Optimal Configuration and Energy Scheduling Algorithm for an Off-Grid Hybrid Microgrid

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ORIGINAL RESEARCH

Abstract- Off-grid hybrid microgrid which combines power sources from different technologies based on the availability of such resources and the economic/environmental considerations is gaining global interest due to the unreliable nature of conventional power systems. This research seeks to obtain an optimal configuration and develop a simple energy scheduling algorithm for a modern market using PV/Battery storage/Diesel generator technologies. HOMER software was used in obtaining the optimal configuration and economic/environmental analysis. The development of the scheduling algorithm was done based on the concept of energy flow in an off-grid hybrid microgrid using MATLAB software. An estimated load of 389.79 kW and average daily solar irradiance of 164.09W/m^2 was recorded for the study site. The simulation results yielded Net Present Cost (NPC) of \$6,405,234.36 and \$0.2414 Cost of Energy (COE). A Greenhouse Gas (GHG) emission reduction of 42% was recorded for an off-grid system with solar renewable source. These clearly indicate that the use of optimized hybrid electrical energy resources with simple scheduling could greatly reduce both operational cost and environmental pollution.

Keywords- Energy, Microgrid, Optimization, Scheduling, Renewable

1 Introduction

Electrical energy being possibly the most used energy form needed for technological and industrial advancements (Wood & Ollenberg, 1996); generated through different means such as electromechanical generators driven by heat engines, wind and flowing water, Photovoltaic (PV) and geothermal power (Dahunsi, et al., 2022). Electrical energy sources can be categorized into renewable and non-renewable sources (Zobaa & Bansal, 2011). The non-renewable sources like natural gas, nuclear, coal, and oil are insufficient due to slow replenishing time. Conversely, renewable sources like wind, water(hydro), solar etc., are naturally replenished over a short duration of time.

As the world energy demand is increasing, the conventional approach using electromechanical methods could not be sustained which resulted to poor and unreliable system with the effect that more people are being cut-off or receive poor electrical energy daily. Owing to this reason, search for other approach or methods of energy generation were initiated. The purpose for these initiatives is to complement the existing methods to ensure a better and more reliable electrical energy system (Premadasa, Silva, & Pathirana, 2021).

Solar photovoltaic is now the most popular form of renewable energy generation across the globe with an installed capacity of about 73 gigawatts in 2016 (conversion, 2016); hence having great potential in Solar PV energy generation in sub-Sahara Africa (David & Opeyemi, 2013). The unpredictability of this solar energy and its dependence on cloud conditions, require it to be hybridized with other more predictable like hydro, gas, etc. which gave rise to microgrid (Tutkun & San, 2013).

Microgrid is a small-scale power production-delivery system consisting of the distributed generation facilities alongside the load they serve (Lasseter, 2002). They are essential for reliable and sustainable energy supply that will meet up with the growing world energy demand. Solar based microgrid is probably the most popular because of its cleanness and eco-friendly nature. For need of sustainability, solar is hybridized with other sources of energy such as diesel generator when configured as a standalone or off-grid system (Wang, Jia, Yang, Cai, & Chen, 2021). This approach will help in meeting up with energy demand of those energy-starved locations as well as reducing greenhouse gas (GHG) emissions. Furthermore, for this off-grid hybrid microgrid to be economically viable there is need for an effective energy scheduling. This will allow for effective use of renewable source when available which is the motivation for this research.

2 Review of Literature

Many studies have been made by various researchers in the field of hybrid microgrids globally with varying results obtained. Kumar, et al. (2016) carried out an optimal design of Hybrid Energy System (HES) considering solar-wind-diesel combination for an ATM machine in remote area (Vather, Kolhapur area) in India and recorded \$48384 Initial Capital Cost, \$82775 Net

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Section B- ELECTRICAL/ COMPUTER ENGINEERING & RELATED SCIENCES
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Present Cost and $0.307Cost of Energy. Yang, et al. (2018) worked on optimal scheduling of Microgrid with distributed power based on Water Cycle Algorithm (WCA). By considering photovoltaic power, micro turbine (MT), wind turbine (WT), diesel generator and energy storage system. Their work showed that WCA has improved capability of computational efficiency, convergence performance and global optimization. Raj & Giftson, (2022) carried out optimal Energy scheduling of Renewable Energy Sources in Smart Grid using Cuckoo Optimization Algorithm with Enhanced Local Search and they reported that their method performs well compared to other Generic Algorithms. However, environmental impact was not taken into consideration.

Abdulwahab et al, (2021) developed a PV, WT, solar thermal power (STP), diesel engine, fuel cell (FC)) hybrid micro-grid autonomous system. For prolonged and improved energy storage, a combined energy storage system consisting of a battery, ultra-capacitor and a flywheel storage system was used aimed also at improving frequency fluctuations due to load demand using Moth Flame Optimization Algorithm; which recorded a 35.95% improvement compared to Quasi-oppositional Harmony search Algorithm with respect to overshoot and settling time. Muhammad et al. (2019) did research on optimal sizing and energy scheduling of isolated microgrid considering the battery lifetime degradation. From their report, a firefly algorithm was used which resulted to reducing cost and optimal sizing of batteries used. No case study was however mentioned, battery storage was never considered as a potential independent source (i.e., being able to serve the load alone independent of other known sources). They did not also consider environmental factors (GHG emission effects). A design of standalone Hybrid power system (HPS) for an entire commercial classroom complex which includes general purpose classroom, labs with low power rating instruments, heavy load driving machines and others using Homer.

Shoeb & Shafiullah, (2018) investigated the performance of a PV/diesel/battery Hybrid Energy System (HES) for standalone electrification of a rural area in southern Bangladesh. Their investigation revealed that the cycle charging (CC) strategy was more economical than Load Following (LF) strategy. Maatallah, Ghodhbane, & Nasrallah, (2016) studied the techno-economic feasibility of a PV/wind/diesel/battery hybrid system with Bizerte, Tunisia serving as a case study. Their work revealed that LF was cost effective compared to CC.; hence saving more than $27,000 all through the project. It is deduced from the forgoing that the nature of the load under consideration and the environmental impact are prime factors to be researched for optimal configuration and economical load scheduling.

3 Materials and Methods

3.1 Description of Study Site

Ogbogonogo market chosen as study site is a modern market located within Asaba metropolis in Delta State, Nigeria with geographical coordinates of 6.2°N and 6.73°E. It has a total of eight hundred (800) units of lock up shops, fourteen (14) units of small offices, three (3) units of big offices, one (1) hall, forty-eight (48) units of single toilets and twenty-eight (28) lines.

3.2 Data Collection

Data for the study site needed for simulation were collected based on the methods explained below. The data includes the electric loads estimation and solar irradiance of the study site.

3.2.1 Electrical Load Estimation

There are various kinds of electric loads distributed within the market. The loads range from lighting points, fans, refrigerator, pumping machine, and so on. A simple random sampling approach was employed. Samples of electric loads were taken from the shops based on the procedure stipulated: i. Total number of samples needed from the ground and first floors (totalling 800 lock up shops) were determined using the sample size calculator (Systems, 2012) .The following parameters were inputted; Confidence Level = 95%, Confidence Interval (Margin of Error) = 5%, Population Size = 800; which gave a total sample size of 260. ii. Each of the floors in the market was divided into 4 (four) quadrants, making a total of eight (8) quadrants of 100 shops in each. iii. The total sample size was divided into eight (8) to determine the number of samples from each quadrant which gave a minimum of 32.5 samples from each quadrant. i.e., 260/8 = 32.5. A minimum thirty-three (33) samples of shops were selected from each quadrant. iv. Electric load of 33 shops were taken from each quadrant as tabulated in Table 1. This gives a total of two hundred and sixty-four (264) samples. Table 2 also show other additional load from various parts of the mark.

Table 1. Electric Load of 264 Shop Samples (Q = quadrant, u = units)

Load type	Ground floor				Top floor				Total number of loads (u)	Power rating (kW) per load	Total load power (kW)
	Q1 (u)	Q2 (u)	Q3 (u)	Q4 (u)	Q5 (u)	Q6 (u)	Q7 (u)	Q8 (u)			
Lightings	65	55	43	48	60	55	40	68	437	0.085	37.15
Fans	37	32	27	35	30	32	20	28	238	0.075	17.85
Refrigerator/water dispenser	4	1	5	3	-	3	4	2	22	0.200	4.40
Air conditioner	-	-	-	-	-	-	-	-	-	-	-
Photocopier	-	2	-	1	-	1	-	-	4	1.200	4.80
Computer/laptop	3	4	7	2	4	3	2	2	27	0.080	2.60
Printers	-	2	-	2	-	1	-	1	6	0.120	0.72
Hair dryer	7	9	2	2	-	3	1	4	28	1.500	42.00
TV set	3	1	2	4	-	2	4	3	19	0.085	1.615
Decoder/DVD	3	1	1	2	-	2	3	1	13	0.070	0.91
Sound system	3	2	7	1	4	2	9	3	33	0.060	1.86
Total (sampled loads)	-	-	-	-	-	-	-	-	-	-	113.90

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Table 2. Additional Loads from Pent Floor, Lines, Walk Ways, Toilets and Security

Load type	Lines (u)	Pent floor (u)	Toilets (u)	Security (u)	Walk-way (u)	Total number of loads(u)	Power rating per load (kW)	Total load power(kW)
Lightings	167	34	48	28	10	287	0.085	24.40
Fans	-	32	-	-	-	32	0.075	2.40
Refrigerator/water dispenser	-	9	-	-	-	9	0.200	1.80
Air conditioner	-	8	-	-	-	8	1.200	9.60
Photocopier	-	1	-	-	-	1	1.200	1.20
Computer/laptop	-	10	-	-	-	10	0.080	0.80
Printer	-	8	-	-	-	8	0.120	0.96
TV set	-	7	-	-	-	7	0.085	0.60
Decoder/DVD	-	5	-	-	-	5	0.070	0.35
Sound system	-	4	-	-	-	4	0.060	0.24
Electric pumping machine	-	-	-	-	-	1	2.300	2.30
Total additional loads (kW)	-	-	-	-	-	-	-	44.64

Statistical determination of population (800 units of shop) load from sample is computed thus:
Sample mean load (kW) = Total sampled load / Sample size (15) = 0.431kW per sample
Total load for 800 units (kW)
= Sample mean load * Total units (16) = 345.15kW
Total load for the market complex
=Total load from 800 units of shops + Total additional loads (17)

Total additional loads=44.64kW
Total load for the market complex= (345.15 + 44.64) kW
Total load for the market complex =389.79kW

3.2.2 Load Categorization

The study site runs business from 6:00 a.m. to 7:00 p.m., Mondays through Saturdays. Based on this scenario, the load will be categorized into running hour (P_{Rh}), non-running hour (P_{Nh}) and running/non-running hour (P_{RN}) loads. P_{Rh} load run from 6:00am through 7:00pm, P_{Nh} load run from 7:00pm through 6:00am and P_{RN} load run 24 hours of the day. From this information, the 24 hours' load estimation of the market complex can be obtained as depicted in Figure 1.

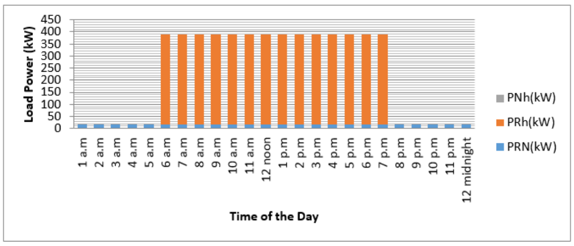

Fig. 1: 24-hour load estimation of the market

3.2.3 Energy Demand Estimation of Study Site

The energy demand of study site, E_{SS} (kWh/day) is given by;

$$E_{SS} = P_{Rh}{*}Rh + P_{Nh}{*}Nh + P_{RN}{*}RNh \tag{18}$$

Where Rh is the running hour load total runtime (hour) and Nh is non-running hour load total runtime (hour), RNh is the total runtime for load that runs as running hour load as well as non-running hour load. Table 3 shows the values of the parameters needed to statistically determine the total energy demand estimate of the study site with reference to Figure 1.

Table 3. Parameters for Energy Demand Estimation

Parameter	Value
P_{Rh}(kW)	370.25
P_{Nh}(kW)	2.38
P_{RN} (kW)	17.345
Rh(hr)	14
Nh(hr)	10
RNh(Hr)	24

From equation (18), the total energy demand estimate of the study site can be computed as;

$$E_{SS}\,(\text{kWh/day}) = (370.25{*}14) + (2.38{*}10) + (17.345{*}24)$$

This gives the energy demand estimate of the site per day as 5,623.58kWh/day.

3.2.4 Solar Irradiance Data of Study Site

The daily solar irradiance data of the study site was obtained from NASA website (NASA, 2022) by inputting the latitude and the longitude of the study site. This represents the solar irradiance incident on the horizontal surface. Figure 2 shows the monthly average for three consecutive years (2017 to 2019). Figure 3 shows a typical solar irradiance hourly average (W/m^2) for 3 October, (2018 and 2019).

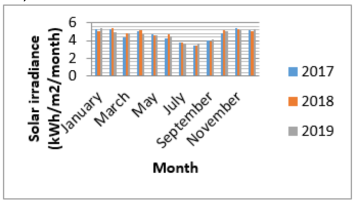

Fig. 2: Solar Irradiance Monthly Average (kWh/m^2/month) for Study Site.

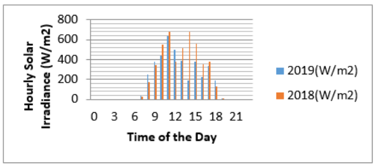

Fig. 3: Typical Hourly Solar Irradiance of Study site

3.3 Proposed Off-grid Hybrid (PV/Battery/Diesel) Microgrid

Figure 4 is a modelled block diagram of the proposed off-grid hybrid microgrid. It consists of the load, solar resources, battery storage system, converter, diesel generator set and the control system. The model is made up of two power buses (DC and AC). DC bus contains DC power sources such as solar modules which is connected to the bus through a charge controller, and battery storage system which receives DC power from the bus in cases of excess power on the bus or supplies the bus in cases of shortage of DC power on the bus. Also, connected to the DC bus is the bidirectional inverter which from the bus takes DC power and converts it to AC for the connected AC load. This component can also from the AC bus take AC power and converts it to DC for energy storage at solar downtimes. For this work, the sources of AC power for the AC bus are the diesel generator and the bidirectional converters. The diesel generator should work on standby to serve the load and charge the battery

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bank when the energy from the solar modules is not enough to sustain the system. The load is connected directly to the AC bus. It can be supplied by the diesel generator or DC bus through the bidirectional converter or both as the case maybe.

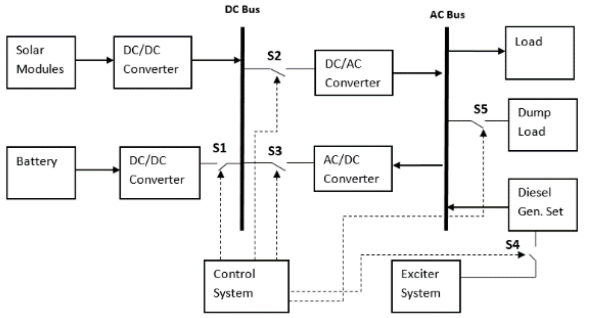

Fig. 4. Modelled Block Diagram of Proposed Off-grid Hybrid Microgrid Power System with Scheduling (Control) System.

3.3.1 System Simulation and Optimization

For a successful simulation and optimization of any power system, certain conditions have to be met which includes objective functions and system constraints. These conditions which are inputs to the HOMER simulation software, serve as guide for the simulation.
HOMER is a powerful simulation software from the National Renewable Energy Laboratory (NREL) for system sizing, optimization, and sensitivity analysis of a power system. It simulates the operation of a system by making energy balance calculations, and as well calculate energy flow of components within the system. It also determines whether a configuration is feasible and estimates the cost of installation and operation of the system over the project lifetime (HOMER, 2022).

3.3.2 Proposed Energy Scheduling Algorithm

The major idea behind this simple scheduling algorithm is to ensure that no solar generated power is wasted without meeting the load demand and storage need of the battery. Secondly, the battery storage will be considered a very important source of power capable of supplying power independently. This approach will have a minimum utilization of diesel generator thereby lowering diesel fuel usage. This will result to both economic (less diesel purchase) and environmental (less GHG emission) benefits. This is conceptually captured in the energy flow diagram shown in Figure 5. The sources are the solar, diesel generator and battery storage system. Energy flow from source to load is indicated by the arrow direction. It can be seen that the battery storage serves both as a load and as a source at one point. The control switches that achieve the scheduling are labelled S1 to S5.

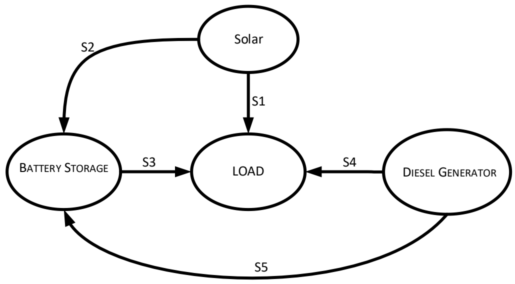

Fig. 5: Conceptual Energy Flow Diagram of Proposed Simple Energy Scheduling Algorithm

The switch scenarios (which are automatically operated) that exist as shown in Figure 6 are;

S1: The load being supplied by only PV source (When $P_{Load} = P_{PV}$)
S1 and S2 only: The load and battery energy storage being supplied by PV source (When $P_{PV} > P_{Load}$ and $P_B = P_{PV} – P_{Load}$)
S1 and S3 only: The load being supplied by combined PV source and battery energy storage (When $P_{PV} < P_{Load}$ and $P_{Load} =< P_{PV} + P_B$)
S1, S4 and S5 only: The load being supplied by combined P_{PV} and P_{DG} (When $P_{PV} < P_{Load}$ and P_B being minimum or below minimum ($P_B =< P_{B,min}$)
S2 only: P_{PV} supplying the battery energy storage (When $P_{Load} = 0$)
S2, S4 and S5 only: Diesel generator source supplying the load and battery storage in the presence of PV source that is less than the load demand (When $P_{Load} > P_{PV} + P_B$)
S3 only: The load being supplied by the battery storage only (When $P_{PV} = 0$ and $P_B >= P_{Load}$)
S4 and S5 only: The diesel generator supplying the load and battery energy storage (When $P_{PV} = 0$ and $P_{DG} = P_{Load} + P_B$).

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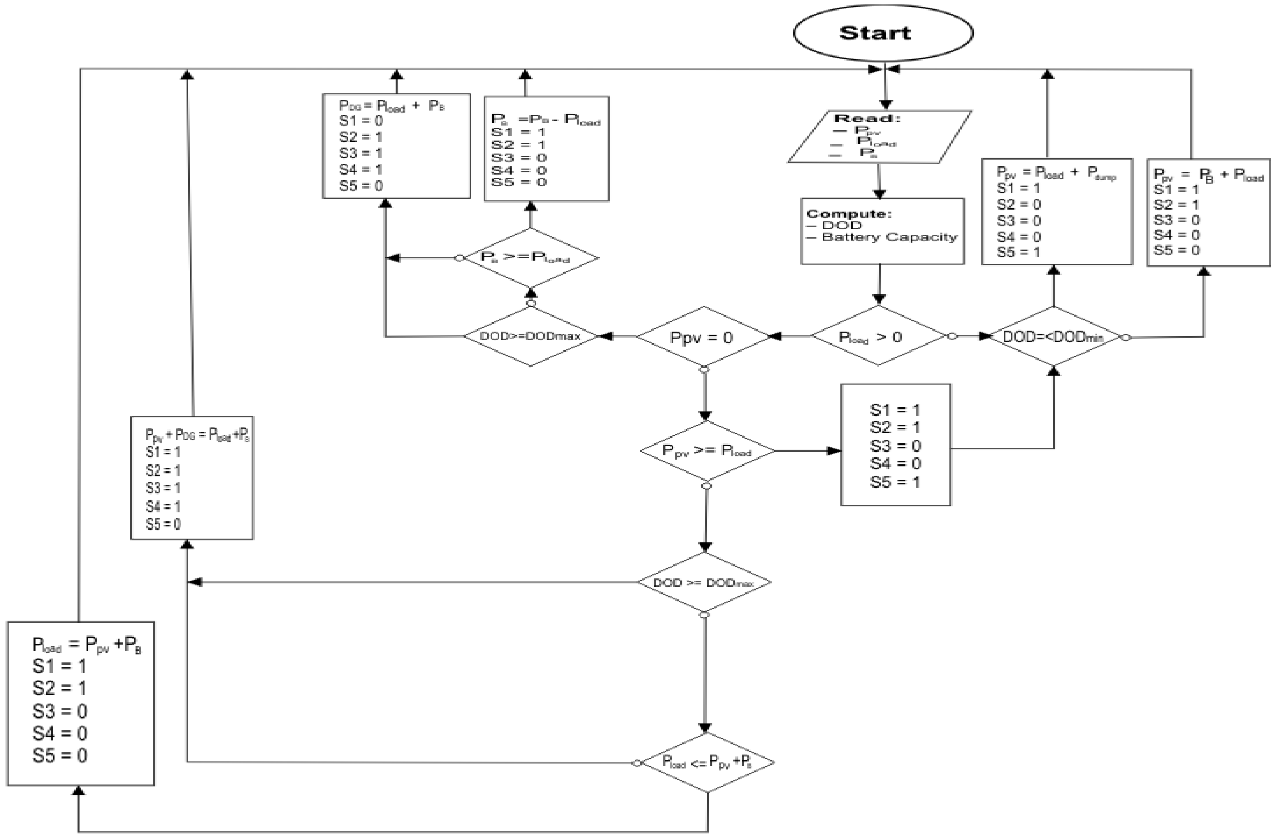


Fig. 6: Flowchart Diagram of the Proposed Energy Scheduling Algorithm

Table 4. Cost Contribution of Various Components of the Off-grid Hybrid Microgrid

Component	Capital ($)	Replacement ($)	O &M ($)	Fuel ($)	Salvage ($)	Total ($)
Battery	867,200	586,429.59	103,420.13	0.00	79,916.90	1,480,133.22
Diesel gen.	88,000	323,513.92	1,981.79	3,520,705	9,262.90	3,924,937.83
PV	640,000	0.00	129,275.17	0.00	0.00	769,275.17
Converter	165,000	57,276.97	19,391.27	0.00	10,780.10	230,888.14
System	1,760,200	970,220.47	254,068.36	3,520,705	99,959.51	6,405,234.36

Table 5. Volume of GHG Emissions (a) with Solar Renewable Included (b) without Solar Renewable Included

(a)

GHG	Value
Carbon Dioxide (kg/year)	800,154
Carbon Monoxide (kg/year)	294
Unburned Hydrocarbon (kg/year)	9.08
Particle Matter (kg/year)	18.2
Sulfur Dioxide (kg/year)	1,985
Nitrogen Oxide (kg/year)	6,391

(b)

GHG	Value
Carbon Dioxide (kg/year)	1,383,539
Carbon Monoxide (kg/year)	508
Unburned Hydrocarbon (kg/year)	15.7
Particle Matter (kg/year)	31.4
Sulfur Dioxide (kg/year)	3,432
Nitrogen Oxide (kg/year)	11,051

4 Result and Discussion

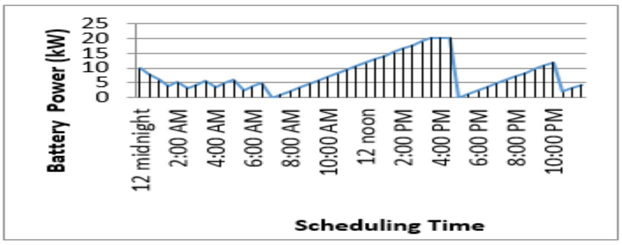
The off-grid hybrid microgrid system was simulated in HOMER ran for about 16,236 simulations so as to obtain the optimum configuration. Though search space was given, HOMER was able to select and arrange the optimum configuration in order of increasing NPC (Net Present Cost). From the simulation, it was observed that the most optimal configuration has one (1) unit of 400kW rated diesel generator set, PV of 1,000kW rated capacity, BAE PVS 140 storage battery has about 1,600 units and converter rated for 300kW.

From the economic point of view, the optimal system has a total capital investment, replacement, operation and maintenance, fuel and salvage costs as shown in Table 4. This gave rise to NPC of $6,405,234.36 and Cost of Energy (COE) of $0.2414. The operating cost stood at $359,313.80. The breakdown of the contributions from individual components from results obtained, the renewable fraction stood at 45.3 % which implies that solar contributed up to 45 % of the total energy of the system. This shows a viable system with solar.

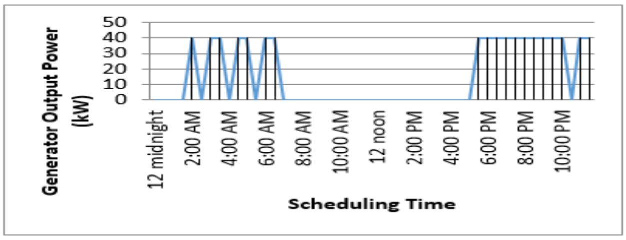
From environmental stand point, it is important to analyse the benefit of including a renewable source in the hybrid micro-grid by comparing the volume of GHG emitted when solar renewable is included and when the system run only on diesel generator. Tables 5a and 5b shows the volume of GHG emission with and without solar renewable inclusion respectively. This represents about 42% reduction in GHG emission.

4.2 Energy Scheduling Result

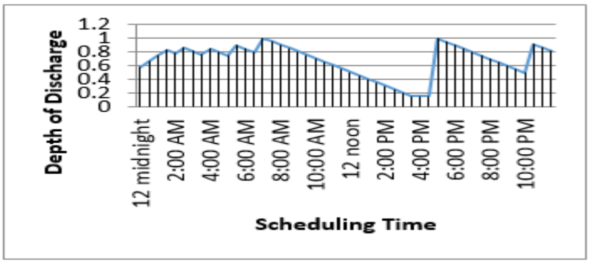
To check the operations and effectiveness of the energy scheduling algorithm as indicated in Figure 6, MATLAB software program was used and the results are as shown in Figure 7a to Figure 7f. It can be clearly seen (Figure 7a) that between 12midniht and 1:30a.m when there was low load, the battery storage was able to serve the load demand as expected. At this point, the generator was OFF and solar power was not available. This resulted to increase in the battery's depth of discharge (DOD). DOD continued to increase to the point that the battery power was unable to serve the load any further, at this point the generator is turned ON (Figure 7b). The generator was ON until 7:00am to serve the prevailing load as well as charge the battery storage. Around 6:30am, solar power started increasing (Figure 7f) up till 7:00am when it has the capability to serve the load and at the same time charge the battery, this situation caused the generator to go OFF at about 7:00am (Figure 7b). As the battery was being charged by the increasing solar power, the DOD started to drop until around 3:30pm when the minimum DOD was reached (Figure 7c). At this point, the battery has become fully charged. Because the solar power continued to increased, it has extra power to be dumped which occurred between 3:30pm to 4:30pm (Figure 7d).



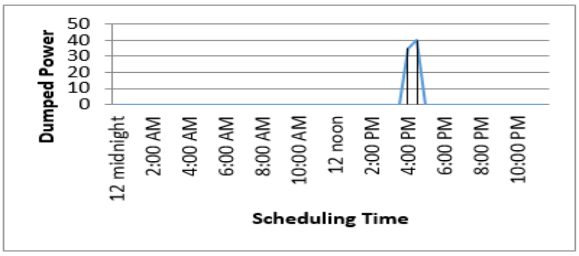
(a) Battery Power during Scheduling



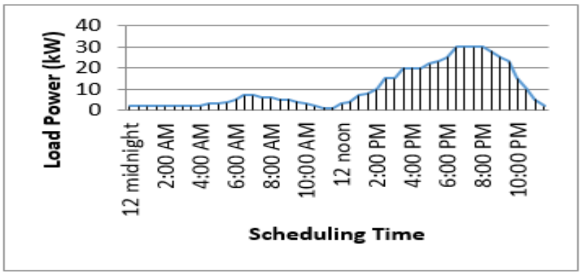
(b) Generator Output Power during Scheduling



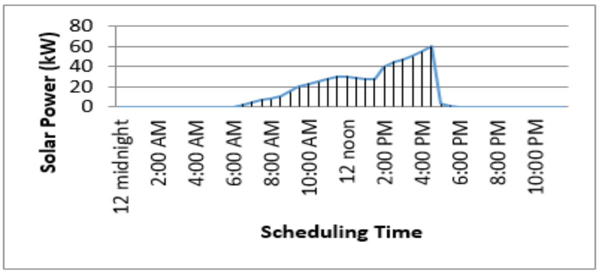
(c) Battery Depth of Discharge during scheduling



(d) Dumped load power during Scheduling



(e) Synthesized load power during Scheduling



(f) Synthesized solar power during Scheduling

Fig. 7: Load and Solar Power Analysis at different times

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Between 4:30pm and 5:00pm, there was a sharp drop in solar generated power and increasing load demand. The load, which pick within the hours of 6.00pm to 8.00pm due to the large number of lightings (including large security lights) reduced drastically as market activities winds down. This caused the battery storage to discharge its power up till 5:00pm when it could no longer serve the prevailing load (Figure 7e). At the point, the generator came ON to serve the load and charge the battery up to 10:00 p.m. This can be seen from the increasing battery power and decreasing DOD between 5:00pm and 10:00 p.m. Between 10:00pm and 11:00pm, the battery storage was able to serve the prevailing load which has reduced considerably as can be seen from the reducing battery power and increasing DOD. As DOD increased up to its maximum value at around 11:00pm, the generator took over the servicing of the load and charging of the battery.

As discussed, it could be seen that the load. This load was continuously being served from the three power sources (solar, battery and diesel generator). Emphasis should be made on the battery storage being able to serve the load independently of other sources. Again, the solar generated power was never wasted or dumped until the load and battery were fully served.

5 Conclusion

This research objective was to solve prevailing problem of unreliability in conventional power supply systems, solving economic and environmental problems associated with the usage of small generators especially in public places like a market. From the research findings, it was obvious that unconventional power sources could be sort for in other to solve the remote problem of unreliability in conventional power systems and the immediate problem of avoiding the usage of small generators in public places which greatly constitute nuisance in terms of placement and air pollution. The solution to these problems was found by obtaining an optimum configuration and developing a simple energy scheduling algorithm for a chosen public place using HOMER and MATLAB software tools.

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