Australian Journal of Basic and Applied Sciences

2021 February; 15(2): pages 1-12
https://doi.org/10.22587/ajbas.2021.15.2.1
ORIGINAL PAPER AENSI PUBLICATIONS

Enhancing Energy Accessibility And Climate Change Adaptation Via Community Solar Energy With Smart Energy Metering

Thomas Ojonugwa Daniel[1*], Goodness Ore Edaogbogun[2], Ishaku Borok Maren[3] Abdulmutolib Olajide Olaoye [4] and Bitrus Pam[5]

[1]Department of Physics/Geology/Geophysics, Alex Ekwueme-Federal University Ndufu-Alike Ikwo, Ebonyi state, Nigeria
[2] Physics/Electronics unit, Federal Polytechnic, Ede, Osun State, Nigeria
[3]Department of Mechanical Engineering, University of Jos, Jos, Plateau State
[4]Science Technology Department, Physics with Electronics Unit, Federal Polytechnic Offa, Kwara State
[5]Bititech Renewable solutions, Bukuru-Jos, Plateau State

Correspondence Author:T.O. Daniel, [1]Department of Physics/Geology/Geophysics, Alex Ekwueme-Federal University Ndufu-Alike Ikwo, Ebonyi state, Nigeria
E-mail: danielojonugwathomas@gmail.com & daniel.thomas@funai.edu.ng

Received date: 12December 2020, Accepted date: 12 February 2021

Cite as:T.O. Daniel., G.O. Edaogbogun., I.B.Maren., A.O. Olaoye and B.Pam., 2021. Enhancing Energy Accessibility And Climate Change Adaptation Via Community Solar Energy With Smart Energy Metering. Australian Journal of Basic and Applied Sciences, 15(2): 1-12. DOI: 10.22587/ajbas.2021.15.2.1.

ABSTRACT

BACKGROUND: Instability and unavailability of electricity supply in most developing countries of Africa has necessitate the use of fossil fuel power generators which is not only associated with environmental pollution and global warming but its reserve is also finite and non-renewable. Solar energy technology has been characterized as eco-friendly and abundantly available. However, many energy end users are not able to implement individual's solar energy installations for financial or technical reasons.
OBJECTIVE: The study present a model for climate change mitigation/Adaptation by enhancing energy accessibility via people group energy installation called solar garden where a group of persons come together according to their energy need to set up a solar energy grid or a an individual set up the solar energy grid with a system of load control for subscribers via smart metering and payment adherence control using Global System for mobile communication smart application control and is based on method of empirical research supplemented by theoretical analysis via the use of computational models and formulas.
RESULTS: A choice of five residence with daily total energy consumption of 35kW was made for the model design which can be extended or reduced depending on energy need. The solar garden with smart meter control gives energy access at reduce cost of 0.0831USD/kWh, the total unit of consumption, unit balance and other power/energy status per time.
CONCLUSION: The model empirical design of a community solar of five residence gave energy accessibility and availability to the households with real time energy services for the households thereby enhancing climate change adaption by reduction of greenhouse gas emission..

Keywords: Solar garden/energy, charge controller, inverter, battery, Smart meter, Photovoltaic array, Climate change

INTRODUCTION

The increase in energy consumption due to increase in industrialization, human population and urbanization has proven to be a cause of the gradual energy crisis witnesses today. The extensive use of fossil fuel is not only associated with environmental pollution and global warming but its reserve is also finite and non-renewable (Sagar, 2005; Fashina, 2019). The imbalance between energy demand and supply and power failure in electrical energy has necessitated the proliferation of generators (especially “I better pass my neighbor generators” as used and called in Nigeria for instance) which are depended on fossil fuel, gasoline and diesel for operation especially in some countries of Africa. This alarming mass dependence on it, exposes communities/people groups to harmful emission of greenhouse gases and air pollution. Aside the environmental factors associated with the fossil fuel, the depletion of the fuel reserve is also of concern. These problems lead scientists to search for alternative energy sources as a way of climate change mitigation/adaptation which are clean and renewable (Saleh *et al.*, 2015). Among the existing clean and renewable energy sources, solar energy is one of the most promising as the other sources are limited in their applications due to geographical conditioning among other factors. Solar energy technology has been characterized as eco-friendly, abundantly available with no geographical restrictions and is based on the photovoltaic phenomenon.

Photovoltaic is the conversion of light into electricity using semiconducting materials that exhibits the photovoltaic effect. It is initiated by the photoelectric effect followed by an electrochemical process where crystallised atoms ionised in a series generate an electrical current (Shaahid*et al.*, 2008). Photovoltaic (PV) power system also called Solar PV system is a power system or energy system designed to supply usable solar power by means of photovoltaic. The photoelectric effect is a process of generating voltage/current in photovoltaic solar system. The PV system consists of an arrangement of solar arrays which encompasses the ensemble of solar panel to absorb and convert sunlight into electricity, a solar inverter to change the electric current from direct current (DC) to alternating current (AC), installations cables, batteries for storage of surplus energy for use at night and the solar charge controller also called an integrated battery solution for providing regulated DC output as well as monitoring of battery voltage among other components of the systems (Guda and Aliyu, 2015). Each of the solar array comprises of a number of solar cells which are the fundamental power conversion units and are often connected in series or parallel to form modules while the modules are connected either in series or parallel for solar array formation to give maximum power output since one module seldom produces enough power that can meet the need of a residential building (Pal, 2015).

PV system ranges from roof top mounted, ground mounted, wall mounted or building integrated system with capacities from a few to several thousand watts and to a large power stations megawatts generation. PV systems has no moving parts as such do not produce noise, it is highly module in nature, reliable, pollution free, requires little or no maintenance cost and can be easily installed at a choice location. Though the output from PV generator is zero at night, the incorporation of battery ensures that the PV generator charges the battery during the day while the battery serves as the power source at night so as to mitigate the issue of PV intermittency hence enhancing reliability (Hasan *et al*., 2016).

However, the accessibility of solar energy to individual homes as an alternative to the inadequacy or unavailability of power supply to most Nigerians homes is limited as many electricity end users are not able to implement individual’s solar energy installations for financial or technical reasons. Although there are reports on PV system design, these reports are limited to standalone PV system for a single residential building (Abu-Jasser, 2010; Guda and Aliyu, 2015; Hasan *et al.*, 2016), local government offices (Johnson and Ogunseye, 2017), Laboratories (Saleh *et al.*, 2015; Mahmood, 2019) and Hybrid off-grid solar system (Chukwuemeka and Felix, 2018). Solar garden/community solar for energy accessibility is rarely report.

A community solar energy also called solar garden or shared renewables is a community or persons group shared solar array. It is a mini solar plant whose electricity is shared by more than one property/building. Solar garden are generally ground mounted solar photovoltaic energy arrays which are smaller in installation size/power output than the utility scale solar PV systems but significantly larger than most individual rooftop installations (Markvart*et al.*, 2006). The primary purpose of community solar is to allow members of a community the opportunity to share the benefits of solar power even if they cannot or prefer not to install solar panels on their property. Homes and businesses, even if shaded by trees, receive a bill credit as if the panels were on their own roof using “virtual net metering” or smart energy meter which cost less than they would ordinarily pay to their utility. The solar garden allows people to go solar even if they do not own property or roof top thereby making it an attractive option for renters or those who lived in shared building. The community solar has two mode of participation namely the ownership and the subscription mode/model of participation (Joshi and Yenneti, 2020).

The ownership model allows participants to own some of the panels or a share in the solar energy installation project such that they benefit from all the power produced by their share of the solar panels or in the installed solar energy system. In such a model, an individual can purchase enough share to meet the individual’s annual or monthly energy requirement or electricity use such that a matching proportion of the installed system actual output is credited through the individual’s electricity bill or through some other form of arrangement with the solar energy system or project administrator.

The subscription model allows participants to become subscribers and pay a lower price for the electricity sourced from the community solar farm without owing the panels or paying for the installation. A third party or a utility company could develop and own the project and then extend an opportunity to the public to participate. Such third party could be the “landlord” who will be in possession and control of the solar Garden. A financially privileged individual could set it up and open it up for subscription to selected interested households according to agreed energy requirement which will be monitored using smart meter so as to enhance real time energy consumption and costing (Chan *et al*., 2017). A block diagram of a typical solar garden array concept is shown in figure 1, figure 2 shows an offsite shared solar while figure 3 shows how a solar garden works.

The study proposes a model for enhancing energy accessibility, energy investment, climate change adaptation and real time energy costing using a community solar/solar garden concept with smart energy metering.

Figure 1: A solar garden array (https://www.sunshinecoast.evolutionsolar.com.au)

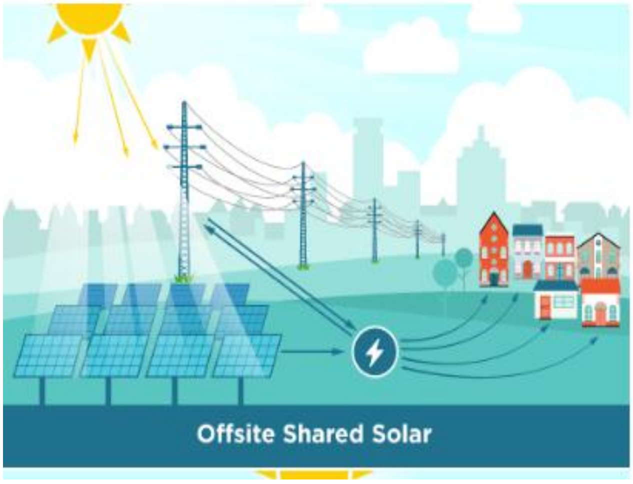

Figure 2: Offsite Solar garden concept

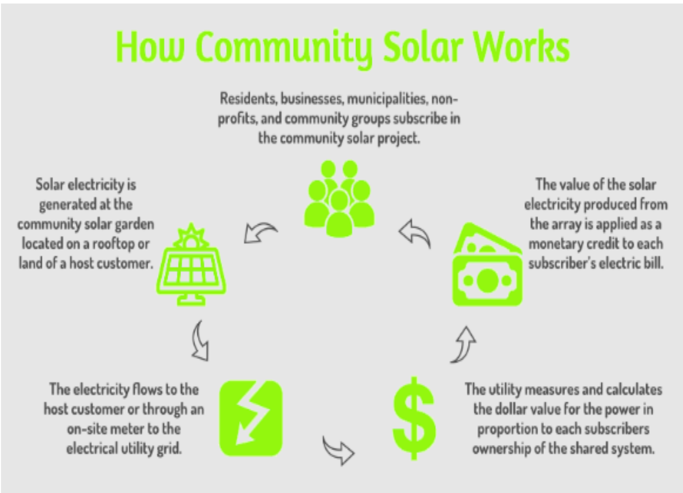

Figure 3: How solar garden works

Solar garden design Considerations/sizing

A basic block diagram of the solar energy generation is shown in figure 4 consisting of solar PV array, Charge controller, inverter, Battery and AC/DC loads.

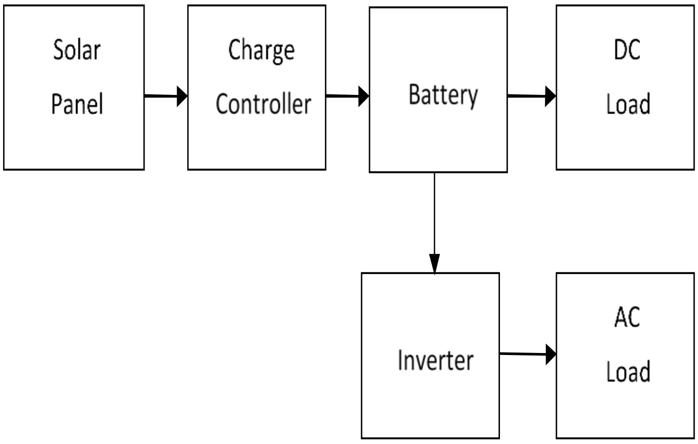

Figure 4: Basic block diagram for a solar system

The PV system design is essential for determining the voltage, current and power capacity of the system components for participating residential load profile balance/requirement. Choice of typical energy consumption/load usage in homes were made using the typical Nigeria/African home as case study. The load/power requirement were averaged based on available products manufacturers, company make and specifications for each of the items. Nine items were selected which were deemed basic daily house hold energy consuming loads/appliances. These consist of electric Fan, a Television set, Digital Video Disk (DVD) player, Decoder/Satellite, Laptop, Lighting bulb, cell Phone, Refrigerator and electric pressing Iron. The loads are the power consuming units of the PV system which could be resistive or inductive loads. A choice of two electric fan was made given that most of Nigeria couples/families live in at least a two rooms apartment (typically called room and parlour apartment) while a choice of 6 (15W each) lighting energy saving bulb was made to cover parlour/siting room, a bed room, the kitchen and the bathroom and two security lights outside. A choice of one Television, one DVD player, one electric Laundry Iron, one decoder, one refrigerator for preservation/cooling, four cell phones, two Laptop and miscellaneous load of 108 watts was made. The miscellaneous load was allowed due to the variation in energy consumption with days and seasons. Demand for cooling and refrigerating increases during dry seasons. The miscellaneous also helps to give a balance to the total actual consumption in the long run. Each of the block items are discussed below taking into consideration energy demand, materials required/availability, cost consideration and efficiency factors. A five house hold model was selected which can be extended to other numbers. The load profile could also be reduce depending on energy need so as to reduce overall cost of installation.

Consumer energy demand (CED)/Residential load profile

The consumer energy demand (CED) which is the sum total of the energy demand by the chosen loads was calculated to determine the choice of other solar system design parameters taking into cognisance the duration of usage of loads given the power requirement of the load as shown in table 1.The consumer energy demand for a given load which was used to obtain table 1 is expressed by equation 1 (Guda and Aliyu, 2015):

$$CED = Q \times P \times T \quad (1)$$

Where Q= Quantity of the load, T= Duration of usage of the load per day in hour (H) and P= Power rating of the load.

Table 1: Consumer energy demand

S/N	Load	Quantity Q	Power rating per unit P (Watt)	Total power rating (W)	Usage/Duration T (H) per day	CED (WH)
1	Television (LCD/LED)	1	60	60	6	360
2	DVD player	1	110	110	4	440
3	Decoder	1	67	67	6	402
4	Laptop charging	2	75	150	4	600
5	Cell Phone	4	2.5	10	5	50
6	Lighting bulb(Compact fluorescent lamp)	6	15	90	12	1080
7	Electric Fan	2	90	180	12	2160
8	Electric pressing Iron	1	1200	1200	0.5	600
9	Refrigerator	1	150	150	8	1200
10	Miscellaneous	N.A	N.A	N.A	NA	108
	Total consumer energy demand (CED) =7000					

For the five house hold/residential model selected;
Total CED= 5 × 7000= 35,000 Watts-Hour.

The Solar panel

The solar panel exist as a combination of p or n type silicon semiconductor separated by a p-n junction and comprises of solar cells connected in series according to the total required output voltage or in parallel to increase current (Guda and Aliyu, 2015). The generation of voltage and current is dependent on the area of the cell. For a solar garden comprising of five households as a model the panel requirement will be based on the total consumer energy demand (CED) as calculated in table 1. Although different type of solar panels exist with varying efficiency, for a design involving interconnections of solar panels; panels of the same make or type is of optimum importance for required efficiency. For the model design of five house hold community solar, a choice of monocrystalline solar panel with a rated efficiency of 80 % was made. Monocrystalline solar panel was chosen due to its higher efficiency of conversion of solar energy into electric energy than its other counterparts and its sleeker aesthetics.

The solar panel was selected taking into cognisance factors which affect the efficiency of solar panel such as resistance, reflection, recombination and non-usable energy since only 20% of the about 1000W, 1 $m^2$of solar energy radiated by the sun can be harnessed using solar panel which is often mounted on a roof top or a chosen site with provision for free movement in between the arrays for inspection.

A solar module: AE EXTREME 320P6-72 was selected for the design/ PV array sizing with specifications of: Rated voltage of one module $(V_{rm}) = V_{mp} = 36.75V$, rated current of one module$(I_{rm}) = I_{mp} = 8.71A$, Short circuit current $(I_{sc}) = 9.28\ A$,

Power rating of module $= 320W$; dc voltage of the system/system voltage$V_{dc} = 96V$. Other parameters for the PV array sizing are: Average sun hours per day $T_{sh} = 5\ Hours$
Average daily energy demand $(E_d) = 35{,}000\ watt - hours$
The required daily average energy demand is obtained by dividing the daily average energy demand by the product of the efficiency of all the basic system components and is given by equation 2 (El Shenwy et al., 2017):

$$E_{rd} = \frac{E_d}{\eta_b \eta_i \eta_c} \quad (2)$$

Where η_b=Battery efficiency=0.90;
η_i=Inverter efficiency=0.97
η_c=Charge controller efficiency=0.98

$$E_{rd} = \frac{35{,}000}{0.90 \times 0.97 \times 0.98}$$

$$E_{rd} = 40.910kWh/day$$

The average peak power $P_{av,peak} = \frac{E_{rd}}{T_{sh}} = \frac{40910}{5}$

$$= 8182w$$

The total dc current of the system is given by equation 3 (Chukwuemeka and Felix, 2018) while equation 4 and 5 (Mahmood, 2019) gives the number of modules to be connected in series and in parallel respectively.

$$I_{dc} = \frac{P_{av,peak}}{V_{dc}} \quad (3)$$

$$= \frac{8182}{96} = 85.23\ A$$

Number of modules in series $N_{sm} = \frac{V_{dc}}{V_{rm}}$ (4)

$$= \frac{96}{36.75} = 2.61$$

$$\cong 3 \text{ modules}$$

Number of modules in parallel $N_{pm} = \frac{I_{dc}}{I_{rm}}$ (5)

$= \frac{85.23}{8.71} = 9.79$

$\cong 10$

Approximately three (3) module is needed in series while ten (10) modules are needed in parallel. The total number of modules (N_{tm}) that forms the array was determine by multiplying the number of parallel modules by the series modules to give the total required number of modules as 30 as follows using equation 6:

$$N_{tm} = N_{sm} \times N_{pm} \quad (6)$$

$$= 3 \times 10$$

$$=30$$

The distance (D) of separation between the panel and the battery was limited to 10 m in order to reduce the voltage drop along the cable from the solar panel since the solar panels are often mounted at some distance away from the battery in order to achieve maximum energy thus causing a distance of separation.

Solar charge controller

The charge controller provides a regulated DC output and stores excess energy in a battery thereby monitoring the battery voltage so as to prevent under/overcharging of the battery. It is rated in Amperes and is dependent on the quantity of photovoltaic current presents. The standard practice of sizing the charge controller is to ensure that it is able to withstand the product of the total short circuit current of the solar array. The required charge controller current is given by equation 7 (Btineth and Dalahal, 2012):

$$I_{rcc} = I_{sc}^{m} \times N_{pm} \times F_{safe} \quad (7)$$

The safe factor (F_{safe}) allows for a reasonable system expansion and has a value of 1.25, while I_{sc}^{m} is the short circuit current of the selected module and has a value of 9.28 A. Using the number of parallel modules (N_{pm}) as 10 as calculated in equation 8 (Btineth and Dalahal, 2012):

$$I_{rc} = I_{sc}^{m} \times N_{pm} \times F_{safe} \quad (8)$$

$$= 9.28 \times 10 \times 1.25$$

$$= 116\ A$$

Selecting a charge controller, I-Panda MPPT Solar converter (System voltage 96V/192V/216V/240V/384V automatic recognition, Rated current: 50A; 60A; 70A; 80A) with preferred $V_{cc} = 96V \text{ and } I_{cc} = 60A$;

Number of charge controllers $N_{cc} = \frac{I_{rcc}}{I_{cc}} = \frac{116}{60} = 1.93$

$$\cong 2$$

As such two charge controllers of 60 A each will be suitable and hence were preferred for the design.

Battery, Battery connection and battery capacity calculation/Sizing

A deep cycle battery was preferred which is also the mostly recommended battery for a solar PV design with an advantage of many times of recharging cycles after discharge. The estimated energy storage (E_{est}) is determined using equation 9 (Hasan *et al*., 2016);

$$E_{est} = E_d \times D_{aut} \tag{9}$$

Where E_d is the average daily energy demand of the participating residences and was calculated as 35,000 watt-hours.D_{aut} is the number of autonomous days and was taken to be 3days. Substituting into equation 7:

$$E_{st} = 35000 \times 3 = 105kWh$$

Selecting a deep cycle VRLA/SMF Luminous battery with specification C_b(Capacity of a single battery in Ah)= 200 Ah, V_b (Rated dc voltage of one battery)=12V and D_{disch} (Maximum depth of discharge also called depth of discharge DOD)=80%. The safe energy storage by the battery was calculated using equation 10 while the total battery capacity was calculated using equation 11 (Hasan *et al*., 2016):

$$E_{safe} = \frac{E_{est}}{D_{disch}} = \frac{105kWh}{0.8} = 131.25kWh \tag{10}$$

The total capacity of the battery bank in ampere hours (C_{tb}) is determined by dividing the safe energy storage by the rated dc voltage of one battery V_b as follows:

$$C_{tb} = \frac{E_{safe}}{V_b} = \frac{131.25kWh}{12} = 10937.5\ Ah \tag{11}$$

The total number of batteries N_b is obtained by dividing the total capacity of the battery bank by the capacity of one of the selected batteries and is given by equation 12:

$$N_{tb} = \frac{C_{tb}}{C_b} = \frac{11000Ah}{200\ Ah} = 55 \tag{12}$$

The number of batteries in series was determined using equation 13 (Pal *et al*., 2015):

$$N_{sb} = \frac{V_{dc}}{V_b} \tag{13}$$

$$= \frac{96}{12} = 8 \text{ Batteries}$$

Number of parallel battery strings was determined using equation 14 (Abu-Jasser, 2010):

$$N_{pb} = \frac{N_{tb}}{N_{Sb}} \tag{14}$$

$$= \frac{55}{8} = 6.88$$

$$\cong 7 \text{ Batteries}$$

Using efficiency of 90% which is typical for lead acid battery, the required battery capacity was determined as 11000 Ah to allow for load surge. Fifty five (55), 12V batteries with capacities of 200 Ah each is preferred to give the total capacity of 11000 Ah. Battery of same capacitance of 200 Ah each were selected for connection in order to ensure optimum performance. Parallel connection of the batteries will give a net current sum of the individual current of the batteries to a total of 11000Ah while the net voltage is the same to a total of 12V since all the barriers are of the same capacity.

The depth of discharge (DOD) is the percentage of the battery charge that has been discharged or can be discharged. The DOD determines the longevity of a battery as the higher the DOD the higher the longevity and can be fixed for a given battery. A choice of 80% DOD with a life span of 3 years was made to allow for switching to the natural grid and electrochemical cell balance since the batteries can charge during periods of low demand and avail the stored energy for use when demand is high thereby levelling out peak loads. A modified version of the conventional deep cycle lead acid battery called the valve regulated acid battery was selected for the model design due to its high reliability, low self-discharge, low investment and maintenance cost despite its lower energy density and life span.

Inverter rating

A PV inverter or solar inverter converts the variable direct current (DC) output of a photovoltaic solar panel into alternating current (AC) that would supply the house holds involve in the electrical energy network. Solar PV systems delivers DC voltage/power as such an inverter which converts DC power to AC power was preferred. An inverter is rated by its output power (P_{kva}) and DC input voltage (V_{dc}). The inverter was designed to have a power rating that is equal to 125% of the sum of the power of all loads running simultaneously (inductive and non-inductive appliances) and 3.5 times the sum of the power of all inductive appliances. The total power consumed by the defined loads is expected to have same nominal voltage of the battery bank that is charged by the solar PV module. Thus the inverter power was determined using equation 15 (Saleh *et al*., 2015):

$$P_{inv} = 1.25\,(P_{sum} + 3.5P_{ind}) \tag{15}$$

Where P_{inv} = Power of the inverter

P_{sum} =Power of all loads running simultaneously (Resistive loads +Inductive loads)

=2017 W × 5 Households/residence=10085W

P_{ind}= Power of all inductive loads with large surge current=330× 5 Household=1650W

$$P_{inv} = 1.25\,(10085 + 3.5 \times 1650)$$

$$P_{inv} = 19825W\text{=19.83 kW}$$

The power rating of an inverter is related to the real power that is delivered by the output of the inverter and is given by the equation 16 (Saleh *et al*., 2015):

$$Power\ factor\ (PF) = \frac{Deliverable\ real\ power}{Power\ rating\ of\ the\ inverter\ (P_{KVA})} \tag{16}$$

The real power is the power consumed for work on load while the PF is generally taken as 0.8.

$$0.8 = \frac{19.83kW}{P_{KVA}}$$

$$P_{KVA} = 24.79kVA$$

The standby mode power consumption which is the power consume by the system when it is not delivering power to the load was taken into cognisance. It is usually 5VA per hour. Assuming the system runs for 24 hours, then the standby mode power consumption will be 120VA.Thus the rating of the inverter preferred for the design is 25 kVA.

Cable sizing

There are two types of cable which consist of the inverter to distribution board (DB) system (AC current) of the individual residence and the PV array to battery bank (DC current) through charge controller which is calculated thus:
The PV array to battery bank through the charge controller' is obtained using the relation

$I_{cab} = I_{rcc} = I_{sc}^{m} \times N_{pm} \times F_{safe}$ Where each parameter has the same meaning and value. $I_{cab} = 9.28 \times 10 \times 1.25 = 116\ A$

Hence a $3 \times 35\ mm^2$ insulated flexible copper cable was selected. For the inverter to distribution board system of the residential cable, the cable is based on the maximum continuous input current which is obtained from equation 17 (Saleh *et al*., 2015) as:

$$I_{oi} = \frac{P_i}{V_{oi} \times PF} \tag{17}$$

Where V_{oi}=Output AC voltage of inverter, Io_i=Current at inverter output

$$= \frac{19825W}{240 \times 0.8} = 103.25\ A$$

For each residence, I_{oi}=20.65 A. Hence a $3 \times 10\ mm^2$ insulated flexible copper cable was selected.

Smart metering

A smart meter was employed in the model design to provide a means of energy control and real time energy consumption costing using telecommunication for the automated transmission of data to facilitate energy costing and energy consumption evaluation. The smart meter gives information on energy unit consumed, energy unit remaining, and other energy status at a given point in time using the short message service (SMS). The smart meter design for the energy consumption by the modelled five (5) residence/households consists of a GSM modem, a microcontroller, a liguid crystal display, a Relay, output load, Analogue to digital converter (ADC) and power supply. While an embedded "C" language program consisting of attention (AT) command string/set was selected for installation as the communication gate way for exchange of instructions/data after conversion of the source code to Hex file for interpretation or use by the microcontroller. This is shown in form of a block diagram in figure 5.

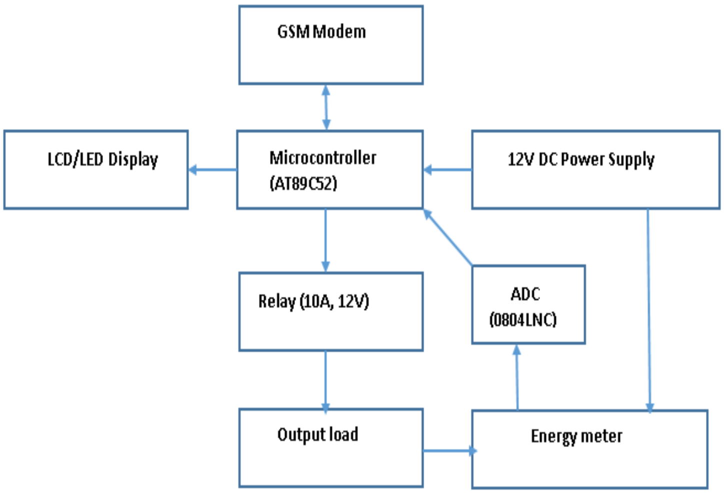

Figure 5: Block diagram of the smart energy meter

The entire system is powered by a 12V dc power supply unit. The microcontroller receives input from the GSM unit and send it to trigger ON or OFF the relay. The relay receives the signal and either switches ON or OFF the energy supply to the participating households. The microcontroller also receives signals from the phone and triggers the relay accordingly. At the interface between the smart energy meter and the microcontroller is the analogue to digital converter which receives analogue signals from the meter, converts to digital signal/equivalence in the form of unit of energy consumption, energy unit balance, low unit alert and other energy status as the case may be for processing by the microcontroller and further display by the liguid crystal display. A control centre will be in charge of the data base of each subscriber's data such as name, phone number, SIM ID and energy consumption records where amount of energy unit paid for, unit used and energy unit balance are used to update the individual's subscriber's data base for energy evaluation, planning, maintenance and management per time. As the energy is consumed by the loads in the individual participating residence, the smart meter sends units consumed to the prepared card which converts the unit consumed into expenditure (E) at every given instant after which it subtracts it from the recharged/subscribed unit amount to obtain a balance B which is mathematically given by equation 18 (Joy, 2006) as:

$$R_A - E = B \qquad (18)$$

The expenditure is calculated from the relation $E = N_A + C_C$, The current charge $C_C = E_C \times E_N \times M_F$ while the energy charged per kWh $E_C = L_R - P_R$. Where

L_R =Last system reading, E_C=Energy consumed, E_N=Energy charged per kWh

M_F=Multiplier factor, N_A=Net arrears, R_A=Recharged amount

P_R=Present reading

Safety and protective devices

A fuse would be installed in series with each of the string to protect the modules and conduction from excess current and also to isolate faulty strings so as to enhance continuous energy supply. According to Greacen*et al.*, 2013, the rating of protective fuse should be$\geq 1.56 \times I_{sc}$ and $\leq 2.0 \times I_{sc}; \geq 1.56 \times 9.28 \leq 2 \times 9.28$ $such\ that\ it\ is \geq 14.48 \leq 18.56A$.While the voltage rating should be$\geq 1.2 \times M \times V_{oc}; \geq 1.2 \times 30 \times 45.72$. As such the voltage rating for the fuse to each residence will be$\geq 329.18V$.
A lightning arrestor was recommended for installation to divert any surge which could be caused by lightning strike given the outdoor instalment of the solar garden. Selected earthly standards for the model design are BS6651, BS7430 and BS7671. DC disconnector at the DC side are also recommended as isolation devices to allow easy disconnection of the solar energy source in the event of system maintenance or fault. Other components such as ac isolator, AC bus and power diode could be selected depending on energy design in terms of connectivity to national grid or stand-alone requirements.

Summary of PV model system components

A summary of the designed, selected or preferred components of the PV system comprising of the solar module, batteries, charge controller, cables, metering/control and safety/protection devices is shown in table 2 in terms of component model, power rating, voltage and current.

Table 2: Summary of PV model system components

S/N	Component	Quantity	Model	Power rating (W/Ah)	Voltage (V)	Current (A)
1	Solar module	30	AE EXTREME 320P6-72	320 W	36.75	8.71
2	Battery	56	LUMINOUS VRLA/SMF Deep cycle Battery	200 Ah	12	-
3	Inverter	1	LUMINOUS 25kVA/240V	20000 W	360 Vdc/240Vac	66A dc/66A ac
4	Charge controller	2	I-Panda 240v/60A MPPT Solar controller	Not applicable	96	60
5	Cables	As required	Array to Battery Inverter to DB	3× 35 and 3× $10mm^2$	Insulated copper cable & flexible copper	
6	Smart energy meter	6	Not applicable	Not applicable	Not applicable	Not applicable
7	Protective/Safety devices	As required	Not applicable	Not applicable	Not applicable	Not applicable

Economic/investment cost analysis

Table 3: A summary of the components cost of the modelled solar energy system.

S/N	Component	Quantity	Unit cost (USD)	Total cost (USD)
1	PV Module	30	197.24	5917.16
2	Charge controller	02	631.16	1262.33
3	Battery	56	341.88	19145.30
4	Inverter	01	3944.77	3944.77
5	Cables (PV to battery & Inverter to Distribution board)	140 yards each	2.63 per yard 2.76 per yard	368.18 386.59
6	Smart meter	06	78.90	473.37
7	Design,Labour, installation/control cost	Not applicable		2629.85
Total			34127.55	

The life cycle cost (LC_C) analysis is used to evaluate the behaviour of the proposed energy system. The life cycle cost analysis covers initial capital cost of components purchase and installation stage operation and maintenance stage and the replacement stage. The operation and maintenance costs (OM_C) include annual periodic expenses for system management, site supervision and maintenance. The LC_C analysis take into cognisance the longest life component of all systems parts. The storage batteries in the PV system are expected to be replaced every 5-10 years according to the battery type and operating conditions. The life cycle of the luminous battery used is 10 years while that of the PV modules is 25 years. The possible escalation trend in the overall costs of the system called inflation (i) and the possible decrease in the components cost with future mass production called the discounts (d) were considered for future estimation. The annual operation and maintenance cost is 2% of the PV initial cost (Shenawy, 2017) while the inflation rate (i) and the discount rate (d) was considered as 5 and 10% respectively. The annual OM_c cost was calculated using equation 19;

$$OM_c = 2\%\ PV_c \times \left(\frac{1+i}{1+d}\right)\left|\frac{1-\left(\frac{1+i}{1+d}\right)^{25}}{1-\left(\frac{1+i}{1+d}\right)}\right| \quad (19)$$

$$OM_c = 2/100 \times 5917.16 \times \left(\frac{1+0.05}{1+0.1}\right)\left|\frac{1-\left(\frac{1+0.05}{1+0.1}\right)^{25}}{1-\left(\frac{1+0.05}{1+0.1}\right)}\right|$$

$$= 1626.68\ USD$$

The battery replacement costs are usually calculated for the first time after 10 years and for second replacement after 20 years since the battery life is considered as 10 years. This is calculated using equation 20 (Mahmood, 2019):

$$B_{C1} = BC\left[\frac{1+i}{1+d}\right]^{10} \quad (20a)$$

$$B_{C2} = BC\left[\frac{1+i}{1+d}\right]^{20} \quad (20b)$$

Where BC, the storage battery cost is 19145.30 USD

$$B_{C1} = 19145.30\left[\frac{1+0.05}{1+0.1}\right]^{10}$$

= 11487.18 USD

$$B_{C1} = 19145.30\left[\frac{1+0.05}{1+0.1}\right]^{20}$$

= 6892.31 USD

The system's life cycle cost was calculated using equation 21 (Shenawy*et al.*, 2017) by adding PV_c, B_{C1} (Battery cost), B_{C2} (Battery replacement), Inverter cost (Inv_c), Controller cost (C_C), Installation cost (I_C), Operation and maintenance cost (OM_c).

$$LC_C=PV_C+B_C+B_{C1}+B_{C2}+Inv_C+I_C+OM_C \quad (21)$$

= 5917.16 + 1914.53 + 11487.18 + 6892.31 + 3944.77 + 1262.33+3595.00+1626.68

= 53870.73 USD

The annual life cycle cost (ALC_C) was estimated using equation 17 (Shenawy*et al.*, 2017).

$$ALC_C = LC_C\left[\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^{25}}\right]$$

$$ALC_C = 53870.73\left[\frac{1-\left(\frac{1+0.05}{1+0.1}\right)}{1-\left(\frac{1+0.05}{1+0.1}\right)^{25}}\right]$$

= 3770.95 USD

The unit electrical cost (U_C) in USD/kWh can be estimated from the annual life cycle cost and the annual energy generation by the system using equation 22 (Mahmood, 2019);

$$U_C = \frac{ALC_C}{365 \times E_L} \quad (18)$$

$$= \frac{3770.95}{365 \times 35000}$$

= 0.0003 USD/kWh

This is the unit cost of the install system over 20 years of operation. A charge of 0.0003 USD /kWh is far cheaper than the present 0.0813 USD/kWh currently charged by the privatised Nigerian Power holding company.

CONCLUSION

In a bid to enhance energy accessibility to household especially in the developing African societies where electrical energy availability is a challenge a model solar garden was designed taking into consideration nine basic day to day load usage and energy consumption of typical African home/household. The solar garden which forms a mini electrical energy grid can be set up by a community/group of persons or an individual to open it up for subscribes with control using smart meter for energy consumption/pricing thereby reducing cost of an individual setting up the system especially the low income earners, increasing energy accessibility/availability especially to low income earners even in cities, rural dwellers, small scale firms/industries and hence the enhancement of climate change adaptation via the reduction of carbon emission/greenhouse gases. Solar garden/community solar concept has proven to be a fast growing approach to photovoltaic energy generation, transmission/utilisation. Given the pollution free, sustainability, reduced cost, reduction on fossil fuel reliance and other economic benefits of solar energy it becomes essential in contributing to the national energy mix and a promising alternative energy to households, firms and industries depended on electrical energy for operation. Solar PV system with 44 batteries of 12V, 250 Ah and 56 modules have been estimated to meet the energy demand of five residential buildings considered with a total appliances energy demand of 10085W. Amidst the initial cost of installation of the system, its consistency, toughness, environmental friendliness and ease of maintenance make the system worthy of consideration as it is beneficial for long-term energy investment since the payback period is less than 5 years while the life expectancy of the system is above 25 years. Also with the advent/improvement in technology for the production of PV component materials especially the solar module the initial cost of installation is expected to decrease thereby reducing the payback period. The model design can be extended to more households, persons, people group, organisations or firms depending on energy requirement and setup capital especially in the developing countries of Africa. The model design could be standalone power grid or a grid connected system depending on location, energy availability from national grid or interest.

ACKNOWLEDGEMENT

The authors acknowledge the embassy of France in Nigeria under the ongoing AIRRAC project for bringing us together from our various institutions from where the idea of this study was conceived. However, this research did not receive any funding.

REFERENCES

Abu-Jasser, A., 2010. A stand-alone photovoltaic system-case study: A residence in Gaza. Journal of Applied sciences in Environmental sanitation.5(1): 81-92.

Btineth, K., and D.Dalahal., 2012. “Optimal configuration for design of stand-alone PV system” Scientific Research: smart Grid and renewable energy, 3:139-147.

Chan, G., I. Evans, M.Grimley, B. Ihde and P.Mauder. (2017). Design choices and equity implications of community shared solar. The Electricity Journal, 30 (9), 37-41. https://doi.org/10.1016/j.tej.2017.10.006

Chukwuemeka, O., and A.A. Felix., 2018. Design of a hybrid off-grid solar system for residential buildings in remote Benja Village. International journal of Mechanical Engineering and Technology (IJMET), 9(8), 2018, 141-152.

El Shenawy, E.T., A.H. Hegazy and M.Abdellatef, 2017. Design and optimisation of stand-alone PV system for Egyptian Rural Communities. International journal of Applied Engineering Research, 12 (20): 10433-10446.

Fashina, A.A., 2019. Is there a possibility of Perovskites taking over the solar technology
market by 2030? International journal of physical research, 7(1):1-2.

Guda, H.A., and U.O. Aliyu., 2015. Design of a standalone photovoltaic system for a residence in Bauchi. International journal of Engineering and Technology, 5(1): 34-44.

Greacen, C., R. Engel and T. Quetchenbach, A, 2013. Guidebook on Grid interconnection and Islanded operation of mini-Grid power systems up to 200Kw Lawrence Berkeley National laboratory, April 2013.Retrieved from http://www.cleanenergyministerial.org/portals/2/pdfs/A Guidebook for Minigrids-SERC LBNL March 2013.pdf on 22nd June 2020.

Hasan, R., S.Islam, A. Hossain, U. Sarjana and R. Hasan, 2016. Design and development of a cost effective standalone PV system for a residential building in Pabna, Bngladesh. International journal of scientific and engineering research,7(9): 1664-1669.

Joy.N.K., 2006. Electrical energy accounting methods. Impressed publishers, Lagos, Nigeria.

Joshi, G., and K. Yenneti., 2020. Community solar energy initiatives in India: A pathway for addressing energy poverty and sustainability? Energy and Building, 210: 109736. https://doi.org/10.1016/j.enbuild.2019.109736

Johnson, D.O., and A.A. Ogunseye., 2017. Grid connected photovoltaic system design for local government offices in Nigeria. Nigeria journal of Technology (NIJOTECH), 36(2):571-581.

Mahmood, A.L., 2019. Design and simulation of standalone PV systems for Electronic and communications engineering department laboratories in Al-Nahrain University. EAI endorsed Transactions on Energy web, 6(21): e9. Doi: 10.4108/eai.13-7-2018.156438.

Markvart, T., A. Fragaki and J.N. Ross, 2006. “PV system sizing using observed time series of solar radiation”. ELSVIER Solar energy 80: 46-50.

Pal, A.M., S. Das and N.B. Raju, 2015. Designing of a standalone photovoltaic system for a residential building in Grgaon, India. Sustainable Energy,2015(3): 14-24.doi:10.1269.IIrse-3-1-3.

Saleh, U.A., Y.S. Haruna and F.I. Onuigbo, 2015. Design and procedure for standalone photovoltaic power system for ozone monitor laboratory at Anyigba; North central Nigeria. International Journal of Engineering science and innovative Technology(IJESIT), 4(6): 41-52.

Shaahid, S., and Elhadidy, M., 2008. Economic analysis of hybrid photovoltaic-diesel battery power systems for residential loads in hot regions-A step to clean future renewable and sustainable energy. Energy reviews, 12: 488-503.

Sagar, A.D., 2012. Alleviating energy poverty for the world’s poor. Science Direct, Energy policy, 33(11), 1367-1372.