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Health and Energy at MADEV 2017

Photovoltaic Hybrid Systems for remote villages

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ABSTRACT. Electricity access in remote areas characterised by low population and energy densities in Sub-Saharan Africa is limited due to high grid extension costs. Photovoltaic hybrid systems can be computed using an energy equation involving one unknown. For an average daily demand of 153.6 kWh/d, the monthly energy output of photovoltaic modules at Garoua, Cameroon, enabled the evaluation of a hybrid system comprising a 25 kW diesel generator with an operating time of 9 hr/yr, a PV array of 43.56 kWp for a renewable energy fraction of 99.8%. Similar results have been evaluated using HOMER for medium villages in Senegal.

Systemes Hybrides Photovoltaiques pour les villages isolés

RESUME. L'accès à l'électricité dans les zones isolées caractérisés par les faibles densités de population et de consommation d'énergie électrique en Afrique Sub-saharienne est limité par le coût élevé d'extension des réseaux électriques. Les systèmes hybrides photovoltaïques peuvent être évalués avec une équation énergétique à un inconnue. Pour une demande énergétique de 153.6 kWh/jr, les productions énergétique mensuel des modules photovoltaïques à Garoua, Cameroun, ont permis d'obtenir un système hybride constitué d'un groupe électrogène de 25 kW avec un fonctionnement de 9 heures/an, un générateur photovoltaïque de 43.56 kWc pour une fraction renouvelable de 99.8%. Des résultats similaires ont été déterminés avec le logiciel HOMER pour les villages moyens au Sénégal.

MOTS CLÉS: Systemes hybrides photovoltaïques, model énergétique, heures annuel de groupe électrogènes souhaités

KEYWORDS: Photovoltaic hybrid systems, energy model, desired annual generator hours

1 Introduction

Sub-Saharan Africa had the lowest urban and rural electrification rates of 58% and 12% in 2008 [1]. Achieving universal access to electricity in Sub-Saharan Africa is therefore a serious challenge for individual countries because of high costs of extending centralised grid electricity to urban and rural areas characterized by low population and energy densities. Microgrids powered by photovoltaic/diesel hybrid systems (PVHS) which can be expanded as energy demand increases could be used to ensure the economic development of such underprivileged localities. The power system components of the PVHS can be evaluated using an energy based model and an iterative method while the cost of energy of the PVHS is evaluated using the Net Present value technique [2-4] or alternatively using HOMER software [5-7]. The objective of this current work is to show that PVHS option should be preferred option instead of standalone PV systems for villages with large energy demand in Sub-Saharan Africa. PVHS require a smaller PV array size and have higher power system reliability because the diesel generator can be used for peak power following as well as for reducing energy storage requirements.

2 PVHS energy model

An AC-bus configuration of a PVHS system is shown in Figure 1. Photovoltaic modules convert variable solar radiation into a DC voltage that is often optimised with a maximum power point tracking device. The optimised DC voltage is converted to AC voltage by a string inverter and supplied to AC loads through an AC-bus. A battery inverter connected to the AC-bus and battery bank charges the battery in the case of excess power from solar panels or diesel generator. The battery inverter also converts stored energy in the battery to AC-power when the battery bank is sufficiently charged. In Figure 1, $S(k)$ is the energy output of the solar generator SP in the k th month, η_{mppt} is the efficiency of the maximum power point tracker MPPT, η_{stri} is the efficiency of the string inverter SI, η_{batt} is the round trip efficiency of the battery bank BB, η_{inv} is the efficiency of battery inverter BI, $G(k)$ is the energy output of the diesel generator DG in the k th month and $D(k)$ is the energy demand of AC-loads in the k th month.

The energy demand of the AC loads in the k th month is satisfied in the solar hybrid system by the relation:

$$D(k) = \eta_{mppt} \eta_{stri} S(k) + G(k) \quad (1)$$

The monthly energy supplied by the diesel generator is given by:

$$G(k) = P_g \times q \times h(k) \quad (2)$$

where P_g is the rated power of the generator, q is the constant load fraction at which the generator is operated and $h(k)$ is the number of hours the generator is operated in the k th month.

The energy deficit in the k th month that is supplied by the generator can be expressed as:

$$R(k) = D(k) - \eta_{mppt} \eta_{batt} \eta_{inv} S(k) \quad (3)$$

If the minimum parallel and serial connection numbers of solar modules that make up the solar generator are denoted N_{pvp} and N_{pvs} respectively, then the energy output of the solar generator in the k th month is of the form:

$$S(k) = N_{pvp} \times N_{pvs} \times W(k) \quad (4)$$

where $W(k)$ the energy output of a solar module in the k th month and is expressed as [8,9]

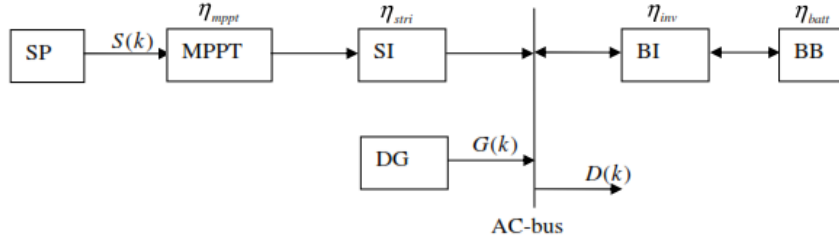


Figure 1: Energy flows in PVHS hybrid system [8]

$$W(k) = F_c F_o d(k) \int_{t=6}^{18} I_{pv}(t) \times V_{pv}(t) dt \quad (5)$$

From equation (4) the energy deficit in the k th month is re-written as:

$$R(k) = D(k) - \eta_{mppt} \eta_{batt} \eta_{inv} N_{pvp} N_{pvs} W(k) \quad (6)$$

From equations (6) and (2), the number of generator operating hours in the k th month due to insufficient renewable energy generation is derived as:

$$h(k) = \begin{cases} 0 & R(k) < 0 \\ R(k) / qP_g & R(k) > 0 \end{cases} \quad (7)$$

where q is the diesel generator load factor and P_g in the rating of the diesel generator. From equations (6) and (7) the annual number of generator operating hours due insufficient renewable energy generation is given by:

$$h = \text{int} \left[\sum_{k=1}^{12} \left(\frac{D(k) - N_{pvp} N_{pvs} \eta_{mppt} \eta_{stri} W(k)}{P_g \times q} \right) \right] \quad (8)$$

If the energy demand of the AC loads is supplied uniquely by the solar generator, equation (6) reduces to:

$$D(k) = \eta_{mpp} \eta_{stri} N_{pvp} N_{pvs} W(k) \quad (9)$$

From which the minimum parallel connection number of PV module strings is determined as:

$$N_{pvp} = \max \left[\text{int} \left(\frac{D(k) / \eta_{stri} \eta_{mpp}}{N_{pvs} W(k)} \right) \right] \quad (10)$$

with the serial connection number of PV modules defined by:

$$N_{pvs} = V_{op} / V_{np} \quad (11)$$

where V_{op} is the operating voltage of the PV array, V_{np} the nominal output voltage of PV module.

When a diesel generator is included, the power rating of the generator in PVHS can be computed with the relation [5]:

$$P_g = \frac{L_f L_{\max}}{365 q_{\max}} \sum_{k=1}^{12} D(k) \quad (12)$$

where L_f is load factor accounting for unexpected variations in maximum demand, L_{\max} is maximum hourly load contribution to daily energy demand, q_{\max} is the maximum load factor. The maximum number of desired annual generator hours in PVHS can be determined with the relation [5, 6]:

$$hh_{\max} = \frac{(1 - rf_{\min})}{q \times P_g} \sum_{k=1}^{12} D(k) \quad (13)$$

where hh_{\max} maximum desired generator hours in PVHS, rf_{\min} is the minimum desired renewable energy fraction. The PV array size required in PVHS options can be determined by solving the following inequality derived from equation (8) [5, 6]:

$$\sum_{k=1}^{12} \left| \frac{D(k) - N_{pvp} N_{pvs} \eta_{mpp} \eta_{stri} W(k)}{q \times P_g} \right| \leq hh \quad (14)$$

$$0 \leq hh \leq hh_{\max}$$

The numerical solution of equation (14) is initialised with the initial value of N_{pv1} computed with equation (10) [6]. The final value N_{pv2} for a selected value of hh is then used to compute the PV array power with the relation:

$$P_{pv} = N_{pvp2} N_{pvs} P_{mp} \quad (15)$$

where P_{mp} is the nominal rating of the PV module. The PV array capacity computed with equation (15) is then used to evaluate the monthly energy outputs of the PV array leading to the calculation of the annual operational time of the diesel generator with the relation:

$$h_2 = \text{int} \left[\sum_{k=1}^{12} \left(\frac{D(k) - N_{pvp2} N_{pvs} \eta_{mppi} \eta_{stri} W(k)}{P_g \times q} \right) \right] \quad (16)$$

The renewable energy fraction of the PVHS is found with the relation:

$$RF = N_{pvp2} N_{pvs} \sum_{k=1}^{12} W(k) / N_{pvp2} N_{pvs} \sum_{k=1}^{12} W(k) + q \times P_g \times h_2 \quad (17)$$

3 Energy storage model

In the absence of renewable and diesel generators, the battery bank capacity in Figure 1 must be sufficient for the number of days of autonomy that are desired. The battery bank is usually designed using the average daily energy demand of the AC loads which can be obtained with the relation:

$$X = \sum_{k=1}^{12} D(k) / \sum_{k=1}^{12} d(k) \quad (18)$$

where X is the daily energy demand computed from the annual energy demand and $d(k)$ is the number of days in the k th month.

The battery bank capacity required for desired autonomy is given by:

$$C_{bank} = \frac{d \times X}{DOD \times \eta_{dch} \times \eta_{inv}} \quad (19)$$

where C_{bank} is the battery bank capacity, d is the number of days of autonomy required, DOD is the depth of discharge of the battery bank, η_{dch} is the discharge efficiency of the battery bank and η_{inv} is the efficiency of the battery inverter.

From equations (18) and (19) the battery bank capacity is obtained as:

$$C_{bank} = \frac{d}{DOD \eta_{dch} \eta_{inv}} \left(\sum_{k=1}^{12} D(k) / \sum_{k=1}^{12} d(k) \right) \quad (20)$$

An alternative expression for the battery bank capacity is of the form:

$$C_{bank} = N_{bp} N_{bs} C_{batt} \quad (21)$$

where N_{bp} is the minimum parallel connection number of battery cell strings, N_{bs} is the serial connection number of battery cells and C_{batt} is the nominal capacity of battery cell. The minimum parallel connection number of battery cell strings in the battery bank can be computed from equations (20) and (21) as:

$$N_{bp} = \text{int} \left[\frac{d}{N_{bs} C_{batt} DOD \eta_{dch} \eta_{inv} \left(\sum_{k=1}^{12} D(k) / \sum_{k=1}^{12} d(k) \right)} \right] \quad (22)$$

with the serial connection number of battery cells computed as:

$$N_{bs} = \frac{V_{ob}}{V_{nb}} \quad (23)$$

where V_{ob} is operating voltage of battery bank and V_{nb} is the nominal output voltage of battery cell.

4 Data for sizing of PVHS

The electricity consumption data of a hypothetical village with 50 low voltage grid-connected customers is shown in Table 1. This data is derived from the characteristics of AES-SONEL electricity consumption data of 2007 for Bandjoun, located in the West Region of Cameroon. The information of diesel generators that can be selected in feasible power configurations is shown in Table 2.

Table 1: Electricity consumption of a village with 50 low voltage customers

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Typical	4571.1	3830.5	4373.5	4567.3	4401.5	4868.4	5080.7	4421.8	4657.3	4741.3	4873.9	4920.1	4609.0
Average	152.37	127.68	145.78	152.24	146.72	162.28	169.36	147.39	155.24	158.04	162.46	164.00	153.63

Table 2: Diesel generator cost and fuel consumption rates for selected load factors

P_g (kW)	C_g (€/kW)	F_{cr} (l/hr)		
		25%	50%	75%
2.5	375	0.6	0.9	1.3
5.0	265	1.0	1.4	1.9
7.5	175	1.4	1.9	2.5
10.0	158	1.7	2.3	3.1
12.5	149	2.1	2.9	3.6
15.0	142	2.4	2.6	4.2
17.5	136	2.6	3.8	4.8
20.0	129	2.9	4.4	5.5
22.5	124	3.2	4.9	6.2
25.0	122	3.5	5.5	6.7

The monthly energy output of PV modules at Garoua used for the evaluation of feasible PVHS for village energy demand is presented in Figure 2.

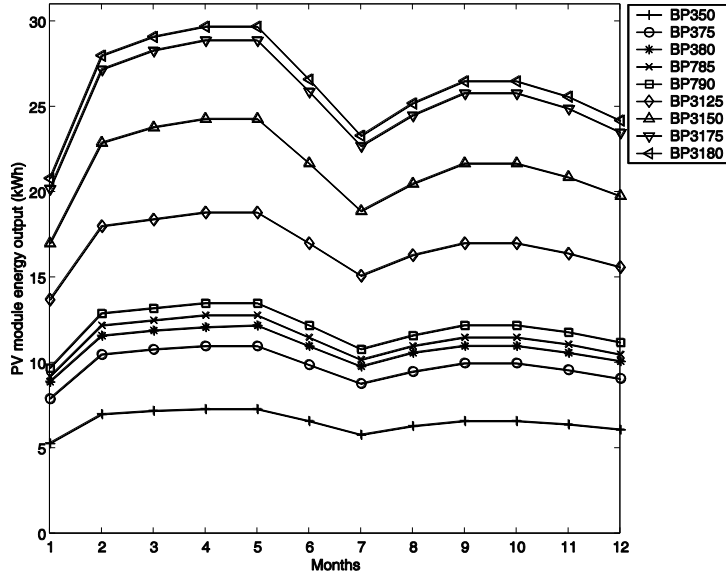


Figure 2: Monthly energy output of selected PV modules [8]

Sunny Boy PV string inverter Model SB3000 is selected for AC-coupling of strings of PV modules. A battery bank with an operating voltage of 48 V is selected and a bidirectional inverter is selected for connection to the AC-bus as in previous studies [4-6].

5 Results and discussions

The feasible power system configurations obtained for the electricity consumption profile of the village is shown in Table 3. The variation of PV array size and the renewable energy fraction with annual number of diesel generator hours are shown in Fig 3.

Table 3: Feasible power options for a village with 50 low voltage customers

C	Hh	P_{mp}	P_{pv}	P_s	C_{bank}	P_g	h	D	E_g	E_{pv}	E	RF
1	0	180	43560	33000	561.6	25	9	55307	168.8	67965	68133	0.998
2	10	180	39600	30000	561.6	25	65	55307	1218.8	61786	63005	0.981
3	70	180	35640	27000	561.6	25	170	55307	3187.6	55608	58795	0.946
4	175	180	31680	24000	561.6	25	377	55307	7068.9	49429	56498	0.875

5	380	180	27720	21000	561.6	25	649	55307	12169.0	43250	55419	0.780
6	650	180	23760	18000	561.6	25	978	55307	18338.0	37072	55410	0.669
7	980	180	19800	15000	561.6	25	1309	55307	24544.0	30893	55437	0.557
8	8850	0	0	0	0	25	8854	55307	55338.0	0	55338	0.000

The PV array size decreases exponentially for annual generator hours between 0-1300 hours and the renewable energy fractions are in the range 0.557-0.998. The maximum PV array size of 43.56kWp found at a renewable energy fraction of 0.998 is the range of 30 – 45 kWp which has been determined for three medium villages in Senegal with 750 inhabitants having energy demands in the range 127.67 – 178.82 kWh/d using HOMER software [5-7]. It is noted that a diesel generator with very low operating time of 9 hr/yr is selected when the desired renewable energy fraction is 100%. This generator will ensure power supply reliability during prolonged hours of low solar radiation and unexpected variations in power demand or growth in energy demand due to increase over time of the number of household connections [10]. The results obtained are in line with previous studies involving economic analysis [2-4] and therefore PVHS should be used in stead of standalone PV systems for the electrification of rural areas in Far North Cameroon and other remote areas of Sub-Saharan Africa which are characterised by high solar radiation levels. A PV array size of 23.76 kWp is found at a renewable fraction of 0.557 and is approximately 55% of 43.56 kWp for a renewable energy fraction of 0.998. Considering high initial costs for the implementation of PVHS with a renewable energy fraction of almost 100%, PVHS implementation can begin with 55% PV rating and then expanded.

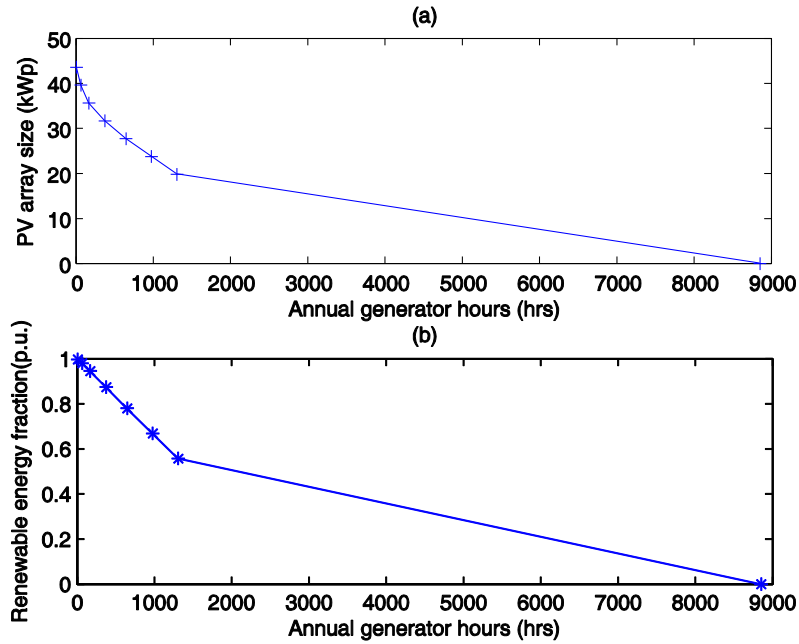


Figure 3: Annual generator hours versus (a) PV array size (b) Renewable Fraction

6 Conclusion

Photovoltaic hybrid systems (PVHS) have been computed for a village with a daily energy demand of 153.6 kWh/d. An energy inequality in one unknown is resolved using a numerical approach based on desired annual number of diesel generator hours. PVHS were obtained for all desired annual generator hours. These results are in line previous studies. PV array ratings of 43.56kWp and 23.76 kWp were found at renewable energy fractions of 0.577 and 0.998 respectively and diesel generator hours were determined as 9h/yr and 1309 hr/yr respectively. Considering the high initial costs for the implementation of PVHS with a renewable energy fraction of almost 100%, PVHS implementation can begin with 55% PV rating and then expanded. PVHS implementation with expandable PV array can therefore be adopted for electrification of remote villages in Far North Cameroon and Sub-Saharan Africa which have high solar radiation levels. The diesel generator with low annual

generator hours can respond to growth in energy demand following electrification. A pilot PVHS system with grid-interconnection can be implemented in Bambui, Cameroon (6° 01' N, 10° 17' E) which has a solar insolation estimated at 5.36 kWh/m²/d given that a 100 Wp solar home system implemented by a grid-connected home supplies energy to dc and ac loads satisfactorily since 2015 [11]. The implementation of a PVHS project in Bambui would supply electrical energy to rural schools, industries, businesses during the day and to rural homes at night during prolonged grid failures.

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Biography

Dr. E. M. NFAH obtained a Bachelor’s of Engineering Second Class Upper Division in 1995 and also a Master’s of Engineering in Electrical/Electronics Engineering in 1997 from the University of Benin, Nigeria. In the grade of Assistant Lecturer at the FOTSO Victor Institute of Technology Bandjoun of the University of Dschang, Cameroon, he obtained the Diplome d’Etudes Approfondies and PhD in Electrical Engineering from the National Advanced School of Engineering of the University of Yaounde I in 2003 and 2007 respectively. In December 2008, he was promoted to grade of Lecturer and was appointed as the Head of Department of Electrical and Power Engineering at the Higher Technical Teacher Training College and Head of Development Division in the Directorate of Development, Physical Plant and Infrastructure of The University of Bamenda in December 2011. In November 2015 he was promoted to the grade of Associate Professor and was appointed Head of Department of Electrical and Electronic Engineering at the College of Technology of The University of Bamenda.

He is a researcher in the area of Renewable Energy. The results of his research findings have resulted in nine publications in international peer reviewed journals. He has attended national and internal conferences to present his research findings in the area of Renewable Energy. The national and sub-regional dimension of his research contributed to the award of a 10-month post-doctoral study at université Catholique de Louvain-la-Neuve, Belgium by “Agence Universitaire de la Francophonie” for the 2009-2010 academic year. His current research activities involve evaluation of photovoltaic systems for energy security of urban homes and public buildings and industries. The economics of these systems for poverty alleviation is also of interest since this will facilitate the deployment of these technological options which have high initial costs.