter\ of\ rotor = 1140\ mm = 1.14\ m$. Therefore $A = \pi \frac{1.14^2}{4} = 1.0207\ m^2$.

- Rotor speed

For the given tip speed ratio $\lambda = 5$, the rotor speed in (8) is thus [20].

$$\lambda = \frac{\pi}{30} \frac{R n_{rotor}}{V} \quad (8)$$

$$n_{rotor} = \frac{30}{\pi}\frac{V\lambda}{R} = \frac{30 \times 6.29 \times 5}{\pi \times 0.57} = 526.89\ rpm = 8.78\ m/s$$

Where, n_{rotor} rotor speed in rpm, V rated speed m/s, and R is the rotor radius, m.

- Number of blades

The (9) determine the number of blades, B used [20].

$$B = {}^{80}/_{\lambda^2} = {}^{80}/_{5^2} = 3.2 \approx 3 \quad (9)$$

Therefore, the available wind power [21] is given as (6).

$$P = \frac{1}{2}\rho A V^3$$

Where:

$$\rho = density\ of\ air = 1.225\ kg/m^3$$
$$A = area\ swept\ by\ rotor = 1.0207\ m^2, V = av\ wind\ speed = 4.726\ m/s$$

Therefore:

$$P = \frac{1}{2} \times 1.225 \times 1.0207 \times 4.722^3 = 65.824\ W$$

Applying in (6) at varying wind speed, the corresponding output power that would be generated by the wind turbine is shown in Table 5.

Table 5. Power output at varying wind speed

Wind velocity (m/s)	Output power (W)
4.726	65.82
5.194	87.55
5.714	116.43
6.285	154.86
6.913	205.96
7.605	273.93
8.365	364.33

2.4. Power electronics circuit

Despite the gear drive in a wind turbine being optimized to achieve the rated power output by regulating the generator speed, it falls short in increasing the generator voltage enough to surpass the capacity of a 12 V DC battery when the wind speeds are below 10 m/s. To achieve the desired voltage level, the power electronic circuit was implemented as shown in Figure 1. The voltage from the generator is fed through the transformer rectified and the output is regulated through the Insulated Gate Bipolar Transistor (IGBT) control.

2.5. Battery

To define a hybrid system, it is crucial to incorporate energy storage systems. According to the International Renewable Energy Agency (IREA), doubling the share of renewable energy by 2030 would require a threefold increase in electricity storage capacity from the current 4.67 terawatt-hours (TWh) in 2017 to 15.72 TWh in 2030 [22]. For PV systems, deep cycle (Li-ion) batteries are mostly recommended due to their ability to be discharged to low energy levels and be recharged rapidly [23]. To obtain a suitable battery size for this design, the (10) was applied.

$$Battery\ Capacity\ Required(Ah) = \frac{total\ Watt-hour/day}{0.85 \times 0.6 \times nominal\ battery\ voltage} \times days\ of\ autonomy \quad (10)$$

Where: 0.85 signifies battery loss; 0.6 signifies the depth of discharge of the battery; nominal battery voltage = 12 V; days of autonomy (number of days that the battery will be expected to function without any charge from the either the PV/WT system or the Grid) = 8 $hours\ in\ a\ day = 0.33\ days$

$$\therefore \quad Battery\ Capacity(Ah) = \frac{20.664\ kWh}{0.85 \times 0.6 \times 12\ V} \times 0.33 = 1124.36\ Ah$$

Using standard deep cycle batteries of rating 200 Ah, 12 V.

$$Number\ of\ batteries\ required = \frac{1124.36\ Ah}{200\ Ah} = 5.62 \approx 6\ batteries$$

The energy generated by Hybrid system involving let say three sources of energy like wind turbine, grid and PV array for hour *t*, $E_{G(t)}$ can be expressed as (11).

$$E_{G(t)} = E_{1(t)} + E_{2(t)} + E_{3(t)} \quad (11)$$

Where $E_{i(t)}$ is the energy generated by i[th] source. Since it is assumed that the battery charge efficiency is set equal to the round-trip efficiency and the discharge efficiency is set equal to 1. Let to consider two cases in expressing current energy stored in the batteries for hour *t*. If the supplied energy from all energy sources exceeds that of the load demand at a time instant. The batteries will be charged with the round-trip efficiency according to (12).

$$E_{B(t)} = E_{B(t-1)} + \left\{ E_{G(t)} - E_{L(t)} / \eta_{charging\ controller} \right\} * \eta_{Battery} \quad (12)$$

Where:

$\eta_{charging\ controller} = efficiency\ of\ charging\ controller$;
$\eta_{battery} = round\ trip\ efficiency\ of\ battery$;
$E_{B(t)} = energy\ stored\ in\ battery\ in\ hour\ t\ E_{B(t-1)}$
$= energy\ stored\ in\ battery\ in\ previous\ hour$;
$Lt = load\ demand\ in\ hour\ t$

When the load demand is greater than the available energy generated, the batteries will be discharged by the amount that is needed to cover the deficit [24]. It can be expressed in (13).

$$E_{B(t)} = E_{B(t-1)} - \left\{ E_{L(t)} / \eta_{charging\ controller} - E_{G(t)} \right\} \quad (13)$$

The energy stored in batteries at any hour t is subject to the following constraint.

$$E_{Bmax} \geq E_{B(t)} \geq E_{Bmin}$$

Thus, it was ensured that the batteries did not discharge or overcharged at any time. This protects the batteries from being damaged.

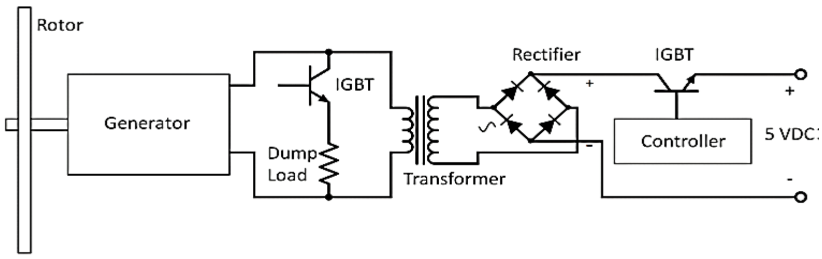

Figure 1. Power electronics schematic diagram [20]

2.6. Charge controller

The charge controller acts as the system's central connection device and performs two key functions [25]. First, it rectifies the three-phase AC output from the alternator into DC and regulates the DC output and charges the battery bank [21]. Also, it charges controller/maximum power point tracker (MPPT) compensates for the changing voltage-current characteristic of a solar cell. i.e., it varies the electrical operating point of the modules so that the modules can deliver the maximum available to the batteries. Mathematically defined in (14).

$$\left(\frac{V_{module}/Vwind}{V_{battery}}\right) \times I_{module} = I_{battery} \quad (14)$$

2.7. Hybrid system

The hybrid energy system in this paper comprises the PV solar system, wind turbine system, and grid power with the battery storage system as illustrated in Figure 2. The power from these sources, solar PV and wind turbine would feed the DC bus that powered the BTS load in the absent of grid power. And whenever these renewable sources are unavailable or there is minimum generation, the grid or the battery would supply the needed power to the DC bus. This topology ensures that power is continually available to the BTS, thus eliminating the need for a diesel generator. The DC load of the BTS is fed directly from the DC bus while the AC loads are fed through the inverter. As (15), the total power generated, P_T by the hybrid system is given as the addition of the power generated by the solar PV panel, wind turbine and grid supply [26].

$$P_T = n_{WT} * P_{WT} + n_S * P_S + P_{grid} \quad (15)$$

Where $P_{WT} = power\ generated\ by\ wind\ turbine$; $P_S = power\ generated\ by\ solar\ panel$; $P_{Grid} = power\ supplied\ from\ grid$; $n_{WT} = number\ of\ wind\ turbine$(s); and $n_s = number\ of\ solar\ panel(s)$.

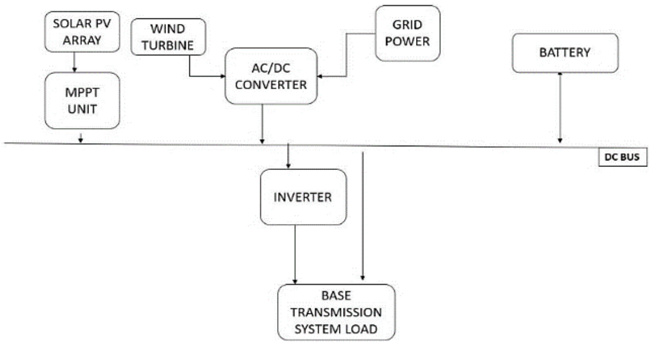

Figure 2. Overall schematic diagram of the hybrid solar PV, wind turbine, and grid power with a battery storage system

2.8. MATLAB simulation

The MATLAB simulation of in (1)-(15) representing the mathematical modelling of the various sub-units of the hybrid system is as shown in Figure 3. The sizing of the hybrid sub-systems using MATLAB Simulink is to test functionality. The outputs of the simulated sub-units are discussed in section 3.

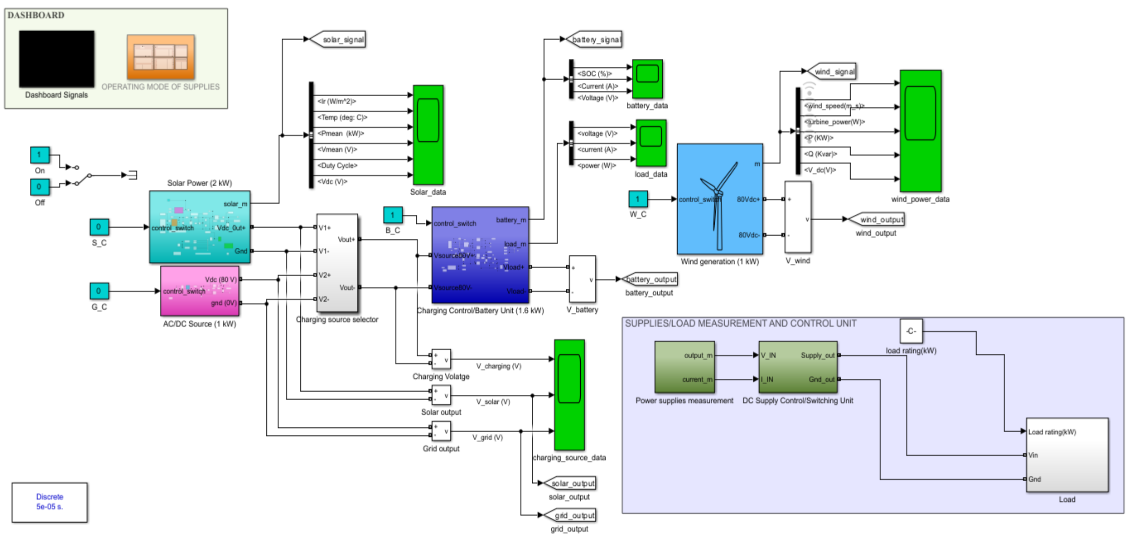

Figure 3. Image of the MATLAB simulation of the PV/WT/grid hybrid system

3. RESULT AND DISCUSSION

3.1. Solar PV

The output from the MATLAB simulation (Figure 4) describes the energy conversion capability of the modules at existing conditions of irradiance (light level) and temperature. The curves which represent the combination of current and voltage at which the modules could be operated shows that as solar radiation increases the energy generated by the PV also increases, until the V_{dc} is made constant by the MPPT. This constant voltage is maintained provided the irradiance and temperature are held constant. The results, as seen in Figure 4, of this simulation are validated by (2) and solar output power is shown in Table 6 (see in Appendix).

3.2. Wind turbine

Typically, the turbine begins generating power, once the wind turbine goes above cut-in speed at 2m/s as shown in Figure 5 which is the minimum required speed. The amount of wind power available for extraction by the turbine increases with a cube of the wind speed until it reaches the rated wind speed. This is the wind speed (4.726m/s), at which generation acquires its rated capacity P.

Thus a 10% increase in wind speed means a 33% increase in available power. However, a turbine can only capture a portion of this cubic increase in energy because power above the level for which the electrical system has been designed (referred to as the "rated power") is allowed to pass through the rotor. The power produced by this generator is used to directly charge a battery.

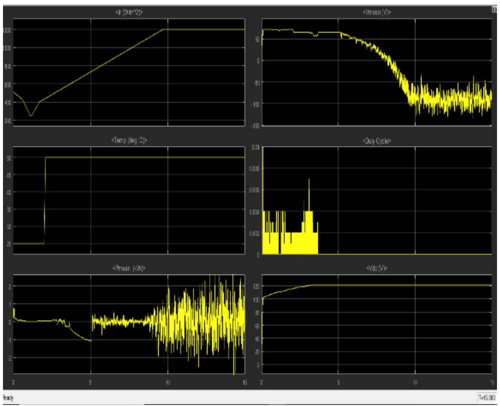

Figure 4. MATLAB simulation of the solar irradiance versus solar power generated

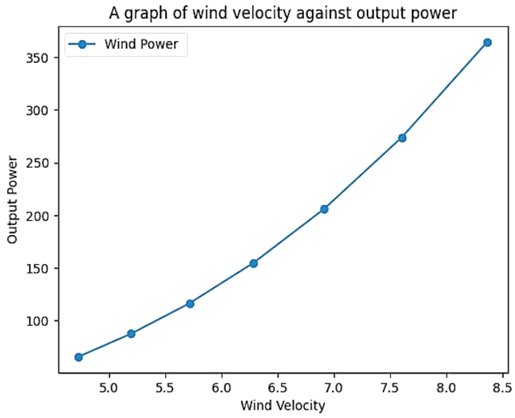

Figure 5. Graph of varying wind speed against wind power generated

3.3. Battery

In the MATLAB simulation of the battery, the battery capacity was pegged at 10 Ah to make charging and discharging visible within simulating time. The simulation result in negative slopy curves as seen in Figures 6 and 7. These slopy curves can simplify the estimation the state of charge (SoC) since the battery voltage is closely related to charge remaining in the battery cell. i.e., as battery discharges at constant current drawn, it trades off the amount of charge present in battery and consequently a reduction in terminal voltage as shown in Figure 6 and Figure 7 respectively. In addition, the power from cells falls throughout the discharge cycle, hence it may be necessary to 'oversize' the batteries. This explains why the approximation in number of batteries to six in section 2.5.

3.4. Hybrid system daily total power output

The daily power generation from the wind turbine and photovoltaic panel at the BTS site with ID No: UNIBEN0006 is shown in Table 6 with the varying wind speed and solar irradiation from daily weather recording of the site at the time interval of 0900hr, 1300hr and 1600hr respectively. Table 6 shows the corresponding output power (kW) recorded over these intervals and Figure 8 shows the characteristics of the output power confirming the intermittent nature of renewable energy sources.

Power outputs recorded (Table 6) at the time intervals of 0900, 1300, and 1600 hours respectively indicates that the hybrid system can supply the base transceiver station (BTS) with the required power. And this supply time can be extended to cover the 24hr period required for uninterrupted service delivery by the BTS. It can also be observed from the Table 6 and Figure 8 that although the outputs power from the hybrid system appears fluctuating, the average of these outputs from the hybrid solar PV/wind turbine/grid power supply system is sufficient to cater for the BTS by guaranteeing 21hrs/day of stable and quality power supply. Hence eliminating the need for diesel-backup generator for a grid connected BTS or non-grid BTS sited in a rural area.

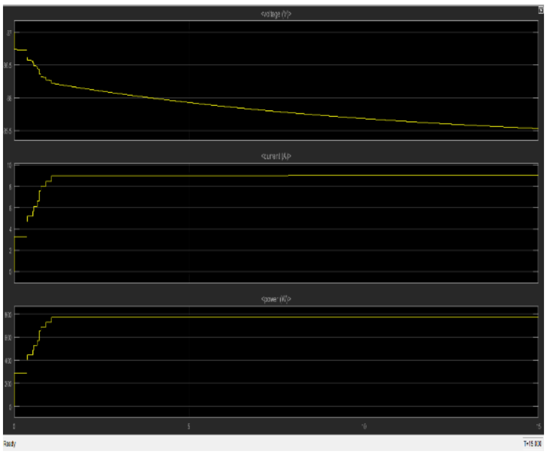

Figure 6. Battery operation charging load data

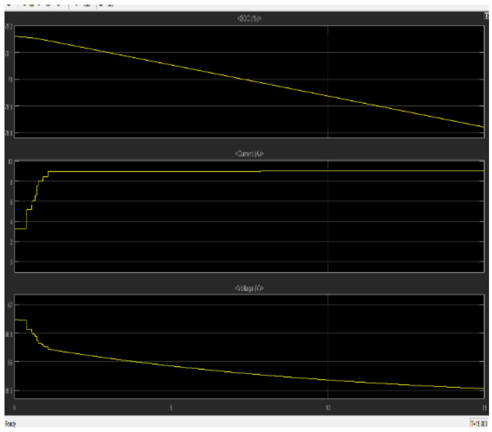

Figure 7. Battery operation discharging load data

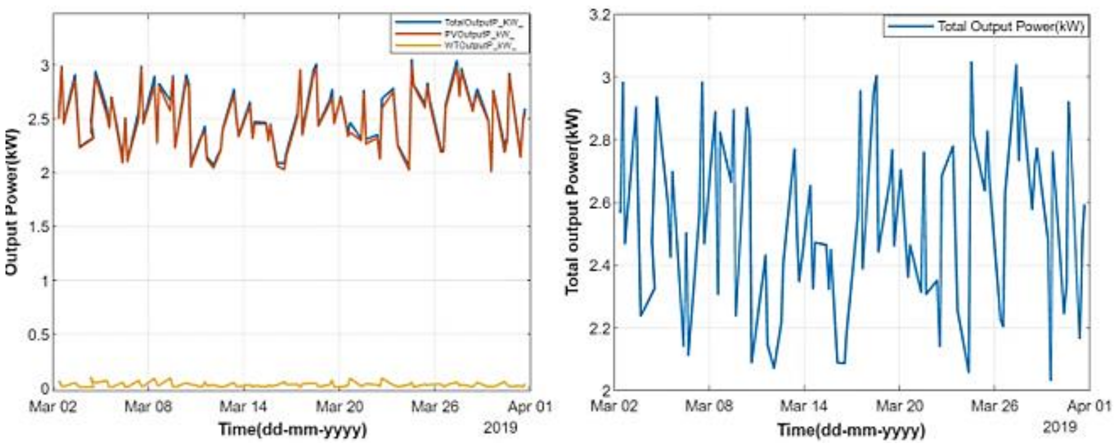

Figure 8. Daily power generated from WT, PV, and combined total output power (kW)

4. CONCLUSION

The result of this paper shows the feasibility of deploying renewable energy resources in a telecommunication infrastructure. The hybrid solar PV/wind turbine/grid power supply system designed and implemented offers a significant reduction in the cost of energy (electricity) vis-a-viz the perennial annual cost of load losses due to power outages in the telecommunication industry, and greenhouse gas emission when compared to diesel-grid based or diesel generator power supply currently deployed in the telecommunication industry. By installing this hybrid system of 1.3 kW, approximately 2.55 kg of diesel(C10H20) would be un-utilized by one BTS, thereby preventing 3.6 kg of CO_2 from been emitted to the atmosphere daily. Extrapolating these values shows 930.75 kg of diesel can be saved and reduce 1314 kg of CO_2 emission within a year. The technology implemented in this research can also serve as a reference for mass rural electrification and SMEs projects thereby stimulating techno-socio-economic growth across the country. For future research study, it is recommended that since the MPPT is an electronic system and not a mechanical tracking system, a groove can be coupled to the PV modules to help track the position of the sun throughout the day. The research presented in this paper shows that a hybrid of these two (solar & wind) renewable sources with grid power, is a viable and sustainable power supply alternative essential for improving BTS penetration especially in rural areas of Nigeria.

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APPENDIX

Table 6. Wind turbine and PV daily power output for the month of March 2019

SITE ID – UNIBEN 006_ updated_02_March_2019. UNIBEN 006									
		Wind Turbine				Photovoltaic			
Time	Site-ID	Record S/N	W/S(m/s)	P(W)	P(kW)	kWh/m2/day	Vsolar(V)	P(kW)	Total P(kW)
3/2/2019 0900	N006	1	6.29	69.06	0.07	4.49	13.98	2.50	2.57
3/2/2019 1300	N006	2	4.10	19.20	0.02	3.30	14.20	2.96	2.98
3/2/2019 1600	N006	3	3.73	14.44	0.01	3.01	13.87	2.45	2.47
3/3/2019 0900	N006	4	5.61	49.11	0.05	3.96	14.50	2.85	2.90
3/3/2019 1300	N006	5	3.02	7.66	0.01	3.32	15.69	2.23	2.24
3/3/2019 1600	N006	6	2.98	7.36	0.01	5.64	15.43	2.32	2.32
3/4/2019 0900	N006	7	7.03	96.64	0.10	5.43	12.23	2.38	2.48
3/4/2019 1300	N006	8	5.91	57.42	0.06	4.90	14.57	2.67	2.73
3/4/2019 1600	N006	9	5.54	47.30	0.05	3.95	15.51	2.89	2.94
3/5/2019 0900	N006	10	6.29	69.22	0.07	5.31	13.20	2.53	2.60
3/5/2019 1300	N006	11	2.77	5.91	0.01	5.54	12.94	2.42	2.43
3/5/2019 1600	N006	12	3.09	8.21	0.01	3.50	15.21	2.69	2.70
3/6/2019 0900	N006	13	5.66	50.44	0.05	3.79	15.81	2.09	2.14
3/6/2019 1300	N006	14	3.22	9.29	0.01	3.37	15.30	2.49	2.50
3/6/2019 1600	N006	15	3.18	8.94	0.01	5.46	13.49	2.10	2.11
3/7/2019 0900	N006	16	6.29	69.06	0.07	4.49	13.98	2.50	2.57
3/7/2019 1300	N006	17	4.10	19.20	0.02	3.30	14.20	2.96	2.98
3/7/2019 1600	N006	18	3.73	14.44	0.01	3.01	13.87	2.45	2.47
3/8/2019 0900	N006	19	6.86	89.60	0.09	4.11	15.24	2.80	2.89
3/8/2019 1300	N006	20	4.74	29.55	0.03	5.30	15.61	2.28	2.31
3/8/2019 1600	N006	21	4.41	23.87	0.02	5.57	14.74	2.80	2.82
3/9/2019 0900	N006	22	6.91	91.90	0.09	3.89	15.50	2.57	2.66
3/9/2019 1300	N006	23	3.48	11.67	0.01	4.70	13.82	2.88	2.90
3/9/2019 1600	N006	24	3.02	7.66	0.01	3.32	15.69	2.23	2.24
3/10/’19 0900	N006	25	5.61	49.11	0.05	3.96	14.50	2.85	2.90
3/10/’19 1300	N006	26	5.06	36.04	0.04	5.39	14.71	2.79	2.82
3/10/’19 1600	N006	27	5.01	34.98	0.03	3.28	13.19	2.05	2.09
3/11/’19 0900	N006	28	3.34	10.40	0.01	3.26	13.10	2.35	2.36
3/11/’19 1300	N006	29	5.92	57.71	0.06	4.46	13.29	2.37	2.43
3/11/’19 1600	N006	30	4.34	22.74	0.02	3.24	13.95	2.12	2.15
3/12/’19 0900	N006	31	4.68	28.51	0.03	5.92	15.51	2.04	2.07
3/12/’19 1300	N006	32	3.31	10.05	0.01	5.25	15.51	2.21	2.22
3/12/’19 1600	N006	33	3.12	8.47	0.01	3.99	13.09	2.40	2.40
3/13/’19 0900	N006	34	5.62	49.42	0.05	4.08	13.79	2.72	2.77
3/13/’19 1300	N006	35	3.71	14.19	0.01	3.11	14.27	2.48	2.49
3/13/’19 1600	N006	36	3.65	13.47	0.01	4.08	14.31	2.34	2.35
3/14/’19 0900	N006	37	4.93	33.33	0.03	3.61	13.57	2.62	2.65
3/14/’19 1300	N006	38	2.98	7.36	0.01	5.64	15.43	2.32	2.32
3/14/’19 1600	N006	39	4.33	22.58	0.02	4.85	15.31	2.45	2.47
3/15/’19 0900	N006	40	3.44	11.35	0.01	3.34	14.17	2.45	2.46
3/15/’19 1300	N006	41	4.67	28.33	0.03	3.81	14.76	2.29	2.32
3/15/’19 1600	N006	42	4.02	18.08	0.02	4.50	13.78	2.43	2.45
3/16/’19 0900	N006	43	4.56	26.30	0.03	3.87	13.55	2.06	2.09
3/16/’19 1300	N006	44	5.92	57.82	0.06	4.01	14.74	2.03	2.09
3/16/’19 1600	N006	45	4.85	31.68	0.03	5.01	13.29	2.15	2.19
3/17/’19 0900	N006	46	5.03	35.4	0.04	5.53	14.51	2.52	2.56
3/17/’19 1300	N006	47	2.31	3.43	0.00	5.58	15.87	2.95	2.96
3/17/’19 1600	N006	48	5.16	38.22	0.04	5.80	15.10	2.35	2.39
3/18/’19 0900	N006	49	5.52	46.85	0.05	3.31	14.45	2.91	2.95
3/18/’19 1300	N006	50	5.27	40.67	0.04	5.39	13.35	2.96	3.00
3/18/’19 1600	N006	51	3.58	12.55	0.01	5.59	15.80	2.43	2.44
3/19/’19 0900	N006	52	4.76	29.93	0.03	5.65	15.23	2.64	2.67
3/19/’19 1300	N006	53	6.35	71.31	0.07	5.27	13.07	2.70	2.77
3/19/’19 1600	N006	54	3.01	7.58	0.01	4.30	15.38	2.45	2.46
3/20/’19 0900	N006	55	3.38	10.74	0.01	5.40	16.00	2.69	2.70
3/20/’19 1300	N006	56	4.48	25.01	0.03	5.63	13.03	2.34	2.36
3/20/’19 1600	N006	57	6.85	89.45	0.09	3.86	15.89	2.37	2.46
3/21/’19 0900	N006	58	3.88	16.26	0.02	5.60	15.07	2.30	2.31
3/21/’19 1300	N006	59	4.50	25.41	0.03	4.30	15.40	2.73	2.76

Table 6. Wind turbine and PV daily power output for the month of March 2019 (continued)

SITE ID – UNIBEN 006_ updated_02_March_2019. UNIBEN 006									
		Wind Turbine					Photovoltaic		
Time	Site-ID	Record S/N	W/S(m/s)	P(W)	P(kW)	kWh/m2/day	Vsolar(V)	P(kW)	Total P(kW)
3/21/'19 1600	N006	60	5.22	39.55	0.04	5.35	13.65	2.27	2.31
3/22/'19 0900	N006	61	4.76	30.00	0.03	4.24	15.54	2.32	2.35
3/22/'19 1300	N006	62	3.77	14.9	0.01	4.97	13.79	2.13	2.14
3/22/'19 1600	N006	63	6.86	89.8	0.09	5.74	13.17	2.60	2.68
3/23/'19 0900	N006	64	4.70	28.86	0.03	4.79	14.87	2.75	2.78
3/23/'19 1300	N006	65	4.29	21.96	0.02	4.13	15.69	2.45	2.47
3/23/'19 1600	N006	66	3.45	11.42	0.01	3.84	15.25	2.24	2.25
3/24/'19 0900	N006	67	4.85	31.73	0.03	4.20	13.48	2.03	2.06
3/24/'19 1300	N006	68	5.70	51.56	0.05	5.84	15.38	3.00	3.05
3/24/'19 1600	N006	69	3.22	9.29	0.01	4.88	13.50	2.80	2.81
3/25/'19 0900	N006	70	5.03	35.40	0.04	3.32	15.67	2.60	2.64
3/25/'19 1300	N006	71	4.50	25.36	0.03	3.13	14.67	2.80	2.83
3/25/'19 1600	N006	72	4.88	32.33	0.03	5.42	15.56	2.64	2.68
3/26/'19 0900	N006	73	5.09	36.68	0.04	3.82	14.44	2.19	2.23
3/26/'19 1300	N006	74	3.29	9.93	0.01	3.04	14.35	2.19	2.20
3/26/'19 1600	N006	75	4.48	24.94	0.02	3.68	13.33	2.60	2.63
3/27/'19 0900	N006	76	5.84	55.33	0.06	4.90	13.07	2.98	3.04
3/27/'19 1300	N006	77	4.31	22.22	0.02	3.32	13.13	2.71	2.73
3/27/'19 1600	N006	78	4.90	32.73	0.03	4.47	13.23	2.93	2.97
3/28/'19 0900	N006	79	3.41	11.03	0.01	4.36	13.07	2.57	2.58
3/28/'19 1300	N006	80	5.01	34.98	0.03	5.91	14.26	2.69	2.72
3/28/'19 1600	N006	81	5.65	50.26	0.05	4.34	14.55	2.72	2.77
3/29/'19 0900	N006	82	3.32	9.29	0.01	4.00	15.82	2.47	2.48
3/29/'19 1300	N006	83	4.11	19.31	0.02	4.07	14.25	2.01	2.03
3/29/'19 1600	N006	84	3.29	9.41	0.01	4.27	13.28	2.75	2.76
3/30/'19 0900	N006	85	5.93	58.00	0.06	3.50	14.47	2.19	2.25
3/30/'19 1300	N006	86	4.64	27.79	0.03	5.05	13.01	2.30	2.33
3/30/'19 1600	N006	87	3.82	15.51	0.02	5.76	14.47	2.90	2.92
3/31/'19 0900	N006	88	4.23	21.05	0.02	3.70	15.78	2.15	2.17
3/31/'19 1300	N006	89	3.33	10.29	0.01	5.16	15.10	2.49	2.50
3/31/'19 1600	N006	90	5.37	43.07	0.04	3.84	15.04	2.55	2.59

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