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Design of a DC Microgrid System for a Remote Community in Nigeria

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***Abstract* — This paper presents the design of a DC microgrid for a remote community in Edo State, Nigeria having a solar irradiance of 4.63 kWh/m²/day. The community is isolated and located far away from the city with no access to the electricity grid. There is a need for lighting and running of electronics, as the main source of lighting presently is kerosine, which is not efficient and leads to health issues. The community is made up of 9 residences that are not more than 100 m apart. House 1 was selected as the standard house with a load of 1 kWh/day, while the other 8 houses have a load difference of ±10% with reference to house 1. Using a 48 V DC bus, the designed PV system components comprise of a 100W solar photovoltaic (PV) panel and a 12 V 45 A·hr battery. The system was sized using Homer Pro. Optimization results presented various design for the various houses. The result obtained showed reasonable and feasible cost-effective solution in terms of the Net Present Cost in both installation and running of the hybrid system for the community. Sensitivity analysis was also carried out to test the adaptability of the system using a solar irradiation input of ±10%. Detailed result of the analysis is presented in the paper.**

***Keywords* — Homer Pro; Optimization; Solar energy; renewable energy.**

I. INTRODUCTION

The problems faced in increasing electrification are infrastructure and distribution of power plants, especially in remote areas [1]. Lack of electricity in most African countries has been an issue that is yet to be resolved, Nigeria is not an exception from this situation of lack of electricity/insufficient power supply. Most remote areas in the country suffer from a total electrical blackout for days and in worse cases, no access to electricity grid. In this remote area, Kerosine lantern is mostly used for lighting purpose. Due to the moderate temperature in these areas, there is usually no need for heating. Conventional approach to meet such needs is to connect these remote areas to the electrical grid, but this would be very expensive and unpractical because most of these remote residences are so far from the common cities that the line loss and maintenance cost would be too much and non-feasible to implement. Notwithstanding, Electricity is needed in this area for proper lighting and running of electronics.

Renewable energy is the most appropriate solution to supply energy in isolated areas. Utilization of locally available resources is the best possible option to meet the energy requirement. Single technology-based system (solar photovoltaic/wind/small hydro) is a viable option to supply energy in isolated areas. Un-electrified rural areas like village hamlets or small villages that are far away from the utility grid can be electrified by single technology [2]. One solution that can be done is to build a power generation using off-grid power system. Off-grid power system can consist of PV-Battery or Genset-Battery to supply the communal load [3]. STANDALONE Photovoltaic (PV) systems are designed and sized to supply certain AC and/or DC electrical loads [4].

Adithya designed a small off-grid PV system for a rural home. The system comprised of a 5W PV, and a 6 V, 7 A·h lead acid battery. The system was used to power small loads like LED (Light emitting diode) lamp and mobiles. Simulation result shows the system was efficient in powering the resident [5]. Sini designed a system for a rural residence in Bhilai, Chhattigarh which experiences breakdown and tripping in power supply. The house has an estimated energy consumption of 30.41 kWh/d and 3.24 kW peak power. Simulation was carried out using Homer Pro. The result showed that among other possible configuration, the PV-battery system has the lowest Net Present Cost (NPC) and COE and would yield reasonable returns in the long run [6]. Nunu designed a solar PV system for Mapetja rural village having a solar radiation of 5.96 kWh/m². The village is located far away from the National grid. The total load consumption of a single house in the village was found to be approximately 11 kWh/d. The PV system required for sufficient supply comprised of 728 modules (7 series, 104 parallel), a charge controller, 18 deep cycle batteries of 12 V, and an inverter. Result showed that the use of the designed stand-alone PV system would be the best suitable sustainable solution for the village in terms of electricity supply [7]. Chin designed and optimised a PV hybrid system for the residential community of Basco island in the Philippines to replace the diesel generator only system. the proposed energy system is made up of 4611 kW PV, 116 batteries of 12823 kWh, 10 kWh wind generators, 1000 kW diesel generator, and 1500 kW converter. The system was found to be both power efficient enabling the use of electricity supply for 24-hours and cost-effective with the cost of energy (COE) equals to $0.409/ kWh for $1/litre diesel fuel cost [8].

Chaudry proposed an off-grid PV system for a house in Pakistan having a load of 7.81 kWh/day, the system comprised of 8 batteries and 36 PV. From the design, simulated results showed that the configuration is sufficient enough to power the house efficiently independently from the national grid [9]. Arif carried out a design for an off-grid solar system for a house with average energy consumption of 40

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kWh per month located in a remote community in Pakistan, the system comprised of 4 solar panels of 140 W, giving a total of 560 W PV, 4 batteries each having 125 A·hr and a 1kW inverter. The result showed the system provided a better electrification solution with an energy production of 726 kWh per annum [10].

The selected site is located using the google earth pro, with coordinates (6.182863, 5.933505) Latitude: 6°10'58.3"N Longitude: 5°56'00.6"E. Having a solar irradiance value of 4.63kWh/m^2/day. The community is made up of 9households which are completely cut off from the utility grid. The houses are not more than 100 m apart as shown in Fig. 1.

The purpose of this research is to design a system where each house has a photovoltaic (PV) panel and a battery. The loads are all connected with a 48 V bus. All loads are DC loads. The sizing of the system has been done using the Homer Pro optimization software. Smaller loads are supplied through 48 V to 12 V and 48 V to 5V DC-DC converters

Fig. 1. Location of the remote community in Nigeria.

II. Electrical Load

Each household in the community has a few loads to be powered, comprising mostly of lighting points, table fan, radio, and TV. A detailed breakdown of a load of each household is presented in Table I below. Some residents have cell phones that they take to nearby villages for charging.

TABLE I: Daily Energy Requirement for House 1 in the Community

Appliances	Quant.	Watt.(W)	Total(W)	Usage (hours)	Energy (Wh/day)
LED bulb	3	18	54	10	540
Fan	2	10	20	9	180
Radio/cell phone	1	5	5	8	40
Television	1	30	30	8	240
Total:			**109**		**1000**

The figure below shows the percentage load distribution of the 9 households in the community for a converter less isolated DC microgrid. With house 1 as a reference and a load variation of ±10%, the load distribution from house 1 to house 9 are 1 kWh/day, 1.1 kWh/day, 1.2 kWh/day, 1.3 kWh/day, 1.4 kWh/day ,0.9 kWh/day, 0.8 kWh/day, 0.7 kWh/day and 0.6 kWh/day. Each house has a PV system, a battery bank, and an ON/OFF switch to connect/disconnect from the microgrid if they decide to do so.

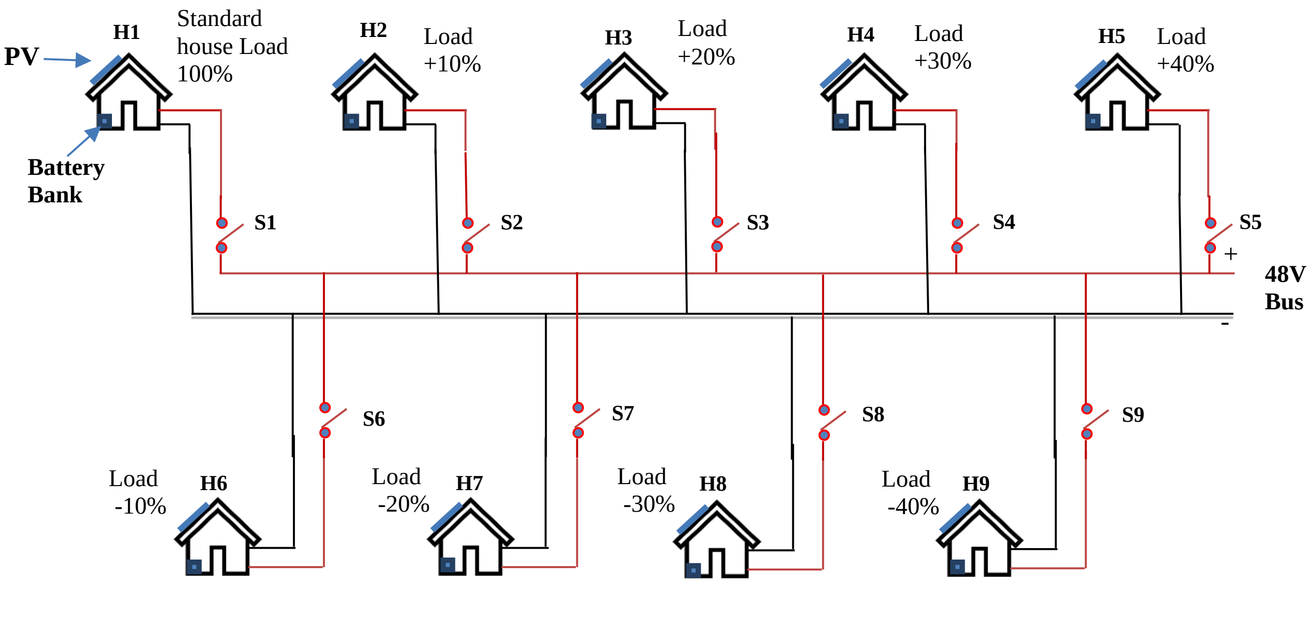

Fig. 2. block diagram showing load distribution of households in the community.

III. System Component Design

The system comprises a Donghui High efficiency 100 W Mono solar panel, and a PowerStar battery of 12 V, 45 A·hr all connected to the 48 V bus, there is no inverter in the system. the MPPT ensures the PV reaches maximum powerpoint. House load is 48 V/12 V/5 V. Two DC-DC converters are used to get 12 V and 5 V from 48 V. TV and some lights are 48 V. Some lights and fan run on 12 V. Radio/cell phone needs 5 V for charging.

The system was designed in Homer Pro. Fig. 5 above represents the optimization result for the 9 houses with various electrical loads. Using a 100W PV and 12 V, 45 A·hr lead acid battery, For the house with 0.6kWh/d of load, the required components would be 0.417 kW PV and 4 batteries. For the house with 0.7 kWh/d of load, the required components are: 0.323 kW PV and 8 batteries with this configuration come the highest autonomy of 88.9 hr, which means in the absence of solar power the backup battery can run for up to 4 days. For the house with 0.8 kWh/d of load, the required components are 0.396 kW and 8 batteries. For the household with 0.9 kWh/d of load consumption, the required components include 0.863 kW PV and 4 batteries. For a house with 1.10 kWh/d of energy consumption, required components: 1.21 kW PV and 4 batteries. For a house with 1.20 kWh/d of load, the required components are 0.827 kW PV and 8 batteries. For a house with 1.30 kWh/d of load, the required components would be 0.958 kW PV and 8 batteries. For the house with 1.4 kWh/d of load, the required components are 0.759 kW PV and 12 batteries. For the house with 1 kWh/d of load, the required components are 0.576 kW PV and 8 batteries. All houses show a renewable fraction of 100% and the initial cost, capital cost, and operational cost vary from one house to another. Say a house needs 0.759 kW PV and each PV module is 100 W, 12 V then four modules will be used in series (800 W total) to have a 48 V system. Small PV modules and batteries were selected that could be carried and moved around without any need for a vehicle and road that does not exist in the community.

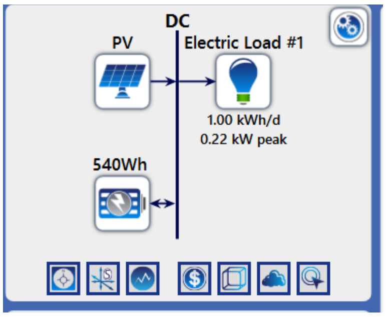

Fig. 3. Homer Pro system block diagram.

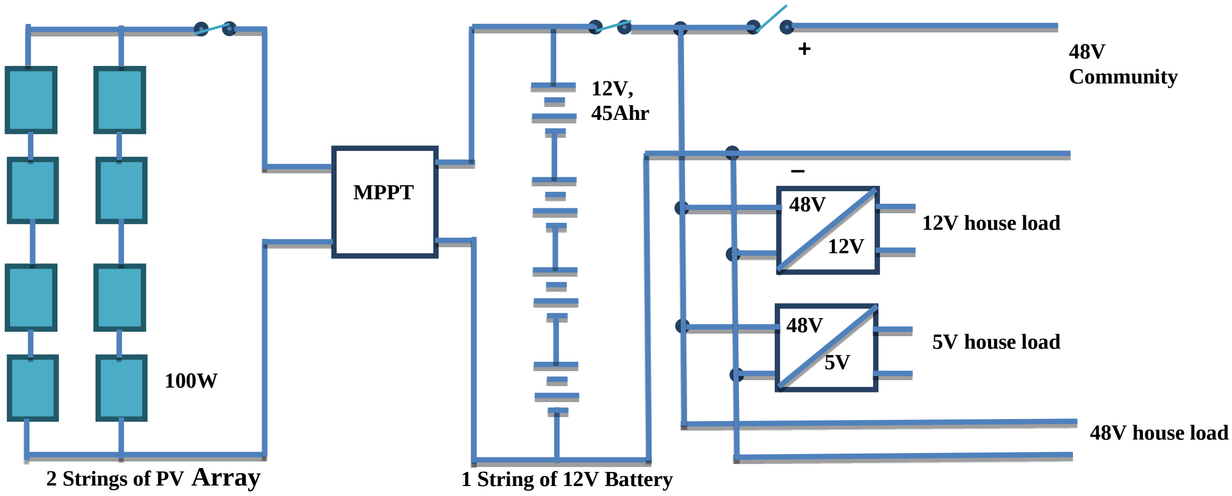

Fig. 4. System component in a house.

Sensitivity	Architecture					Cost				System		PV		540Wh	
Electric Load #1 Scaled Average (kWh/d)			PV (kW)	540Wh	Dispatch	NPC (US$)	COE (US$)	Operating cost (US$/yr)	Initial capital (US$)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost (US$)	Production (kWh/yr)	Autonomy (hr)	Annual Through (kWh/yr)
0.600			0.417	4	CC	$2,407	$0.851	$108.49	$1,004	100	0	304	569	51.8	131
0.700			0.323	8	CC	$3,780	$1.15	$165.90	$1,636	100	0	236	440	88.9	160
0.800			0.396	8	CC	$3,928	$1.04	$173.22	$1,689	100	0	289	540	77.8	182
0.900			0.863	4	CC	$3,310	$0.780	$153.13	$1,330	100	0	630	1,178	34.6	191
1.10			1.21	4	CC	$4,015	$0.774	$188.00	$1,585	100	0	885	1,654	28.3	231
1.20			0.827	8	CC	$4,799	$0.848	$216.29	$2,003	100	0	603	1,128	51.8	263
1.30			0.958	8	CC	$5,066	$0.827	$229.47	$2,100	100	0	700	1,308	47.9	283
1.40			0.759	12	CC	$6,226	$0.943	$276.33	$2,654	100	0	554	1,036	66.7	314
1.00			0.576	8	CC	$4,293	$0.911	$191.27	$1,821	100	0	421	787	62.2	223

Fig. 5. System design for each house in the community.

IV. Economic Analysis

Homer Pro also performs economic analysis to determine the feasibility of implementing the system with financial considerations. The cost summary of the simulated result shows the detailed breakdown of the cost of the system which comprises the capital cost, replacement cost, operation, and maintenance (O&M) cost, salvage cost, and total cost of each component. The total cost of all the components gives the Net Present Cost (NPC) of the system per household. Table II below provides all cost details for all houses in the community.

House 9 with an electrical load of 0.6kWh/d, Homer Pro analysis shows that the Net Present Cost (NPC) for installation, operation and running of this system is $2,407, initial capital cost of $1,004, operational cost of $108.49. The Fig. 6 below shows the cost summary and breakdown of the cost for the components. Fig. 6 shows the cost summary of

House 9. It also shows the capital cost, replacement cost, operational cost, salvage, and total cost for each component of the system. for the PV it shows a capital cost of $304.17, operation and maintenance (O&M) cost of $538.65, and this gives a total cost of $842.81. The Battery has a capital cost of $700, the replacement cost of $401.08, O&M cost of $517.10, salvage cost of $54.38, which gives a total cost of $1,563.80. the total cost of both components (PV and battery) gives the NPC of the system. Information on capital costs, initial capital, operational cost, and NPC for other houses in the community can be found in Table II.

TABLE II: OPTIMIZED COST FOR EACH RESIDENCE IN THE COMMUNITY

Household	Electric Load (kWh/d)	PV (kW)	Batt. 12V	NPC ($)	Operating cost ($/yr)	Initial capital	Capital cost ($)	Autonomy (hr)
House 1	1.0	0.576	8	$4,293	$191.27	$1,821	$421	62.2
House 2	1.1	1.21	4	$4,015	$188.00	$1,585	$885	28.3
House 3	1.2	0.827	8	$4,799	$216.29	$2,003	$603	51.8
House 4	1.3	0.958	8	$5,066	$229.47	$2,100	$700	47.9
House 5	1.4	0.759	12	$6,226	$276.33	$2,654	$554	66.7
House 6	0.9	0.863	4	$3,310	$153.13	$1,330	$630	34.6
House 7	0.8	0.396	8	$3,928	$173.22	$1,689	$289	77.8
House 8	0.7	0.323	8	$3,780	$165.90	$1,636	$236	88.9
House 9	0.6	0.417	4	$2,407	$108.49	$1,004	$304	51.8

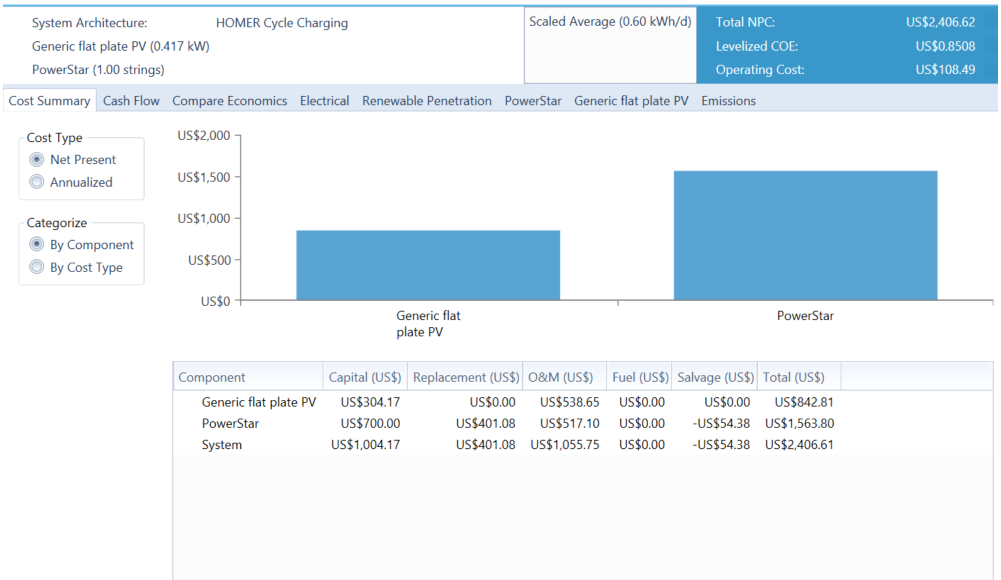

Fig. 6. Cost summary of house 9.

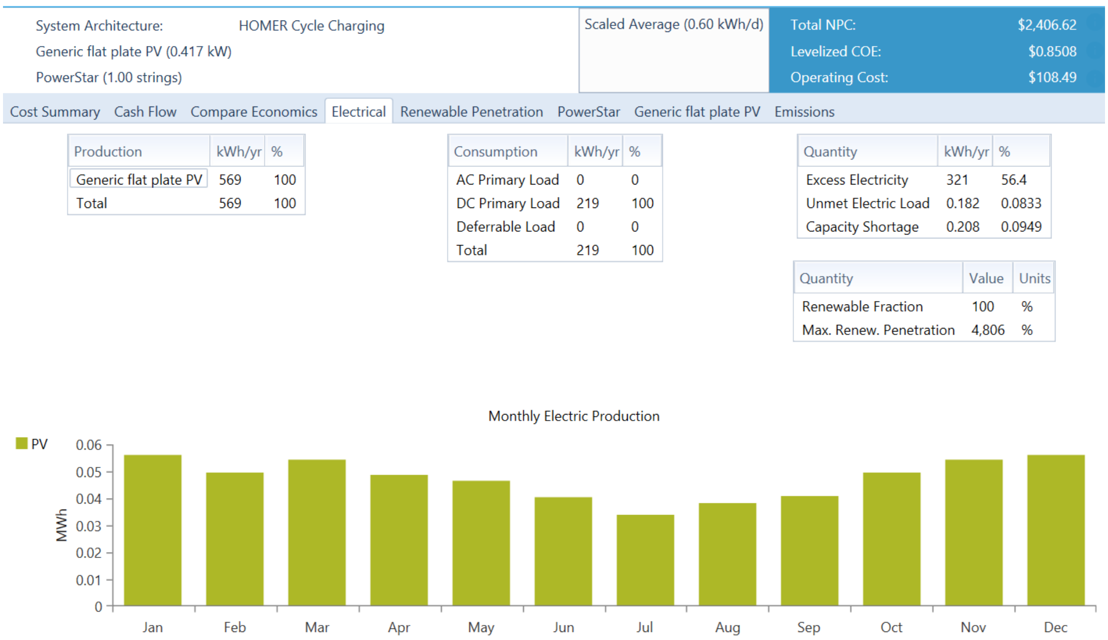

Fig. 7. Electrical output of a house in the community.

V. Electrical Output

Fig. 7 above shows the electrical output for house 1 having a load of 0.6 kWh/d. the homer optimization result showed the most efficient system for the resident is 0.417 kW PV and 1 string of Power battery. For the PV component, a 12V 100 W PV was selected whereas for the battery a 12 V, 45 A·hr PowerStar battery was selected. The system has been simulated using a 48 V bus system, which will require 4 of the selected PV modules connected in series and 4 of the selected battery components connected in series to give 1 string of battery. The result also shows a 100% renewable fraction and excess electricity of 321 kWh/y. Optimization result shows autonomy of the system to be 51.8 h, which means in the case of no solar resource due to rainy days the battery system can supply power for up to 2 days. The monthly electrical production for the year is also shows the monthly production of PV power for the span of one year, the graph showed peak production in the months of January, March, November, and December, while the lowest production in the month of July (days are larger in July and house lighting needs are reduced).

Each house has a PV system that could be connected to the community DC microgrid through a switch. In the selected community of PV system with no measurement system is difficult to maintain due to poor know-how and lack of knowledge. Battery may over discharge due to carelessness. If all houses are connected through DC microgrid then people can share excess production with neighbours and that will lead to a more reliable system. If a house owner forgot to clean PV modules, then for a time being power can come from neighbours. Therefore, a community system connected through 48 V bus as shown in Fig. 2 is recommended and designed.

Fig. 8 above also shows the hourly time series detailed analysis of the battery State of charge and the Solar PV power output for the span of 1 year. From the graph it can be deduced that the period of sharp decline in the state of charge of the battery from 100% to 40% is between the month of June to September, whereas the power output of the solar PV varies almost throughout the year. In a DC microgrid such sharp decline is less likely due to power sharing among neighbours.

VI. Sensitivity Analysis

Sensitivity analysis also called the "what if analysis" is critical in understanding the robustness of a design. It allows you to understand how a changing input will affect the choice of least cost system. In this design model, sensitivity analysis is performed on solar irradiation. Inputting a range of solar irradiation from 4.14 kWh/m^2/day to 5 kWh/m^2/day due to climate change factors such as less cloudiness in certain times of the year (summer/dry season) causes the solar irradiation to increase and dust accumulation on PV leads to decrease in PV efficiency.

Due to climate change factors such as less cloudiness in certain times of the year (summer/dry season) the solar irradiation increases, so therefore the optimization result also takes this variable into consideration by optimizing the system with a solar irradiation value of 5.00 kWh/m^2/day. The optimization result shows the different house loads and est possible configuration for optimal and efficient supply of power to the residence in the community. Fig. 9 below shows system sensitivity analysis results obtained from Homer Pro.

Fig. 9 above shows some of the sensitivity results for the community. For the house with a load of 0.6 kWh/day, the sensitivity cases show three results: case 1 for solar irradiation of 4.14, case 2 for solar irradiation of 4.63 and case 3 for solar irradiation of 5.00. from these three cases, it can be observed that as solar irradiation increases number and cost of components reduces. For example, for 4.14 solar irradiation the required component would be 4 batteries, 0.469 kW PV, and the NPC of the system would be \$2,512. Whereas, for the 5.00 solar irradiation case required components would involve 4 batteries and 0.385 kW PV, which shows an NPC of \$2,343. The same applies to all other sensitivity cases.

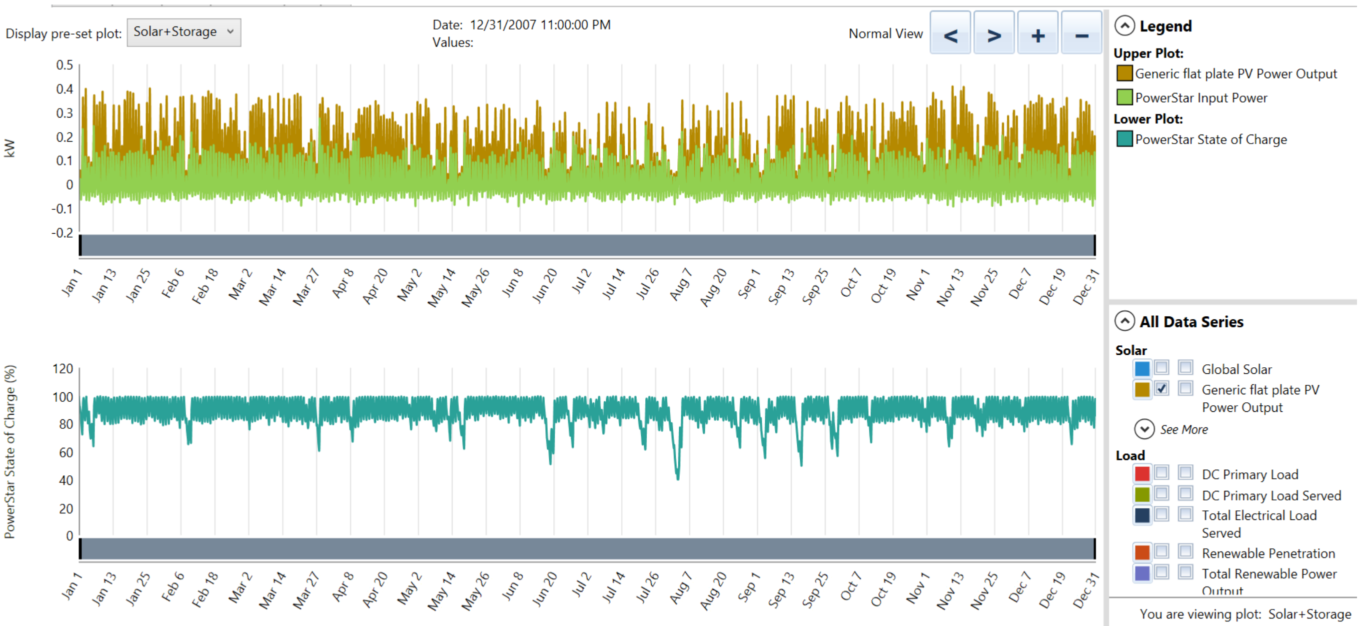

Fig. 8. Time series detail analysis of PV power output for a resident.

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Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

Compare Economics | Column Choices...

Sensitivity		Architecture			Cost				System		PV		
Electric Load #1 Scaled Average (kWh/d)	Solar Scaled Average (kWh/m²/day)	PV (kW)	540Wh	Dispatch	NPC (US$)	COE (US$)	Operating cost (US$/yr)	Initial capital (US$)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost (US$)	Production (kWh/yr)	Autonom (hr)
0.600	4.14	0.469	4	CC	$2,512	$0.888	$113.69	$1,042	100	0	342	571	51.8
0.600	4.63	0.417	4	CC	$2,407	$0.851	$108.49	$1,004	100	0	304	569	51.8
0.600	5.00	0.385	4	CC	$2,343	$0.828	$105.34	$981.18	100	0	281	568	51.8
0.700	4.14	0.364	8	CC	$3,865	$1.17	$170.07	$1,666	100	0	266	444	88.9
0.700	4.63	0.323	8	CC	$3,780	$1.15	$165.90	$1,636	100	0	236	440	88.9
0.700	5.00	0.299	8	CC	$3,732	$1.13	$163.50	$1,618	100	0	218	440	88.9
0.800	4.14	0.437	8	CC	$4,011	$1.06	$177.31	$1,719	100	0	319	532	77.8
0.800	4.63	0.396	8	CC	$3,928	$1.04	$173.22	$1,689	100	0	289	540	77.8
0.800	5.00	0.364	8	CC	$3,865	$1.02	$170.07	$1,666	100	0	266	537	77.8
0.900	4.14	0.530	8	CC	$4,199	$0.990	$186.62	$1,787	100	0	387	645	69.1
0.900	4.63	0.863	4	CC	$3,310	$0.780	$153.13	$1,330	100	0	630	1,178	34.6
0.900	5.00	0.450	8	CC	$4,037	$0.951	$178.59	$1,728	100	0	328	663	69.1
1.10	4.14	0.777	8	CC	$4,699	$0.906	$211.32	$1,967	100	0	567	946	56.6
1.10	4.63	1.21	4	CC	$4,015	$0.774	$188.00	$1,585	100	0	885	1,654	28.3
1.10	5.00	0.650	8	CC	$4,443	$0.857	$198.68	$1,875	100	0	475	959	56.6

Fig. 9. Sensitivity analysis of system design in Homer Pro.

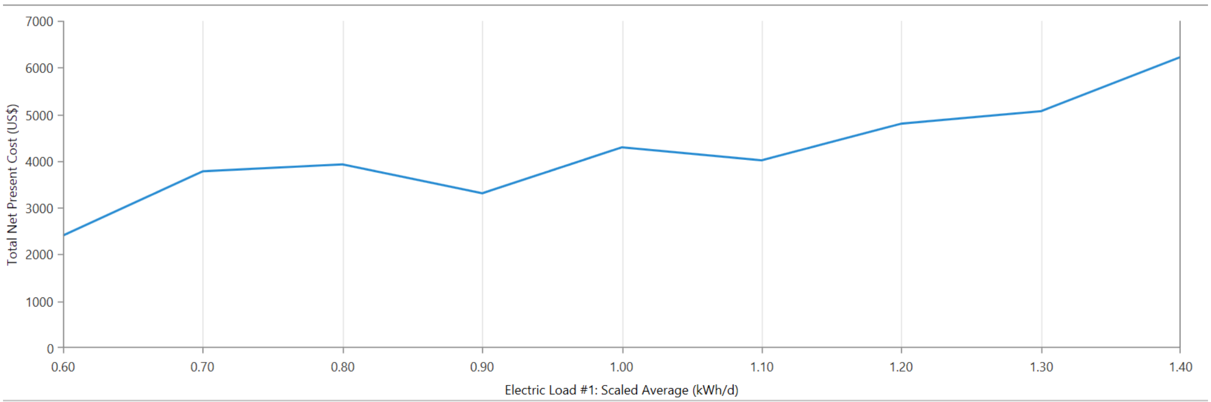

Fig. 10. Line plot with NPC for remote Edo community for 4.63kWh/m^2/day solar scaled average.

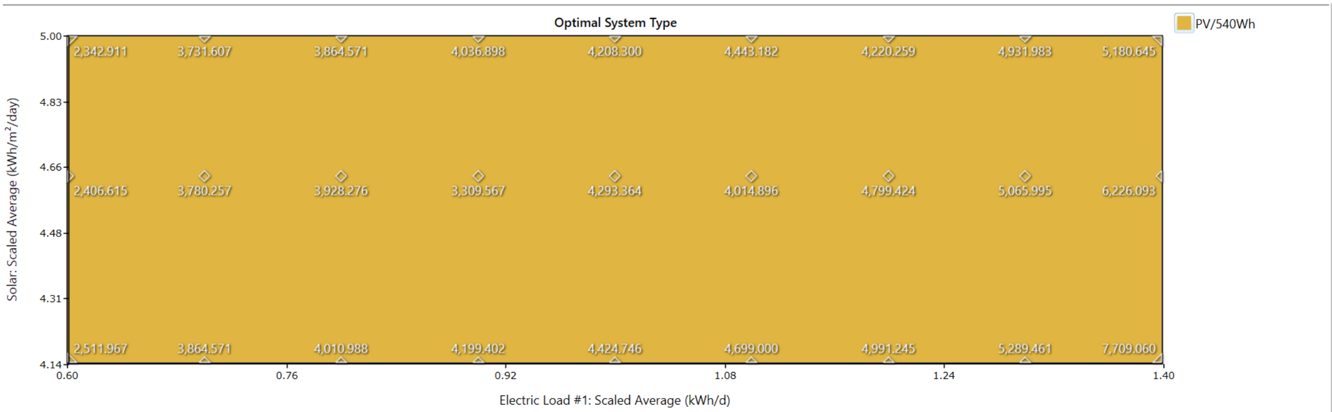

Fig. 11. Optimization surface plot with NPC for 4.14kWh/m^2/day solar scaled average.

Fig. 10 represents the graph for total Net present Cost (NPC) against Electrical load for 4.63 kWh/m^2/day solar scaled average. The result shows that as the load increases, there in a non-linear increase in system cost. this is because with increase in load demand comes an increase in the required components needed to meet the demand of the system. result for solar scaled average of 4.14 kWh/m^2/day and 5.00 kWh/m^2/day also shows similar results.

Fig. 11 above is a plot of solar scaled average against average electrical load. this graph shows that if solar energy is more, then system cost is going to be low. For instance, in the case of 0.6kWh/d, the NPC of the system at 4.14 kWh/m^2/day is $2,511.967, whereas at a solar scaled average of 5.00 kWh/m^2/day the NPC is $2,342.911, this shows a decrease in cost of about $170. For electrical load of 0.90, NPC at 4.14 kWh/m^2/day is 4,199.402, whereas at 5.00 the NPC reduces to $4,036.898.

VII. Conclusion

The study involved the sizing of a remote community in Edo State, Nigeria having 9 houses located far away from the utility grid and the city. The cost of running electric cables to connect this remote community to the city utility grid would be far more expensive and would lead to huge losses along the line, which would be counterproductive. For this research, solar energy was considered due to the abundance in the supply of solar resources in the region. From simulated results a PV microgrid DC system is the best solution in terms of cost and optimization of energy. Factors such as variation in solar resources, unequal use of energy in the community can be balanced out by sharing excess energy among residents in the community. With an increase or decrease in solar irradiation from 4.14 kWh/m^2/day to 5 kWh/m^2/day due to climatic factors, there would be little to no change in system cost because houses that have less energy consumption will share excess energy with a residence with more need for energy. This system is far better than a standalone system for each resident as it would require much more PV components leading to more cost in installation, operation, and maintenance.

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