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RESEARCH ARTICLE

The use of solar PV systems for off-grid rural electrification projects in Ghana; Consideration of Community level isolated grid systems

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Abstract:

Solar Home Systems has been the major off-grid technology employed for rural electrification in Ghana. The Solar Home technology however has its own limitations ofbeing very sensitive to design and sizing for proper functioning. Usually, the installed peak generating capacity has to be 150-400% higher than the peak load demand. Coupled with the poor load factor of rural communities,Solar Home Systems are underutilized as compared to the installed capacity. The use of community level Isolated-grid systems would help to improve the utilization of the installed capacity of off-grid solar PV systems. This is due to the unlikely use of all connected electrical loadssimultaneously on a power supply system. In this paper, demand factor and diversity factor of 0.3 and 1.7 respectively were considered in designing and sizing the Community-level Isolated grid solar PV system for 100 households; This resulted in 82.5%, 90% and 82.4% reduction of solar panels, battery bank and inverter sizesrespectivelyrequired to provide electricity to the same community as compared to the use of Solar Home Systems. The significant reduction in the size of solar PV components would consequently reduce cost of off-grid rural electrification project that incorporate the use of Community-level Isolated grid systems where viable.

Key Words: Solar Home Systems, Isolated grid systems, rural electrification,off-grid solar PV systems

Aim/Objectives

The main aim of this paper is to conduct a research into the use of solar PV systems as an off-grid technology for rural electrification projects in Ghana with consideration for Community-level isolated grid systems. The specific objectives are to;

i. Identify and analyze the type of solar PV technology currently used for off-grid rural electrification projects in Ghana
ii. Determine load and other design factors considered for typical rural electrification projects in Ghana
iii. Analyze the size of major system components that would be required in Community-level isolated solar PV system as compared to off-gridsolar PV technology used by Ghana in rural electrification projects.

Introduction

Energy is key for development and no country has managed poverty alleviation without increasing access to energy [1]. The International Energy Agencyhighlights electricity as the most critical energy carrier for development [2]. However access to electricity within the Sub-Saharan Africa is very low. The average rate of electrification is 31.8% with only 18.3% rate of rural electrification as compared to urban electrification rate of 55.2% [3].

The adverse rate of rural electrification as compared to urban electrification has therefore created the urgent need to foster electricity access in rural areas of developing countries[4]. However this task represents a huge challenge. Rural electrification is usually not considered to be an attractive investment opportunity. Risk is perceived to be high and returns unsatisfactory [5]. This is because rural areas in developing countries are usually very poor and theirinhabitants' per capita energy consumption is very low. Private energy companies considering the low levels of benefits of electrifying these areas are therefore discouraged from undertaking rural electrification projects [4].The peculiar nature of rural communities has caused countries to resort to the use of off-grid technologies as a means of providing electricity to these communities.The technology predominantly used for off-grid electrification is solar PV in the form of Solar Home Systems[6].

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 [3][7]. However, the major off-grid technology that has been employed for rural electrification has been the Solar Home Systems. The Solar Home technology however has its own limitations. They are very sensitive to design and sizing for proper functioning. Usually, the installed peak generating capacity has to be considerably higher than the peak load demand, about 150 – 400 %.The sizing of the installed generating capacity and energy storage in relation to the load is done within the limits of technical and economic constraints. The sizing of the Solar Home Systemtherefore often entails some compromises unless funds are unlimited[5]. Coupled with the low energy consumption and poor load factor of rural communitiesthe Solar Home Systems are underutilized as compared to the installed capacity[4][8].

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 andthat project preparation is based on adequate information. In many rural electrification projects,the ideal would be if electrification was community based [5]

In a rural community where there are over 100 households within 500 square meter radius and energy demand of about 5kW, community-level isolated grid system could be considered as a sustainable option for rural electrification [5][9]. Where viable, Community-level Isolated grid system is better option as compared to Solar Home Systems.The utilization of power generating equipment, measured as the average capacity installed, is normally higher in in isolated grid systems as compared to Solar Home Systems[5]. 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 it is unlikely all electrical loads on a power supply will be used simultaneously. Although some power supply designers prefer the use of unity (1) diversity factor, local conditions can justify the use of higher diversity factor in design of power supplysystems[10].This will help maximize the utilization of the installed capacity of off-grid solar PV systems used for rural electrification projects.

With cost identified as a major challenge against the use of solar as 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 Home Systems for rural electrification projects[7][11], considering Community-level isolated-grid solar PV system where viablecould significantly reduce the cost of off-grid solar PV rural electrification projects.

Methodology

In designing and sizing the community level-Isolated grid solar PV system100 household units within 500m radiushave been taken into consideration. System load, demand factor and diversity factorsconsidered are based on design factors considered in typical rural electrification projects of Electricity Company of Ghana which is a major utility in the country.Although some designers of power supplies prefer the use of unity (1) diversity factor, the use of a higher diversity of 1.7 in this paper is due to local conditions and the peculiar nature of rural load. Comparative analysis of community-level isolated grid systems and Solar Home Systems has been limited to the size of solar panel, battery bank and inverter size which directlydepend on load demand and form major cost components of off-grid solar PV rural electrification projects.

Load consideration

The loads considered per unit household in typical rural electrification project in Ghana include; lighting, iron and radio cassette recorder. The electrical appliance, number of unit and their respective power rating per unit household for rural electrification projects have been provided in Table 2.8.

Table 1: Load considered per unit house for rural electrification projectsin Ghana

Appliance	Unit power (W)	Quantity	Total power (W)
Lighting	40	2	80
Iron	750	1	750
Radio Cassette Recorder	20	1	20
Total load per household			850

(Source: JICA, 2006)

Specification of system components

Storage Battery specifications
OpzSSolar 280 battery has been considered in design, its specifications is shown in Table 2.

Table 2: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 specification of KYOCERA type 70-1P solar module has been considered in design, its specifications is shown has in Table 3
Table 3: 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 4 below

Table 4: Minimum daily solar irradiation

Location	Takoradi
Minimum daily solar irradiation (*Hi*)	4.2 kWh/m^2/day
Peak Sun Hours (*PSH*)	4.2 h/day

Source: (www.retscreen.org)

Power factor of electrical load considered for design

The power factor considered in design have been shown in Table 5

Table 5: Power factor of electrical load

Electrical appliance	Duration Used (h)	Power Factor
Lighting	5	0.8
Iron	0.13	1.0
Radio cassette recorder	5	0.7

(Source: DSTC Solar Training Center)

Assumed Design considerations

Other assumed design considerations have been shown in tables 6a and 6b below

Table 6a: Other design considerations

Parameter	Factor considered
Inverter efficiency (*Inv%*)	94%
Derated output factor of solar PV (*Egen*)	80%
Depth of Discharge (*DOD*) of battery	50%
Days of Autonomy (*Taut*)	2 days
Allowable percentage voltage drop	3%

Table 6b: Other design considerations

Electrical appliance	Duration Used (h)
Lighting	5

Iron	0.13
Radio cassette recorder	5

Design 1: Design calculations for Solar Home Systems

Estimation of system voltage

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

$$P_{in} = \frac{P_o}{Inv\ \%} \quad (1)$$

Where (P_o) is the output power of the connected loads and (*Inv%*) is the efficiency of the inverter.
Using inverter efficiency of 94%, the input power of the various electrical appliances is given in Table 7.

Table 7: Input power estimated per unit household

Electrical Appliance	Total load(W)	Input Power(W)
Lighting	80	85.11
Iron	750	797.87
Radio Cassette	20	21.28
Total Input Power		904.23

For the estimated Input power of 904.23 W, system voltage (V_{BB}) of 24V is considered for design of solar PV system

Inverter sizing
The size of the inverter required rated in volt amperes (VA) depends on the total power (*PT*) and the power factor (*p.f*) of the connected load. The equation to determine the apparent power (*PVA*) rating of the inverter is given as

$$P_{VA} = \frac{p_T}{p.f.} \quad (2)$$

From equation 2, the apparent power rating of the various electrical appliances have been computed in Table 8

Table 8: Apparent power estimated per unit household

Electrical appliance	Total power (W)	Power factor	Apparent power (VA)
Lighting	80	0.8	100
Iron	750	1.0	750
Radio Cassette Recorder	20	0.7	28.6
Total VA rating of system			878.6

The apparent power estimated above should be increased by 10% to make provision for any excesses and manufactures tolerances in the inverter. This is computed as the nominal power (P_n), which represent the volt amperes (VA) rating of inverter required for the solar PV system and is given as

$$P_n = 1.1 \times P_{VA} \quad (3)$$

$$P_n = 878.6 \times 1.1 = 966.5 \text{ VA}$$

Estimation of daily energy demand

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

$Wh/j = Pin \times t$ (4)

Where (*Pin*) is the input power of electrical appliances and (*t*) is the duration of use of the appliance in a day. From equation 4, the daily energy demand per unit household is given in Table 9.

Table 9: Daily energy demand estimated per unit household

Electrical appliance	Input power (W)	Duration of use/day (h)	Daily energy demand (Wh)
Lighting	85.12	5	425.60
Iron	797.87	0.13	103.72
Radio Cassette Recorder	21.28	5	106.40
Total Daily Energy Demand			635.72
Adding 10% security coefficient (*Etot*)			699.29 Wh

Battery sizing

The size of capacity bank required depends on total daily energy demand (*Etot*), Days of autonomy *(Taut),* Battery efficiency *(Beff),* System voltage *(VBB)* and Depth of Discharge *(DOD)* of the battery. The equation to determine the capacity of battery bank (C_{BB}) is given as

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

$$C_{BB} = \frac{699.29 \times 2}{24 \times 0.8 \times 0.5}$$

$$= 145.69$$

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

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

$$Nbs = \frac{24}{6}$$

$$= 4$$

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

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

whereC_{BB} is the capacity of battery bank and C_{acc} is the individual battery capacity

$$Nbp = \frac{145.69}{296}$$

$$= 0.49$$

Approximately 1 string is required in this instance

Having estimated the number of batteries in string a (*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

$$NB = Nbs \times Nbp \quad (8)$$

$$NB = 1 \times 4$$

TheCapacity of battery bank installed ($C_{BBinstall}$) is therefore calculated as

$$CBBinstall = 296 \times 4$$
$$= 1184 \text{ Ah}$$

Solar panel sizing

The minimum output power of solar PV panel (*Pcmin*) required in solar PV system depends on the total daily energy demand (*Etot*), 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

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

$$Pcmin = \frac{699.29}{4.2 \times 0.8 \times 0.8}$$
$$= 260.15 \text{ Wp}$$

The number of solar PV modules in series (*NMS*) is given by the equation

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

Where V_M is the nominal voltage of the solar panel

$$NMS = \frac{24}{12}$$
$$= 2$$

The equation to determine the number of parallel strings of solar PV modules (*Nsp*) is given as

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

$$Nsp = \frac{260.15}{70 \times 2}$$
$$= 1.89 \text{ (Approximately 2 strings are required)}$$

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 (*NTM*) is given as;

$$NTM = N_{MS} \times N_{SP} \quad (12)$$
$$NTM = 2 \times 2$$
$$= 4 \text{ modules}$$

The power rating of the PV array (*PV arrayins*) installed is given by the equation

$$PV\ arrayins = Pmax \times NTM \quad (13)$$
$$PV\ arrayins = 70 \times 4$$
$$= 280 \text{ Wp}$$

Table 10 shows the size of solar PV components and the quantity required for installing 100 Solar Home Systems to serve 100 household units.

Table 10: Total solar PV system components required for 100 Solar Home Systems

Component	Quantity	Rating/unit	Total rating
Solar PV	100	280 Wp	28000 Wp
Battery Capacity	100	1184 Ah	118400 Ah
Inverter Size	100	966.5	96650 VA
System voltage		24 V	

Design 2: Design calculations for Community-levelIsolatedgrid solar PV grid system

Demand factor and diversity factor consideration for community level isolated grid system
Table 11 shows the total power estimated for a community of 100 households after considering demand factor of 0.3 and diversity factor of 1.7

Table 11: Total Power estimated for the Community-level isolated grid system, considering demand factor of 0.3 and diversity factor of 1.7 respectively

Electrical appliance	Total power per household(W)	Applying Diversity factor of (0.3)/Demand factor of (1.7)	Total Households	Total Power (W)
Lighting	80	14.12	100	1412
Iron	750	132.35	100	13235.3
Radio Cassette Recorder	20	3.53	100	353

Estimating System Voltage

From eq 1, Input power (*Pin*) of connected load after considering inverter efficiency (*Inv%*) of 94% is shown in Table 12

Table 12: Input Power estimated for Community-level isolated grid system 1

Electrical appliance	Total power rating (W)	Input Power required (W)
Lighting	1412	1502.13
Iron	13235.3	14080.11
Radio Cassette	353	375.53
Total Input Power		15957.77

For input power of the connected load above 10 kW, a system voltage of 120 V is considered in Solar PV system design

Inverter sizing

From eq 2 Apparent Power (P_{VA}) has been estimated in Table 13.

Table 13: Apparent power estimated for Community-level Isolated grid system

Electrical appliance	Total power (W)	Power factor	Apparent power (VA)
Lighting	1412	0.8	1765
Iron	13235.3	1.0	13235.3
Radio Cassette Recorder	353	0.7	504.3
Total VA rating of system			15504.6

Having estimated the total apparent power of connected load to be 18750.38, the nominal power (*Pn*) from eq 3is calculated as

$$Pn = 15504.6 \times 1.1$$
$$= 17055.1$$

Hence nominal power rating of inverter considered is given as 17055.1 VA

Estimation of Daily Energy Demand

From eq 4, Daily energy demand (*Wh/j*) estimated for the Community-level isolated grid system is given in Table 14

Table 14: Daily energy estimated for Community-level isolated grid system

Electrical appliance	Input power (W)	Time/day (h)	Daily energy demand (Wh)
Lighting	1502.13	5	7510.65
Iron	14080.11	0.13	1830.41
Radio Cassette Recorder	375.53	5	1877.65
Total Energy			11218.71
Adding 10% security coefficient (Etot)			12340.58 Wh

Battery Sizing

From eq 5, capacity of battery bank (C_{BB}) is calculated as

$$C_{BB} = \frac{12340.58 \times 2}{120 \times 0.8 \times 0.5}$$
$$= 514.19$$

Fromeq 6,number of batteries in string (*Nbs*) is calculated as

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

From eq 7, Number of parallel strings of batteries (*Nbp*) is calculated as

$$Nbp = \frac{514.19}{296}$$
$$= 1.74$$

Approximately 2 strings are required in this instance

From eq 8,Number of batteries installed (N_B) is calculated as

$$= 20 \times 2$$
$$= 40$$

Capacity of battery bank installed ($C_{BBinstall}$) is calculated as

$$C_{BBinstall} = 296 \times 40$$
$$= 11840 \text{ Ah}$$

Solar panel Sizing

From eq 9, the minimum output power of solar PV panel (*Pcmin*) required is calculated as

$$P_{cmin} = \frac{12340.58}{4.2 \times 0.8 \times 0.8}$$
$$= 4591\text{Wp}$$

Fromeq 10, the number of solar PV modules in series (*NMS*) is calculated as

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

From eq 11, the number of parallel strings of solar PV modules (*Nsp*)calculated as

$$N_{sp} = \frac{4591}{70 \times 10}$$
$$= 6.56 \text{ (approximately 7strings are required)}$$

From eq 12, the total number of solar PV modules to be installed (*NTM*) is calculated as

$$N_{TM} = 10 \times 7$$
$$= 70 \text{ modules}$$

From eq 13, the power rating of the PV array (*PV arrayins*) installed is calculated as

$$PV_{arrayins} = 70 \times 70$$
$$= 4900 \text{ Wp}$$

Table 15 shows the size of solar PV components and the quantity required for installing 100 Solar Home Systems to serve 100 household units.

Table 15: Total solar PV system components required for Community-level isolated grid system

Component	Rating
Solar PV	4900 Wp
Battery Capacity	11840 Ah
Inverter Size	17055.06 VA
System voltage	120 V

Discussion and analysis of results

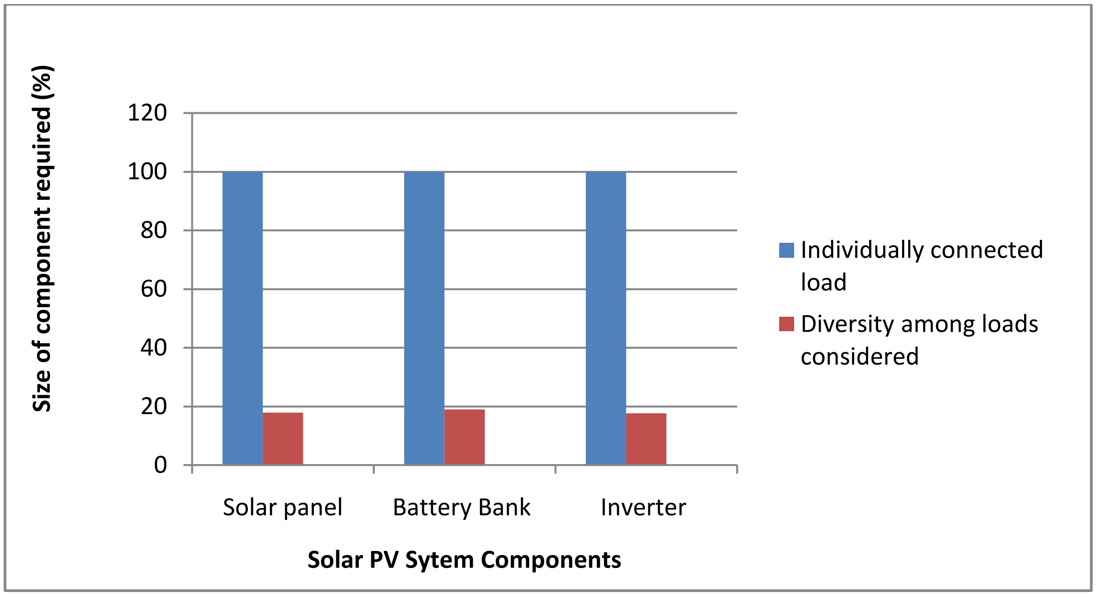

Figure 1: Size of solar PV system component (%) required for Solar Home System and Community-level Isolated grid system (Solar Home Systems considered as the base).

The size of solar PV components required for Community-level isolated grid system and Solar HomeSystems is shown in Figure 1 with Solar Home Systems considered as the base. As compared to 4900 Wp output power rating of Solar PV required for supplying electricity to a community of 100 households in the community-level isolated grid system , 28000Wp would be required in the case of Solar Home Systems for serving the same number of households. This represents an increase of 571% of output power rating of Solar PV modules required for Community-level isolated grid systems. In addition, Inverter and battery bank capacity required in the case of community-level isolated grid system are 17055.06 VA and 11840 Ah while 96650 VA and 118400 Ah are required in Solar Home Systems. This also represents 567% and 1000% increase in inverter and battery capacity ratings required in the case of Solar Home Systems as compared to Community-level isolated grid systems respectively. This resulted in 82.5%, 90% and 82.4% reduction of solar panels, battery bank and inverter size respectively required to provide electricity to the same community as compared to the use of Solar Home Systems. SWECO (2009) reported 150 - 400% oversizing of generating capacity above peak load demand in Solar Home Systems. The higher values obtained in this research can be attributed to the diversity factor of 1.7 considered instead of 1.0 as used by other power supply designers. However, the use of higher diversity factor of 1.7 instead of 1.0 is accepted in designing power generating systems depending on local conditions in the community as considered in the case of rural electrification projects of Ghana. Also considering the minimum number of 100 households within 500m radius for sustainable isolated grid systems proposed by SWECO (2009) in designing and sizing the Community-level isolated grid system, the total solar PV system power rating required is estimated to be 4.9kWp. The power rating of the solar PV system required is within the capacity range of 5kW recommended by ASEAN (2013) for operating solar PV mini-grid systems.

Conclusion and recommendation

The non-simultaneous use of all electrical loads on community level isolated grid systems can significantly reduce the quantity of solar PV component required to provide electricity to rural communities. Considering a diversity factor of 1.7 and demand factor of 0.3,there is significant reduction of 82.5%, 90% and 82.4% reduction of solar panels, battery bank and inverter size respectively required to provide electricity to the same community as compared to the use of Solar Home Systems. The significant reduction in the size of solar PV components would reduce cost of off-grid rural electrification project that incorporate the use of community level isolated grid systems and must be considered where viable.

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