Impact of Load Diversity on the Design of Isolated Grid Solar PV systems for Rural Communities in Ghana

Stephen Afonaa-Mensah[*], **David Asante**[**]

[*]Electrical/Electronics Department, Takoradi Polytechnic
[**]Mechanical Engineering Department, Takoradi Polytechnic

Abstract- Rural communities are characterized by low energy consumption and poor load factor. The use of off-grid systems to provide electricity to these communities must be done taking into consideration the peculiar nature of rural communities to improve the utilization of the installed capacity. In many situations where off-grid technology is employed for rural electrification, community-level power supply systems could have been a better option as compared to other off-grid technologies such as the stand-alone systems. This is due to the fact that all individual loads connected to power supply systems are not used simultaneously; there is always some degree of diversity. In this paper, community-isolated grid solar PV system has been designed for Yabiw rural community. In the design, demand factor and diversity factor of 0.3 and 1.7 were considered respectively. This resulted in 82.35% reduction of daily power estimated for the community in the design of community level isolated grid system from 109.856kW to 19.386kW. There was subsequent reduction in the size of all solar PV components estimated for the community level isolated grid system. The size of inverter and the charge controller reduced in equal proportion of 82.35% as the reduction in the power demand. The sizes of Solar panel, battery bank and cable required also reduced by 82.14%, 81.08% and 77.14% respectively. Considering community-level isolated grid system where viable, for rural electrification project can significantly reduce the size of solar PV systems and subsequently the cost of off-grid rural electrification projects.

Index Terms- Diversity factor, Isolated grid, Rural electrification, Solar PV systems

I. INTRODUCTION

The aim of this research is to analyze the impact of load diversity in the design of community-level isolated grid solar PV systems by using a selected rural community as a case study. The specific objectives are to:

i. Identify a rural community that meets the criteria for sustainable community-level isolated grid system
ii. Determine and assess load used by the rural community to estimate daily energy demand
iii. Identify design considerations factored in typical rural electrification projects of Ghana
iv. Design community-level isolated grid system to meet the daily electricity need of the rural community
v. Analyze the major solar PV components estimated for the designed community level isolated grid system

II. METHODOLOGY

In this paper, community level-isolated grid system has been designed for Yabiw rural community. This rural community was selected based on the minimum of 100 household units within 500m radius criteria for a community to be considered for sustainable isolated grid system. Load assessment was carried out using load assessment form to determine the kind of load and estimate the daily energy demand of the community. Diversity factor and demand factors considered are based on design considerations of Electricity Company of Ghana in typical rural electrification projects of the country. Finally, the impact of load diversity on the size of major solar PV components in the design of the community-level isolated grid solar PV system has been analyzed. Two (2) design scenarios have been presented where Design 1 corresponds to the design for the community isolated grid system for the individual connected loads without considering load diversity and Design 2 corresponds to the design when load diversity for the rural community is considered.

III. INTRODUCTION

Electricity is considered as the most critical energy carrier for development [1]. However rates of rural electrification as compared to urban electrification in many countries is extremely low and is a major cause of developmental disparity between rural and urban communities[2] .The task of supplying electricity to rural communities is a huge challenge. Rural electrification is usually not considered to be an attractive investment; risk is perceived high and returns unsatisfactory [3]. This is because rural areas in developing countries are usually very poor and their inhabitants' per capita energy consumption is very low [4].
At rural electrification rate of about 52% as compared to urban electrification rate of 90% Ghana aims at achieving 30% rural electrification through decentralized renewable energy projects for the residential by the year 2020 [5,6]. However whereas there is the need to provide electricity to rural communities, there are equally good arguments for assuring that the cost is reasonable in comparison to the benefits; that supply options are adapted to the need and environmental considerations and that project preparation is based on adequate information[3]. The low energy consumption and poor load factor characteristics of rural

communities must be considered in the selection of off-grid solar PV technology for rural electrification [4,7].

In many off-grid rural electrification projects, the ideal would be if electrification was community based [3]. Communities on isolated grid systems have several advantages in comparison with individual systems [8]. Some advantages of such technologies are that user consumption does not depend on the resource in its location. Also costs can be reduced by economies of scale of power generation systems as a lower ratio between the generators cost and the energy produced could be reached. [9]

Rural communities where there are over 100 households within 500 square meter radius and energy demand above 5kW, community-level isolated grid system could be considered as a sustainable option for rural electrification [3,10]. Where viable, Community-level isolated grid system is better option as compared to other off-grid solar PV technologies such as the stand alone systems. The utilization of power generating equipment measured as the average capacity installed, is normally higher in isolated grid systems as compared to other off-grid technologies [3].

By considering demand factors and diversity factors when designing power supply systems, a potential maximum demand could be scaled down to an actual maximum demand. This is because simultaneous operations of all individual loads connected to a power supply system do not occur in practice. There is always some degree of diversity. The degree of diversity in power systems increase as the number of downstream consumers increase. The determination of these design factors is the responsibility of power system designer and requires a detailed knowledge of the existing conditions [11,12]. The greater the degree of diversity considered, the lesser the generation cost of power systems[13] .Considering these factors in design of power supply systems would help to maximize the utilization of the installed capacity of off-grid solar PV systems used for rural electrification projects due to the low energy consumption and poor load factor characteristics of rural communities.

With cost identified as a major challenge against the use of solar as an off-grid technology for rural electrification in Ghana and cost of solar panel and battery bank size contributing over 50% of the cost of solar PV systems for rural electrification projects [6,14], considering Community-level isolated-grid solar PV system where viable could significantly reduce the cost of off-grid solar PV rural electrification projects.

Description of Yabiw

Yabiw is a rural community that is located about 25 km from Takoradi in the Ahanta-West District of Western Region, Ghana. The community has about 110 household units and a total population of about 750. About 65% of the household units are clustered around the community center within 200 m radius while the others are sparsely distributed at an average distance of about 400m from the community center. This community has been selected because it meets the criteria of a minimum of 100 household units within 500 m radius for sustainable community-level isolated grid system.

IV. LOAD ASSESSMENT AND DESIGN CONSIDERATIONS

Load assessment and design considerations for Yabiw has been summarized in Table 1 and Table 2

Table 1: Electricity consumption characteristics of Yabiw rural community

Appliance	Average Power Consumption/unit (W)	Quantity	Average Duration of use/day (h)	Power Factor
Lights	20	708	8	0.8
TV	100	57	5	0.7
Fan	60	46	5	0.7
Sound System	75	45	5	0.7
Iron	1800	31	0.22	1.0
Heater	1000	12	0.2	1.0
Refrigerator	150	21	9	0.7
Electric Kettle	2200	2	0.17	1.0
Mobile phones	5	108	2	0.7
DVD	40	32	5	0.7
Other (P.A. system)	100	1	6	0.7

Table 2: Load diversity considered for typical rural electrification projects of Ghana

Design parameter	Design Factor
Demand Factor	0.3
Diversity Factor	1.7

Source: JICA 2006 [16]

Specification of solar PV system components

Storage Battery specifications

OpzS Solar 280 battery has been considered in design, its specifications is given in Table 3.

Table 3: OPzS Solar 280 battery specifications

Battery Capacity (C_{acc})	296 Ah
Discharge time (D_t)	48 h
Battery voltage (V_{acc})	6 V
Battery efficiency (B_{eff})	80%

(Source: www.battery.co.za)

Solar panel specifications

The KYOCERA type 70-1P solar module has been considered in design, its specifications is shown in Table 4

Table 4: KYOCERA type 70-1P (KD70SX-1P) specifications

Maximum Power (P_{max})	70 W
Open Circuit Voltage(V_{oc})	22.1V
Maximum Power Voltage (V_{mp})	17.9V
Nominal voltage	12V
Short Circuit Current (I_{sc})	4.3 A
Maximum Power Current (I_{mp})	3.91A

(Source: www.kyocerasolar.de)

Solar Irradiation

The solar irradiations considered for the design is shown in Table 5

Table 5: Minimum daily solar irradiation

Location	Takoradi
Minimum daily solar irradiation (Hi)	4.2 kWh/m^2/day

Source: (www.retscreen.org)

Cable

Copper cable is considered for design; its specification is shown in Table 6

Table 6: Cable specifications

Type of conductor	Copper
Resistivity (ρ)	0.0183
Cable length (L)	15m

Assumed Design considerations

Other assumed design considerations have been shown in Table 6

Table 7: Other design considerations

Parameter	Factor considered
Inverter efficiency($Inv_{\%}$)	94%
Derated output factor of solar PV(E_{gen})	80%
Depth of Discharge (*DOD*) of battery	50%
Days of Autonomy (T_{aut})	2 days
Allowable percentage voltage drop($\Delta V\%$)	3%

V. SOLAR PV SYSTEM DESIGN

Estimation of system voltage

The equation to determine input power (*Pin*) to the connected loads from the inverter is given as;

$$P_{in} = \frac{P_o}{Inv_{\%}} \tag{1}$$

Where $(P_o)$the output is power of the connected loads and $(Inv_{\%})$ is the efficiency of the inverter.

Considering inverter efficiency of 94%, the input power of the various electrical load to be considered for Design 1 and Design 2 is given in Table 8

Table 8: Input power estimated for Yabiw rural community

Electrical Appliance	Total Power Design 1	Applying demand and diversity factors (0.3) and (1.7) respectively Design 2	Input Power Design 1	Input Power Design 2
Light	14160	2498.82	15063.83	2658.32
TV	5700	1005.88	6063.83	1070.09
Fan	2760	487.06	2936.17	518.15
Sound System	3375	595.59	3590.43	633.60
Iron	55800	9847.06	59361.70	10475.59
Heater	12000	2117.65	12765.96	2252.82
Refrigerator	3150	555.88	3351.06	591.36
Electric Kettle	4400	776.47	4680.85	826.06
Mobile phones	540	95.29	574.47	101.38
DVD	1280	225.88	1361.70	240.30
Other(P.A. System)	100	17.65	106.38	18.77
Total			**109856.38**	**19386.42**

Since the input power of both Design 1 and Design 2 are above 10 kW, a system voltage of 120 V is to be considered for the design of the Community-level isolated grid system.

Inverter sizing

The size of the inverter required, rated in volt amperes (VA) depends on the total power (P_T) and the power factor (*p.f*) of the connected load. The equation to determine the apparent power rating (P_{VA}) of the inverter is given as

$$P_{VA} = \frac{P_T}{p.f.} \tag{2}$$

From equation (2), the apparent power rating of the various electrical appliances for Design 1 and Design 2 have been estimated in Table 9a

Table 9a: Apparent power estimated for Yabiw rural community

Electrical Appliance	Total Power Design 1	Total Power Design 2	Power factor	Apparent Power (VA) Design 1	Apparent Power (VA) Design 2
Light	14160	2498.82	0.8	17700.00	3123.53
TV	5700	1005.88	0.7	8142.86	1436.97
Sound System	3375	595.59	0.7	4821.43	850.84
Iron	55800	9847.06	1.0	55800.00	9847.06
Heater	12000	2117.65	1.0	12000.00	2117.65
Electric Kettle	4400	776.47	1.0	4400.00	776.47
Mobile phones	540	95.29	0.7	771.43	136.13
DVD	1280	225.88	0.7	1828.57	322.69
Other	100	17.65	0.7	142.86	25.21
Fan	2760	487.06	0.7	3942.86	695.80
Refrigerator	3150	555.88	0.7	4500.00	794.12
Total				**114050.01**	**20126.47**

Surge power (P_s) and nominal (P_n) ratings of Inverter

During the start of loads that incorporate motors in their operation such as refrigerators, there is high initial current rise. This is considered as surge power in designing solar PV systems and is catered for in designing solar PV systems by multiply the apparent power of such loads by a factor represented as (k) in equation (3) below

$$Ps = k \times \text{Power (VA)} \qquad (3)$$

Where (k) is a factor that takes into account surges during the start of loads. This factor is typically considered to be 3 in designs where loads like refrigerators are included [15].

To estimate surge power rating of the inverter, the loads have been grouped into loads that incorporate motors and loads that do not incorporate motors in Table 9b and the surge power rating (*Ps*) and nominal power ratings (*Pn*) of the inverter estimated in Table 10. Design factor 3 has been considered for loads that incorporate motors and 2 for loads that do not incorporate motors. Also design factor of 1.1 is considered for estimating nominal power ratings of the inverter.

Table 9b: Total apparent power of load with motors and load without motors for Yabiw rural community

Load Description	Components	Total Apparent power rating (VA) Design 1	Total Apparent power rating (VA) Design 2
Load without motor	Light, TV, Sound system, Iron, Heater, Electric Kettle, Mobile phones, DVD, P.A. System	105607.15	18636.55
Load with motor	Refrigerator, Fan	8442.86	1489.92

Table 10: Nominal power and surge power ratings of inverter required for Yabiw

Load Description	Total Power Design 1	Total Power Design 2	Nominal Power (VA) Design 1	Nominal Power (VA) Design 2	Surge power (VA) Design 1	Surge power (VA) Design 2
Loads without motor	105607.15	18636.55	116167.87	20500.21	211214.30	37273.10
Loads with motor	8442.86	1489.92	9286.15	1638.91	25328.58	4469.75
Total			**125454.02**	**22139.12**	**236542.88**	**41742.85**

Daily energy demand
The equation used to determine the daily energy demand (*Wh/j)* per unit household is given as

$$Wh/j = P_{in} \times t \qquad (4)$$

Where (P_{in}) is the input power of electrical appliances and (t) is the duration of use of the load in a day. From equation 4, the daily energy demand to be considered for Design 1 and Design 2 are estimated in Table 11

Table 11: Daily energy estimated for Yabiw rural community

Electrical Appliance	Input Power (W) Design 1	Input Power (W) Design 2	Average duration of use/day (h)	Daily energy demand (Wh) Design 1	Daily energy demand (Wh) Design 2
Light	15063.83	2658.32	8	120510.64	21266.58
TV	6063.83	1070.09	5	30319.15	5350.44
Fan	2936.17	518.15	5	14680.85	2590.74
Sound System	3590.43	633.60	5	17952.13	3168.02
Iron	59361.70	10475.59	0.22	13059.57	2304.63
Heater	12765.96	2252.82	0.2	2553.19	450.56
Refrigerator	3351.06	591.36	9	30159.57	5322.28
Electric Kettle	4680.85	826.06	0.17	795.74	140.43
Mobile phones	574.47	101.38	2	1148.94	202.75
DVD	1361.70	240.30	5	6808.511	1201.50
Other	106.38	18.77	6	638.30	112.64
Total				238626.60	42110.58
Considering 10% Security coefficient (*Etot*)				**262489.26**	**46321.63**

Battery Bank Capacity sizing

The size of battery bank capacity required depends on total daily energy demand(E_{tot}), Days of autonomy(T_{aut}), Battery efficiency(B_{eff}), System voltage(V_{BB}) and Depth of Discharge *(DOD)* of the battery. The equation to determine the capacity of battery bank (C_{BB}) is given as

$$C_{BB} = \frac{E_{tot} \times T_{aut}}{V_{BB} \times B_{eff} \times DOD} \qquad (5)$$

Design 1

From equation (5) and considering specifications of OPz Solar 420 as given in Table 3, battery bank capacity (C_{BB}) for Design 1 is estimated as

$$C_{BB} = \frac{262489.26 \times 2}{120 \times 0.8 \times 0.5}$$

= 10937.05

The equation to determine the number of batteries in a string (*Nbs*) is given as ;

$$Nbs = \frac{V_{BB}}{V_{acc}} \qquad (6)$$

From equation (6), number of batteries in string (*Nbs*) for Design 1 is estimated as

$$Nbs = \frac{120}{6}$$
$$= 20$$

The equation to determine the number of parallel strings of batteries is also given as

$$Nbp = \frac{C_{BB}}{C_{acc}} \qquad (7)$$

where (C_{BB}) is the battery bank capacity and (C_{acc}) is the individual battery capacity

From equation (7), number of parallel strings of batteries (*Nbp*) required in Design 1 is estimated as

$$\text{Nbp} = \frac{10937.05}{296}$$
$$= 36.95$$

(Approximately 37 strings are required for Design 1)

Having estimated the number of batteries in string (*Nbs*) and the number of parallel strings of batteries (*Nbp)* required, the equation to determine the total number of batteries installed (N_B) is given as

$$N_B = Nbs \times Nbp \qquad (8)$$

From equation (8), Number of batteries to be installed (N_B) in Design 1 is estimated as

$$N_B = 20 \times 37$$
$$= 740$$

Battery bank Capacity to be installed ($C_{BB\ install}$) in Design 1 is estimated as

$$C_{BB\ install} = 296 \times 740$$
$$= \mathbf{219040\ Ah}$$

Deign 2

From equation (5) and considering specifications of OPz Solar 420 given in Table 3, capacity of battery bank (C_{BB}) for Design 2 is estimated as

$$C_{BB} = \frac{46321.63 \times 2}{120 \times 0.8 \times 0.5}$$
$$= 1930.07$$

From equation (6), number of batteries in string (N_{bs}) for Design 2 is estimated as

$$(N_{bs}) = \frac{120}{6}$$
$$= 20$$

From equation (7), number of parallel strings of batteries (N_{bp})) required in Design 2 is estimated as

$$(N_{bp}) = \frac{1930.07}{296}$$
$$= 6.52$$

(Approximately 7 strings are required for Design 2)

From equation (8), Number of batteries to be installed (N_B) in Design 2 is estimated as

$$N_B = 20 \times 7$$
$$= 140$$

Capacity of battery bank to be installed ($C_{BB\ install}$) in Design 2 is estimated as

$C_{BB\ install}$ = 296×140
= **41440 Ah**

Solar panel sizing

The minimum output power of solar PV panel (P_{cmin}) required in solar PV system depends on the total daily energy demand (E_{tot}), battery efficiency (E_{bat}), Daily Solar Irradiation of the location (*Hi*) and the Derated output factor of Solar PV (E_{gen}). The equation to determine the minimum output power of solar PV panel required is given as

$$P_{cmin} = \frac{E_{tot}}{H_i \times E_{bat} \times E_{gen}} \quad (9)$$

Design 1

From equation (9) and considering total daily energy demand (E_{tot}) of 262489.26Wh in Table 11, battery efficiency (E_{bat}) of 80% in Table 3, Daily Solar Irradiation of the location (*Hi*) of 4.2 kWh/m^2/day in Table 5 and the Derated output factor of Solar PV (E_{gen}) of 80% in Table 7. The minimum output power of solar PV panel (P_{cmin}) required for Design 1 is estimated as

$$P_{cmin} = \frac{262489.26}{4.2 \times 0.8 \times 0.8}$$
= 97652.25Wp

The number of solar PV modules in series(N_{MS}) is given by the equation

$$N_{MS} = \frac{V_{BB}}{V_M} \quad (10)$$

Where V_M is the nominal voltage of the panel which is considered to be 12V. The number of solar PV modules in series(N_{MS}) for Design 1 is therefore estimated to as

$$N_{MS} = \frac{120}{12}$$
= 10

The equation to determine the number of parallel strings of solar PV modules (N_{sp}) is given as

$$N_{sp} = \frac{P_{Cmin}}{P_{max} \times N_{MS}} \quad (11)$$

The number of parallel strings of solar PV modules (N_{sp}) for Design 1 is therefore estimated as

$$N_{sp} = \frac{97652.25}{70 \times 10}$$
= 139.50
(Approximately 140 parallel strings required)

Having estimated the number of solar PV modules in a string (N_{MS}) and the number of parallel strings of PV modules (*Nsp)*, the equation to determine the total number of solar PV modules to be installed (N_{TM}) is given as;

$$N_{TM} = N_{MS} \times N_{SP} \quad (12)$$

The total number of solar PV modules to be installed (N_{TM}) for Design 1 is therefore estimated as;

N_{TM} = 10×140
= 1400 modules

The power rating of the PV array installed ($PV_{arrayins}$) is given by the equation

$$PV_{arrayins} = P_{max} \times N_{TM} \qquad (13)$$

The power rating of the PV array installed ($PV_{arrayins}$) for Design 1 is estimated as

$$PV_{arrayins} = 70 \times 1400$$
$$= \mathbf{98000\ Wp}$$

Design 2

From equation (9) and considering total daily energy demand (E_{tot}) of 46321.63Wh in Table 11, battery efficiency (E_{bat}) of 80% in Table 3, Daily Solar Irradiation of the location (*Hi*) of 4.2 kWh/m^2/day in Table 5 and the Derated output factor of Solar PV (E_{gen}) of 80% in Table 7. The minimum output power of solar PV panel (*Pcmin*) required for Design 2 is estimated as

$$P_{cmin} = \frac{46321.63}{4.2 \times 0.8 \times 0.8}$$
$$= 17232.75\text{Wp}$$

From equation (10), number of solar PV modules in series(N_{MS}) for Design 2 is estimated as

$$N_{MS} = \frac{120}{12}$$
$$= 10$$

From equation (11), the number of parallel strings of solar PV modules (*Nsp*) for Design 2 is estimated as

$$N_{sp} = \frac{17232.75}{70 \times 10}$$
$$= 24.62$$

(approximately 25 strings are required)

From equation (12), the total number of solar PV modules to be installed (N_{TM}) for Design 2 is estimated as;

$$N_{TM} = 10 \times 25$$
$$= 250 \text{ modules}$$

From equation (13), the power rating of the PV array installed ($PV_{arrayins}$) for Design 2 is estimated as;

$$PV_{arrayins} = 70 \times 250$$
$$= \mathbf{17500\ Wp}$$

Charge controller sizing

The charge controller nominal current (I_{cc}) must be greater than the maximum output current of the solar PV installed (I_{PVG}) and the maximum connected load current (I_{load}). The equation to determine the charge controller nominal current is therefore given as

$$I_{cc} \geq \text{Max} (I_{PVG} ; I_{load}) \qquad (14)$$

The maximum output current of the solar PV installed (I_{PVG}) is given as

$$I_{PVG} = N_{SP} \times I_{sc} \qquad (15)$$

Where (N_{SP}) is the total number of strings of solar PV array installed and (I_{sc}) is the short circuit current of each solar PV module.

The maximum connected load current (I_{load}) is given as

$$I_{load} = \frac{P_{in}}{V_{BB}} \tag{16}$$

Where (P_{in}) the input is power and (V_{BB}) is the system voltage

Design 1

From equation (15) and considering total number of strings of solar PV array installed (N_{SP}) of 140 and short circuit current of each solar PV module (I_{sc}) of 4.3 A, maximum output current of the solar PV installed (I_{PVG}) for Design 1 is estimated as

$$I_{PVG} = 140 \times 4.3$$
$$= 602 \text{ A}$$

From equation (16), maximum connected load current (I_{load}) is estimated as

$$I_{load} = \frac{109856.38}{120}$$
$$= 915.47 \text{ A}$$

Since the current of the charge controller to be considered should be the highest of (I_{PVG}) and (I_{load}), the charge controller should have minimum rating of **915.47A**

Design 2

From equation (15) and considering total number of strings of solar PV array installed (N_{SP}) of 25 and short circuit current of each solar PV module (I_{sc}) of 4.3 A, maximum output current of the solar PV installed (I_{PVG}) for Design 2 is estimated as

$$I_{PVG} = 25 \times 4.3$$
$$= 107.5 \text{ A}$$

From equation (16) maximum connected load current (I_{load}) is calculated as

$$I_{load} = \frac{19386.42}{120}$$
$$= 161.55 \text{ A}$$

Since the current of the charge controller to be considered should be the highest of (I_{PVG}) and (I_{load}), the charge controller should have minimum rating of **161.55 A**

Over- current protection
Array protection

The equation to determine the voltage rating of fuse F_s (V) for solar PV array protection is given as

$$F_s \text{ (V)} \geq 1.15 \times (V_{oc}) \times (N_{MS}) \tag{17}$$

Where (V_{oc}) is the open circuit voltage of each solar PV module and (N_{MS}) is the number of solar PV modules in series

The equation to determine current rating of fuse required for solar PV string protection is given as

$$1.5 \times I_{sc} \times N_{sp} \leq F_s \text{ (A)} \leq 2 \times I_{sc} \times N_{sp} \tag{18}$$

Where (I_{sc}) is the short circuit current of each solar PV module and (N_{sp}) is the number of parallel strings of solar PV modules.

Design 1

From equation (17), Fuse voltage F_s (V) of Design 1 is estimated as

$$F_s \text{ (V)} \geq 1.15 \times 22.1 \times 10$$
$$F_s \text{ (V)} \geq \mathbf{254.15}$$

From equation (18), Current rating of fuse F_s (A) required for Design 1 is estimated as
$1.5\times 4.3\text{A}\times 140 \leq F_s$ (A) $\leq 2\times 4.3\text{A}\times 140$
$\mathbf{903} \leq F_s$ (A) $\leq \mathbf{1204}$

Design 2

From equation (17), Fuse voltage F_s (V) of Design 2 is estimated as

F_s (V) $\geq 1.15\times 22.1\times 10$
F_s (V) $\geq$ **254.15**

From equation (18), Current rating of fuse F_s (A) required for Design 2 is estimated as
$\mathbf{161.25} \leq F_s$ (A) $\leq \mathbf{215}$

String protection
The equation to determine the voltage rating of fuse F_s (V) for string protection is given as
F_s (V) $\geq 1.15\times (V_{oc})\times (N_{MS})$ (19)

Where (V_{oc}) is the open circuit voltage of each solar PV module and (N_{MS}) is the number of solar PV modules in series

The equation to determine current rating of fuse F_s (A) required for solar PV string protection is given as
$1.5\times I_{sc} \leq F_s$ (A) $\leq 2\times I_{sc}$ (20)

Where (I_{sc}) is the short circuit current of each solar PV module.

Design 1
From equation (19), voltage rating of fuse F_s (V) for string protection of Design 1 estimated as

F_s (V) $\geq 1.15\times 22.1\times 10$
F_s (V) $\geq$ **254.15**
From equation (20), current rating of fuse F_s (A) for solar PV string protection is estimated as

$1.5\times 4.3 \leq F_s$ (A) $\leq 2\times 4.3$
$\mathbf{6.45} \leq F_s$ (A) $\leq \mathbf{8.6}$

Design 2
From equation (19), voltage rating of fuse F_s (V) of string protection for Design 2 is estimated as
F_s (V) $\geq 1.15\times 22.1\times 10$
F_s (V) $\geq$ **254.15**

From equation (20), current rating of fuse F_s (A) of string protection for Design 2 is estimated as

$1.5\times 4.3 \leq F_s$ (A) $\leq 2\times 4.3$
$\mathbf{6.45} \leq F_s$ (A) $\leq \mathbf{8.6}$

Battery bank and load side protection fuse specifications

The equation to determine the voltage rating of fuse F_s (V) for battery bank protection is given as

F_s (V) $\geq$ Battery bank voltage (21)

The equation to determine the current rating of fuse F_s (A) for battery bank protection is given as

$$F_s\,(A) \geq \text{Maximum load current} \qquad (22)$$

Design 1

Battery bank voltage has already been calculated to be 120V, hence from equation (19), voltage rating of fuse F_s (V) for battery bank protection of Design 1 is estimated as

F_s (V) $\geq$ **120 V**

Maximum load current has already been calculated to be 915.47, hence from equation (19), current rating of fuse F_s (A) for battery bank protection of Design 1 is estimated as

F_s (A) $\geq$ **915.47A**

Design 2

Battery bank voltage has already been calculated to be 120V, hence from equation (19), voltage rating of fuse F_s (V) for battery bank protection of Design 2 is estimated

Fuse voltage F_s (V) $\geq$ **120 V**

Maximum load current has already been calculated to be 915.47, hence from equation (19), current rating of fuse F_s (A) for battery bank protection of Design 2 is estimated

Fuse size F_s (A) $\geq$ **161.55**

Size of cable

The size of cable(A) to be used between the solar PV array and the inverter depends on the resistivity of the cable (ρ), the length of the cable (L) , the total current of the installed solar PV array installed (I_{nsp}), the expected percentage voltage drop ($\Delta V\%$) and the voltage rating of the solar PV array (U). This is given by the equation;

$$A > \frac{2 \times \rho \times L \times I_{nsp}}{\Delta V\% \times U} \qquad (24)$$

Design 1

Considering voltage drop ($\Delta V\%$) of 3%, copper conductor of resistivity (ρ) of 0.0183, cable length (L) of 15 m, current of 140 parallel strings (I_{nsp}) 602 A and voltage rating of solar PV array (U) of 179 V , the thermal size of cable required (A) for Design 1 is estimated as

$$A > \frac{2 \times 0.0183 \times 15 \times 140 \times 4.3}{3\% \times 10 \times 17.9}$$
$$> 61.55\text{mm}$$

The size of the cable should be greater than 61.55 mm. The available standard cable size to be considered is 70mm

Design 2

Considering voltage drop ($\Delta V\%$) of 3%, copper conductor of resistivity (ρ) of 0.0183, cable length (L) of 15 m, current of 25 parallel strings (I_{nsp}) of 107.5 A and voltage rating of solar PV array (U) of 179 V , the thermal size of cable required (A) for Design 2 is given as

$$A > \frac{2 \times 0.0183 \times 15 \times 25 \times 4.3}{3\% \times 10 \times 17.9}$$
$$> 11\text{mm}$$

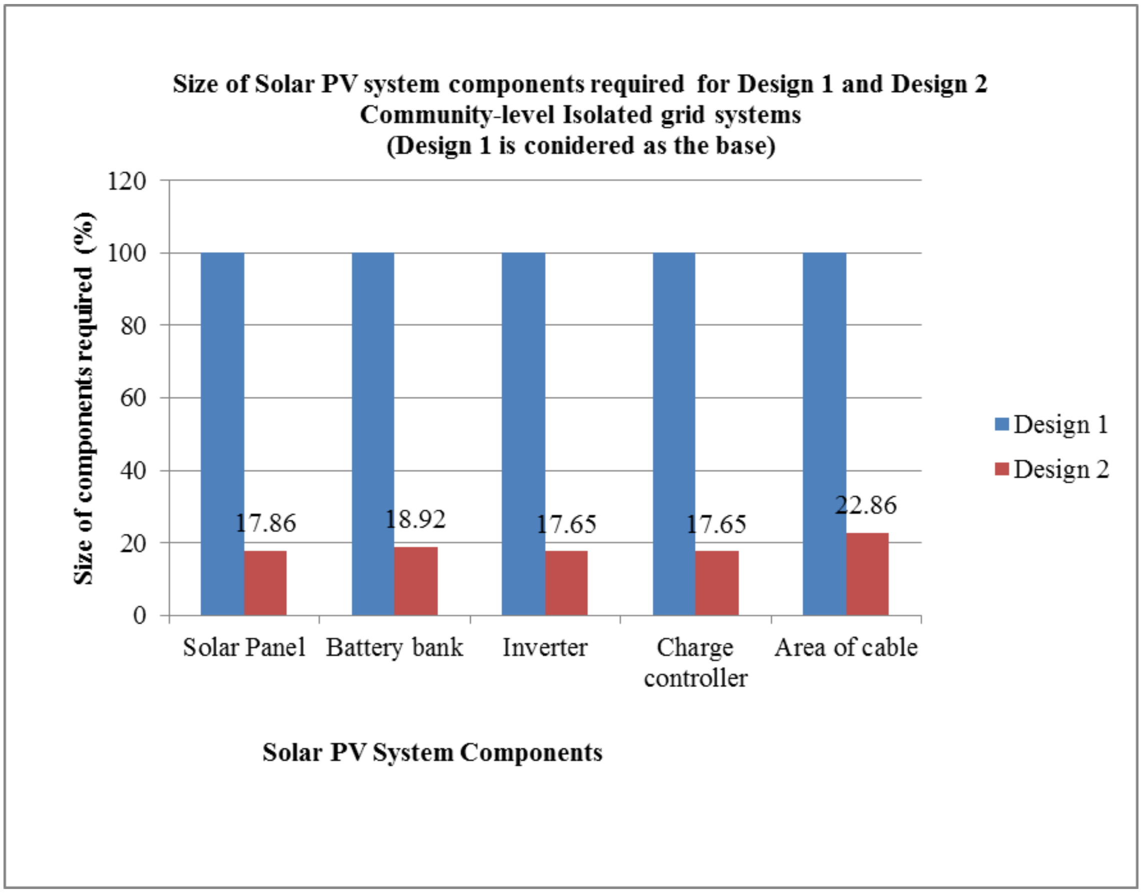
The size of the cable should be greater than 11 mm. The available standard cable size to be considered is 16mm

The estimated quantity and size of solar PV system components required for the community-level isolated grid for Design 1 and Design 2 has been summarized in Table 12

Table 12: Estimated sizes of solar PV system components required for Design 1 and Design 2 Community-level isolated grid Solar PV for Yabiw rural community.

Component	Design 1	Design 2
Battery Bank Capacity	219040 Ah	41440 Ah
Inverter rating:		
(Nominal power)	125454.02VA	22139.12 VA
(Surge power)	236542.88VA	41742.85VA
Solar panel size	98000 Wp	17500 Wp
Charge controller	915.47A	161.55
Fuse rating		
Array		
(Voltage rating)	F_s (V) $\geq$254.15	F_s(V) $\geq$ 254.15
(Current rating)	903 $\leq F_s$ (A) $\leq$ 1204	161.25 < F_s (A) < 215
String		
(Voltage rating)	F_s (V) $\geq$ 254.15	F_s (V) $\geq$ 254.15
(Current rating)	6.45 $\leq F_s$(A) $\leq$8.6	6.45 $\leq F_s$ (A) $\leq$ 8.62
Battery bank		
(Voltage rating)	F_s (V) $\geq$ 120 V	F_s (V) $\geq$ 120 V
(Current rating)	F_s (A) $\geq$ 915.47A	F_s (A) $\geq$ 161.55
Size of Cable	70mm	16mm

VI. RESULTS



The power demand of all individually connected loads (Design 1) of Yabiw community is estimated to be 109.856kW. However considering diversity factor of 1.7 and demand factor of 0.3 as considered in typical rural electrification project in the country (Design 2), the power demand to be considered was scaled down to 19.386kW, which is 17.6% of power demand of the individually connected load. The 82.4% reduction in power demand considered for design resulted in reduction of all the solar PV components required in the community-level isolated grid system. The size of inverter and the charge controller reduced in equal proportion of 82.4% as the reduction in the power demand due to diversity. However the size of Solar panel, battery bank and cable required were 17.86%, 18.92% and 22.86% as respectively. The slightly higher values of these solar PV system components as compared to reduction of power could be attributed to the specifications of the components which were considered in the design. In the case of the cable size, although the design resulted in 61.55 and 11mm for Design 1 and Design 2 respectively, higher cable sizes had to be considered because sizes estimated in the design are not standard cable sizes. Standard cable sizes of 70mm and 16 mm were therefore selected for Design 1 and Design 2 respectively, which resulted in the higher percentage component size of 22.86% as compared to 17.65% in power demand required in design. This supports the findings of Mehta V.K and Mehta R. (2005) that the higher the degree of diversity the lesser the generation cost of power supply systems. According to Shneider Electrical (2014) and Parmar J. (2011) as the number of consumers on power systems increases the degree of diversity increases, while the degree of diversity considered for an individual consumer is unity (1), which is the least in designing power systems. This implies that the generation cost of community-level isolated grid solar PV systems would be lower as compared to other off grid technologies such as stand-alone systems and community-level isolated grid system is a better option as reported by SWECO (2009) and Kirubi C. *et. al* (2009).

VII. CONCLUSION

The degree of diversity considered in community-level isolated grid solar PV systems can significantly reduce the sizes of solar PV components required to supply electricity to a rural community. In this paper diversity factor of 1.7 and demand factor of 0.3 as considered in typical rural electrification projects of Ghana were considered in the design of community-isolated grid solar PV system for Yabiw. This resulted in 82.35% reduction of the sizes of inverter and the charge controller required. It also resulted in 82.14%, 81.08% and 77.14% of solar panel, battery bank and cable sizes respectively.

As degree of diversity in power supply systems increases with increasing consumers, using community-level isolated grid systems would reduce cost of off-grid rural electrification project as compared to other technologies such as the stand-alone systems and must be considered where viable.

ACKNOWLEDGMENT

First of all we would like to show our appreciation to Dr. Albert K. Sunnu for his guidance and motivation throughout this research work. Secondly, we also extend our appreciation to Mr Albert Kenneth Quarm, the assemblyman of Yabiw rural community for giving us the opportunity to use the community for this research work. We also express our gratitude to Frank Kwofie and Esther Afonaa-Mensah for their relentless effort during the load assessment and survey of Yabiw rural community.

REFERENCES

[1] International Energy Agency (2010) The Electricity Access Database, World Energy Outlook. Retrieved from http://www.iea.org/weo/electricity.asp.

[2] World Bank. Global Monitoring Report 2013: Rural-Urban Dynamics and the Millennium Development Goals. Washington, DC: World Bank. DOI: 10.1596/978-0-8213-9806-7. License: Creative Commons Attribution CC BY 3.0

[3] SWECO (2009) Assessing technology options for rural electrification projects. Guidelines for project development. (Appropriate technology options for rural electrification in developing countries.) Report no: 1, Project no: 161830

[4] Dietrich K., Lopez-Pena A. and Linares P. (2011) A new framework for rural electrification programs. International Association for Energy Economics, third quarter (2011), p. 21-25.

[5] IEA (2013) World Energy Outlook . The Electricity Access Database. Retrieved from http:// www.worldenergyoutlook.org [Accessed 2/27/15]

[6] Energy commission of Ghana (2009), Renewable Energy Policy framework for climate mitigation in Ghana; Review of Existing Renewable Energy Resource Data, Energy Policies Strategies, Plans and projects .Retrieved from: http://www.ecowrex.org/.../2009_re-policy-framework-for-climate-change [Accessed 30/01/2015]

[7] Zomers, A.N. (2001) Rural Electrification: Utilities' Chafe or Challenge, Twente University Press, Enschede, Pays-Bas.

[8] Kirubi C, Jacobson A, Kammen D M, Mills A (2009). Community-based electric microgrids can contribute to rural development: evidence from Kenya, World Development 2009;37:1208–21.

[9] Ranaboldo M, Domenech B, Vilar D, Ferrer-Martí L, Pastor R, García-Villoria A. (2014) Renewable energy projects to electrify rural communities in Cape Verde. Applied Energy 2014;118: 280–91. http://dx.doi.org/10.1016/j.apenergy.2013.12.043

[10] ASEAN (2013) Guideline on Off-grid Rural Electrification Approaches, ASEAN Centre for Energy, Prepared by Quang Cu Tran (Full Advantage Co. Ltd) , Indonesia.

[11] Shneider Electrical (2014) Estimating the actual maximum kVA demand. Available fromhttp://www.electricalinstallation.org/enwiki/Estimation_of_actual_maximum_kVA_demand[Accessed 03/03/15]

[12] Parmar J. (2011) Demand –factor, Diversity factor, Utilization factor, load-factor www.electrical-engineering-portal.com [Accessed 03/11/14]

[13] Mehta V.K and Mehta R. (2005) Variable load on power stations (2005 edition). In: Principles of Power System. Chand & Company Ltd ISBN: 81-219-2496-0 pp. 41-68

[14] Ahiataku-Togobo W. (n.d) Challenges of Solar PV for remote electrification in Ghana. Renewable Energy Unit, Ministry of Energy-Accras Ghana. Retrieved from: http://www.zef.de/.../renewables/.../Ahiataku-Togobo_solar%20PV%20Ghana [Accessed 19/01/2015]

[15] Sustainable Energy Industry Association of the Pacific Islands (SEIAPI) Sustainable Energy/ Pacific Power Associations (2012). Off grid PV power systems design guidelines.

[16] Japan International Cooperation Agency (2006) Basic design study report on the project for rural electrification in the republic of Ghana,

[17] July 2006.

AUTHORS

First Author- Stephen Afonaa-Mensah, MSc Renewable Energy Technologies, BSc Electrical/Electronics Engineering. e-mail: safonaamensah@yahoo.com
Second Author- David Asante, MSc Renewable Energy Technologies, BSc Mechanical Engineering, Process Trainer/Assessor, NVQ, e-mail: amacdavidz@yahoo.com

Correspondence Author- Stephen Afonaa-Mensah , e-mail: safonaamensah@yahoo.com, Contact: +233 206 785 681