2014-9

An Assessment of the Energy Generation Potential of Photovoltaic Systems in Cameroon Using Satellite-Derived Solar Radiation Datasets

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Recommended Citation

Ayompe, L. and Duffy, A. (2014) An assessment of the energy generation potential of photovoltaic systems in Cameroon using satellite-derived solar radiation datasets, *Sustainable Energy Technologies and Assessments*, Volume 7, September 2014, Pages 257-264. doi:10.1016/j.seta.2013.10.002

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Sustainable Energy Technologies and Assessments xxx (2013) xxx–xxx

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Sustainable Energy Technologies and Assessments

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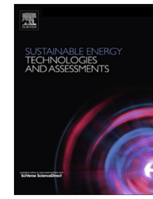

Original Research Article

An assessment of the energy generation potential of photovoltaic systems in Cameroon using satellite-derived solar radiation datasets

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ARTICLE INFO

Article history:
Received 25 January 2013
Revised 28 September 2013
Accepted 7 October 2013
Available online xxxx

Keywords:
Photovoltaic system
Solar irradiation datasets
Energy output
Simple payback period
Levelised cost of electricity

ABSTRACT

Cameroon like most developing countries does not have a reliable network of surface observation stations for collecting weather data. This has been a major drawback for accurate assessment of the energy generation potential of photovoltaic systems in Cameroon. A viable alternative is to obtain site-specific solar irradiation from satellite-derived datasets. In this paper, the energy output, capacity factor and performance ratio of photovoltaic systems in 33 locations spread around ten regions in Cameroon have been evaluated using monthly average daily global horizontal solar irradiation from long-term satellite-derived data available in Solar GIS software.

An economic assessment revealed that a simple payback period of 5.6 years and levelised cost of electricity generation of 6.79 €c/kWh can be achieved in locations with annual electricity generation of 1764 kWh/kW$_p$ if the capital cost of the PV system is 1500 €/kW$_p$ at a discount rate of 5%. Alternatively, the simple payback period would be 15.7 years and the levelised cost of electricity generation 28.82 €c/kWh if the capital cost is 2500 €/kW$_p$ at a discount rate of 10% in locations with annual electricity generation of 1053 kWh/kW$_p$.

Introduction

Cameroon is a Sub-Saharan country covering a total surface area of 475,440 km^2. It is located at latitude 6° 0′0″N and longitude 12° 0′0″E with parts in the central and western parts of Africa. Its population was estimated at 20.1 million in July 2012 with an annual growth rate of 2.1%. 58% of its population lives in urban areas and the annual urbanisation growth rate is 3.3%. There are ten regions in Cameroon with Yaoundé and Douala the largest cities having 1.74 and 2.05 million inhabitants, respectively [1].

The electricity sector in Cameroon is facing both structural and technical difficulties. Out of over 14,000 localities, about 3000 are electrified resulting in a national electrification rate of 22% while the rate of rural electrification is 3.5%. The low rate of electrification has been a major handicap to the production of goods and services [2]. The Government of Cameroon has outlined plans to address this issue in its development vision up to 2035 which aims at reducing poverty and transforming it into an emerging country. Upgrading its energy infrastructure is a key requirement to the achievement of this objective [3].

Increase in global fossil fuel prices have resulted in a rise in the retail price of electricity in Cameroon. Between 2008 and 2012, retail electricity prices increased by an annual average of 4.0%. Therefore, there is a need to explore other energy resources such as renewable energy sources (RES) with low environmental impact.

RES in Cameroon include biomass, solar energy, hydro power, geothermal energy, wind and tidal energy. Despite the availability of a variety of RES only hydro power has been widely exploited for electricity generation. Abanda [4] reported that very little research has been undertaken to evaluate the potential of RES in Cameroon. Literature on different types of RES, their benefits and market potential is therefore very limited or non-existent resulting in an information gap for researchers, potential investors and policy makers. He therefore recommended that there is a need to scale-up research in the development of RES in Cameroon in order to provide information required for evidence-based energy policy formulation that would encourage their adoption in the country's energy mix.

Cameroon is endowed with vast solar energy potential with about 900 trillion kWh of solar energy reaching its land area per annum. Tchinda and Kaptouom [5] reported that the Northern and Southern regions of Cameroon received between 4.00 and 5.80 kWh/m^2 d while Tansi [6] reported that Southern regions typically receive 4.90 kWh/m^2 d. Photovoltaic technologies can be employed to harness this energy and generate power on both a centralized and distributed basis. PV systems are scalable so they can either be used to generate electricity for on-site use in

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2213-1388/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.seta.2013.10.002

Nomenclature

CAPEX	capital investment cost (€)
CF	capacity factor (dimensionless)
d	annual discount rate expressed as the weighted average cost of capital (WACC)
E_{AC}	total AC energy generated by the PV system (kWh)
G_n	net generation in operating year "n" (kWh)
G_m	total incident solar insolation on the PV modules (kWh)
N	operating system life
n	operating year
OPEX	operation and maintenance cost (€)
PR	performance ratio (dimensionless)
$P_{PV,rated}$	installed PV system capacity (kW)
η_{STC}	PV module efficiency (as a fraction) under STC (dimensionless).

domestic dwellings and commercial buildings or exported to the national grid.

Electricity market

In 2010, AES-SONEL an integrated utility company operated 925 MW of generation capacity, three transmission networks and distributed electricity to approximately 700,000 customers under a 20-year concession agreement that was signed in July 2001. It has exclusive distribution rights to all medium voltage and low voltage customers, except for customers with an installed capacity of more than 1 MW ("Major Customers") who are free to negotiate bilateral agreements. Electricity generation in Cameroon is open to competition and independent power producers (IPPs) are authorised to generate and sell electricity to AES-SONEL under a power purchase agreement [7].

AES-SONEL operates three transmission grids: the southern interconnected grid (SIG); northern interconnected grid (NIG); and eastern isolated grid (EIG) through which all electricity generated is transmitted for distribution to its customers. Fig. 1 shows the electric power demand, installed and available capacity in the SIG, NIG and EIG in 2010 in Cameroon. The total electric power installed capacity was 1505 MW of which 1242 was available while the demand was 736 MW. The SIG had the highest electric power demand, installed and available capacity of 654, 1321 and 1090 MW, respectively followed by the NIG and EIG. The national grid is discontinuous thereby preventing the transfer of electricity between the three grids.

In 2010, the installed capacity of hydroelectric power plants in Cameroon was 729 MW (48.4%) of which 620 MW was available for use as shown in Table 1 Thermal power plants (natural gas and diesel) owned by both AES-SONEL and IPPs had an installed capacity of 776 MW (51.6%) of which 622 MW was available. There was no other type of renewable energy technology used in electric power generation in Cameroon in 2010.

Planned investments

Demand for electricity in Cameroon is estimated to reach 1455 MW in 2014 and almost 5000 MW in 2020 taking into consideration the unmet demand due to the low rate of electrification and access to the electricity grid as well as the needs of major industrial projects required to transform the country's economy. Greenhouse gas (GHG) emissions associated with electricity generation in Cameroon was estimated at 0.86 tCO_2/MW compared to the global average of 0.57 tCO_2/MW [2]. This high carbon intensity is as a result of the use of thermal plants based on diesel and heavy oils.

In order to meet the projected increase in domestic electricity demand and that of neighbouring countries while reducing its GHG emissions, the government of Cameroon prepared an Electricity Sector Development Plan (ESDP) up to 2030. The Plan involves ensuring consistency in the development of electricity supply and demand in the context of the country's economic growth. The plan for the development of power generating plants consists of installing about 2500 MW of hydroelectric power between 2012 and 2020 and 298 MW of electricity from thermal plants between 2010 and 2013.

Recently, the government of Cameroon recognised photovoltaics (PV) as a viable source of electricity generation. In July 2012, it signed a memorandum of understanding with a private developer to finance, develop, build and operate 500 MW of grid connected and stand-alone solar photovoltaic systems between 2012 and 2020. The first phase of this project consisting of 100 MW of

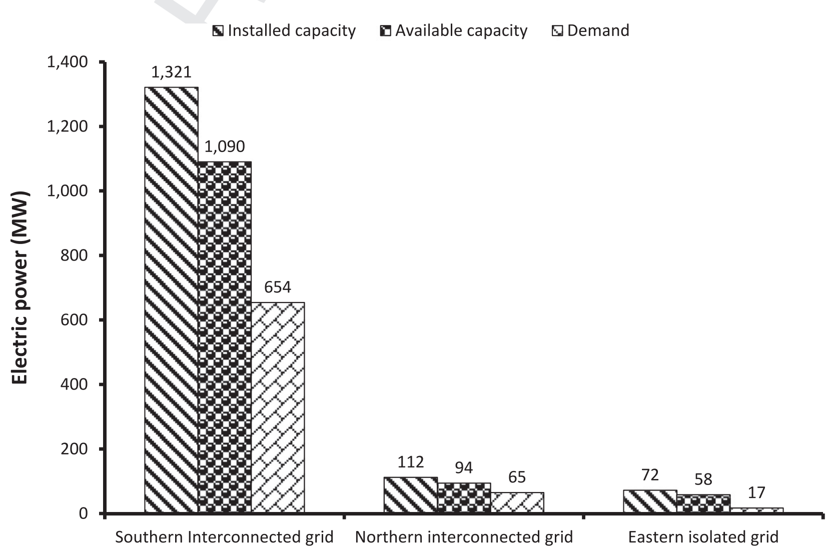

Fig. 1. Installed capacity, available capacity and demand of electric power in 2010 in Cameroon.

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Table 1
Installed and available capacity (MW) of electric power plants in Cameroon in 2010 [2].

Plant Type	Owner	Southern interconnected grid		Northern interconnected grid		Eastern isolated grid		Total	
		Installed capacity	Available capacity	Installed capacity	Available Capacity	Installed capacity	Available capacity	Installed capacity	Available capacity
Thermal	AES-SONEL	268	214	19	16	12	10	299	240
Thermal	IPP	396	317	21	17	60	48	477	382
Hydro	AES-SONEL	657	559	72	61	0	0	729	620
Total		1321	1090	112	94	72	58	1505	1242
Percentage of hydro		49.7	51.3	64.3	64.9	0.0	0.0	48.4	49.9
Demand			654		65		17		

grid connected PV systems was due to commence in October 2012. It is expected that these systems would generate 145,000 MW of electricity annually.

Rationale for PV

From the above, it is seen that despite the enormous solar energy potential available in Cameroon, government policies towards increasing the quantity of electricity generation have largely been in favour of hydro and thermal power plants. Considering that the two main hydroelectric plants in Edea and Song Loulou with installed capacities of 263 and 394 MW had underperformed due to extended droughts between 2000 and 2003 which resulted in load shedding, it is imperative that Cameroon cannot rely to a large extent on its hydro potential. Thermal plants emit large quantities of GHGs and are subject to fossil fuel price fluctuations. Similarly, continuous increase in the cost of fossil fuels would result in an increase in the cost of electricity generation from thermal plants while emitting GHGs.

Electricity generation using PV systems on the other hand uses solar energy which is free and not prone to price fluctuations. PV systems generate electricity with no GHG emissions, so they would contribute towards reducing the CO_2 intensity of electricity generation in Cameroon. Solar radiation in most parts of Cameroon is highest during the dry season when water levels are low and electricity generation using hydro power plants is at its minimum. It therefore has the potential to mitigate the impact of reduced electricity generation from hydro power plants during the dry season. Also, the electricity generation profile from PV systems would suit the consumption profile in most commercial buildings.

Photovoltaic systems have large initial capital cost but small recurrent costs for operation and maintenance. The price of delivered energy varies inversely to the lifetime of the system. Proven technologies such as silicon-based modules exhibit lifetimes of 20–30 years or more [8]. Over the years, the cost of PV modules have decreased at a learning rate of 15–22% [9] and have seen a corresponding reduction in total system costs for every doubling of cumulative installed capacity. The European Photovoltaic Industry Association (EPIA) [10] estimates that the cost of electricity generated from PV systems would become competitive with grid supplied electricity in some sunny climates with similar solar insolation as Cameroon by 2015. The actual period when this parity occurs depends on the cost of PV systems in different countries as well as support policies in place.

Methodology

It is evident that Cameroon has to diversify its energy mix in electricity generation in order to satisfy future demand while reducing its GHG emissions. Exploiting RES such as solar energy using PV systems is therefore imperative. This paper therefore assesses the energy generation potential of PV systems with crystalline silicon (c-Si), amorphous silicon (a-Si) and cupper indium selenide (CIS) PV modules in different locations in Cameroon.

With no reliable ground measurements in Cameroon, the paper compares ground measurements of monthly average daily global horizontal irradiation (GHI) for 22 cities in six neighbouring countries against satellite-derived data from three commercially available softwares. The best dataset for locations in Cameroon was selected as that with the lowest root mean square error. Energy output prediction from Solar GIS pvPlanner software [11] was validated using measured performance data for a PV system. The software was then used to evaluate the energy generated by PV systems with optimally inclined PV modules.

An economic analysis was undertaken to evaluate the conditions under which investment in PV systems would be viable in Cameroon. Simple payback periods and levelised costs of electricity generation were computed for a range of capital costs, discount rates, normalised annual electricity generation and electricity tariff for consumers with annual electricity demand exceeding 800 kWh.

Solar resource

It has long been understood that high-quality time-series solar irradiation data is crucial to the successful design and deployment of solar energy systems since it is the variable which has the greatest impact on electrical power output [12]. Site-specific climatic data is important since design details and economic feasibility are a direct function of variables such as the local solar resource, in both magnitude (high irradiance) and quality (low variability and high predictability) [13]. The key variable for fixed panel PV systems is global horizontal irradiance (GHI), or the amount of radiation received by a horizontal surface.

Little research has been carried out to measure solar irradiation in different locations in Cameroon. Njomo [14] measured solar irradiation in ten meteorological stations in Cameroon between 1982 and 1987. In another study Njomo and Wald [15] compared ground measurements for Yaoundé and Garoua against satellite-derived solar irradiation using the Heliosat_2 method. Their analysis showed that there was good agreement between the measured and satellite-derived data for Garoua (with semi-arid surface and uniformly dry atmosphere) while there was large variability in Yaoundé (forest type surface with a humid and persistently cloudy atmosphere).

It is therefore evident that data obtained from ground measurements in Cameroon is either non-existent or available for short intervals and unreliable because of maintenance issues with malfunctioning devices which were poorly attended. In such cases, calculating site-specific solar irradiance values using satellite-derived data has become an accepted alternative. Within the global atmospheric science community, satellite-derived values have proven to be more accurate than nearby surface observations for locations that are more than 25 km away from a well-maintained ground station. However, there exists a number of satellite-derived solar

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Table 2
Annual average daily wind speed, ambient air temperature and GHI for different locations in Cameroon [11].

Location	Region	Latitude (°)	Longitude (°)	Elevation (m)	Wind speed (m/s)	Ambient air temperature (°C)	Annual average daily GHI (kWh/m^2 d)
Banyo	Adamawa	6.8	11.8	1,123	2.8	21.3	5.82
Meiganga	Adamawa	6.5	14.3	990	3.2	23.1	5.76
Ngoundéré	Adamawa	7.3	13.6	1162	3.3	21.5	5.77
Tibati	Adamawa	6.5	12.6	332	3.2	23.6	5.78
Akonolinga	Centre	3.8	12.3	634	1.4	23.0	4.94
Bafia	Centre	4.8	11.2	517	1.8	24.4	5.22
Abong Mbang	East	4.0	13.2	693	1.5	22.9	4.94
Batouri	East	4.4	14.4	637	2.0	24.4	5.27
Bertoua	East	4.6	13.7	661	1.9	23.6	5.18
Yokadouma	East	3.5	15.1	566	1.7	24.0	5.20
Maroua	Far North	10.6	14.3	404	3.8	28.8	5.99
Mokolo	Far North	10.8	13.8	432	3.7	24.0	5.92
Mora	Far North	11.0	14.1	608	3.9	26.1	5.99
Yagoua	Far North	10.4	15.2	322	3.9	28.9	5.97
Douala	Littoral	4.1	9.7	11	1.8	26.2	4.76
Edea	Littoral	3.8	10.1	31	1.5	25.7	4.71
Garoua	North	9.3	13.4	185	3.5	29.3	5.81
Garoua Boulai	North	5.9	14.6	1002	2.8	22.9	5.62
Tchollíré	North	8.4	14.2	332	3.4	26.2	5.81
Bamenda	North West	6.0	10.2	1255	1.9	18.7	5.36
Kumbo	North West	6.2	10.7	1739	2.3	17.5	5.55
Wum	North West	6.4	10.1	1034	2.3	21.0	5.32
Akom	South	2.8	10.6	316	1.5	22.3	4.72
Ebolowa	South	2.9	11.1	591	1.4	22.3	4.84
Kribi	South	2.9	9.9	20	1.8	25.4	4.85
Buea	South West	4.2	9.2	984	1.8	22.1	4.00
Fontem	South West	5.5	9.9	1046	1.8	20.2	4.35
Kumba	South West	4.6	9.5	226	1.8	25.2	4.85
Mamfe	South West	5.8	9.3	88	1.8	24.8	4.96
Mundemba	South West	5.0	8.9	147	2.2	26.2	4.40
Muyuka	South West	4.3	9.4	47	1.8	25.5	4.73
Nguti	South West	5.3	9.4	231	1.8	23.1	4.94
Baffousam	West	5.5	10.4	1384	1.9	19.1	5.63

radiation datasets that provide estimates for different locations in Cameroon. Selecting the most suitable dataset is important for energy output assessment from PV systems.

In order to choose the best dataset for locations in Cameroon, a comparison of ground measurements of average daily global horizontal irradiation for 22 cities in Burkina Faso (5), Ghana (6), Guinea (2), Mauritania (3), Nigeria (3) and Senegal (3) against satellite-derived solar radiation datasets from three commercially available software which include: Solar GIS, Solar radiation data (SoDa), National Aeronautics and Space Administration (NASA) was undertaken. The results showed that the mean bias errors (MBE) were 2.5%, 2.7% and −6.7% while the root mean square errors (RMSE) were 7.9%, 9.3% and 13.1% for Solar GIS, NASA and SoDa datasets, respectively. The Solar GIS dataset [11] was chosen as the best because it had the lowest MBE and RMSE. The positive MBE shows that it overestimates with maximum average deviation of 7.9%. Predicted PV energy outputs used in the economic analysis were therefore reduced by 7.9%.

Table 2 shows satellite-derived annual average daily GHI available in Solar GIS for different locations in Cameroon. Solar irradiation varies between 4.00 kWh/m^2 d in Buea (South West Region) and 5.99 kWh/m^2 d in Maroua and Mora (Far North Region). The lowest average annual wind speed is 1.4 m/s in Akonolinga (Center Region) and Ebolowa (South Region) while the highest average annual wind speed is 3.9 m/s in Mora and Yagoua (Far North Region). The annual average ambient air temperature varies between 17.5 °C in Kumbo (North West Region) and 29.3 °C in Garoua (North Region).

Energy performance of PV systems

In order to analyse the energy-related performance of PV systems, some important parameters must be computed using weather data for the location of interest. Some of these parameters include: the total AC energy generated by the PV system (E_{AC}); the performance ratio (PR) and the capacity factor (CF). These normalised performance indicators are relevant since they provide a basis under which PV systems can be compared under various operating conditions.

Table 3 shows the optimum inclination of PV modules; annual average daily GHI; global irradiation on the surface of the PV modules; average daily energy output, PR and CF for c-Si, a-Si and CIS PV modules. It is seen that optimally inclined PV modules receive more irradiation than those on horizontal surfaces. The lowest optimum inclination angle is 5° in the South Region while the highest is 15–16° in the Far North Region.

Energy output assessment

Predicting the energy output from a PV system is a matter of combining the characteristics of the major components, that is, the PV array and the inverter with local insolation and temperature data. Energy output prediction using Solar GIS's pvPlanner tool was validated using measured data reported in Ayompe et al. [16]. The pvPlanner tool was therefore used to model the energy output from the PV systems assuming: 95% inverter euro efficiency, 5.5% DC losses, 1.5% AC losses and 99% availability.

It is seen in Table 3 that the energy output is highest for a-Si followed by CIS and c-Si PV modules for all the locations considered in this study. The average daily energy output has lowest values of 3.13, 3.28 and 3.15 kWh/kW_p in Buea (South West Region) and highest values of 4.74, 5.25 and 4.74 kWh/kW_p in Mora (Far North Region) for c-Si, a-Si and CIS PV modules, respectively. These would result in annual energy output ranging between 1143 and 1916 kWh/kW_p. Considering that the Solar GIS dataset overestimates average daily GHI by an average of 7.9%, the energy output range was reduced to 1053 and 1764 kWh/kW_p. The economic

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Table 3
Annual average daily energy output, performance ratio and capacity factor for PV module technologies in different locations in Cameroon.

Location	Region	Optimum inclination (°)	Solar GIS annual average daily GHI (kWh/m^2 d)	Global radiation on PV surface (kWh/m^2 d)	Energy output (kWh/kW$_p$)			Performance ratio (%)			Capacity factor (%)		
					c-Si	a-Si	CIS	c-Si	a-Si	CIS	c-Si	a-Si	CIS
Banyo	Adamawa	11	5.82	5.92	4.56	5.05	4.65	77.0	85.4	78.5	19.0	21.1	19.4
Meiganga	Adamawa	11	5.76	5.86	4.47	4.99	4.56	76.2	85.1	77.8	18.6	20.8	19.0
Ngoundéré	Adamawa	13	5.77	5.90	4.54	5.03	4.63	77.0	85.3	78.4	18.9	21.0	19.3
Tibati	Adamawa	11	5.78	5.79	4.46	5.00	4.56	76.0	85.1	77.6	18.6	20.8	19.0
Akonolinga	Centre	6	4.94	4.97	3.83	4.20	3.88	77.1	84.5	78.2	16.0	17.5	16.2
Bafia	Centre	7	5.22	5.26	4.03	4.45	4.10	76.7	84.7	77.9	16.8	18.6	17.1
Abong Mbang	East	7	4.94	4.97	3.83	4.20	3.89	77.1	84.5	78.2	16.0	17.5	16.2
Batouri	East	7	5.27	5.31	4.06	4.51	4.13	76.4	84.9	77.8	16.9	18.8	17.2
Bertoua	East	8	5.18	5.22	4.01	4.43	4.08	76.8	84.8	78.0	16.7	18.5	17.0
Yokadouma	East	6	5.20	5.23	4.00	4.44	4.07	76.6	84.9	77.9	16.7	18.5	17.0
Maroua	Far North	15	5.99	6.17	4.59	5.20	4.71	74.4	84.3	76.3	19.1	21.7	19.6
Mokolo	Far North	15	5.92	6.10	4.61	5.20	4.72	74.0	83.5	75.8	19.2	21.7	19.6
Mora	Far North	16	5.99	6.19	4.74	5.25	4.74	74.6	84.5	76.5	19.7	21.9	19.7
Yagoua	Far North	15	5.97	6.14	4.57	5.18	4.68	74.3	84.2	76.2	19.0	21.6	19.5
Douala	Littoral	6	4.76	4.78	3.64	4.02	3.70	76.1	84.1	77.3	15.2	16.8	15.4
Edea	Littoral	6	4.71	4.73	3.63	3.97	3.68	76.6	83.8	77.7	15.1	16.5	15.3
Garoua	North	13	5.81	5.96	4.42	5.01	4.53	74.1	84.0	76.0	18.4	20.9	18.9
Garoua Boulai	North	10	5.62	5.62	4.36	4.84	4.44	76.4	84.9	77.9	18.2	20.2	18.5
Tchollíré	North	13	5.81	5.94	4.43	5.01	4.54	74.6	84.3	76.4	18.5	20.9	18.9
Bamenda	North West	10	5.36	5.44	4.25	4.59	4.34	78.2	84.4	79.4	17.7	19.1	18.1
Kumbo	North West	11	5.55	5.64	4.43	4.78	4.49	78.8	84.7	79.7	18.5	19.9	18.7
Wum	North West	11	5.32	5.40	4.18	4.57	4.25	77.5	84.8	78.8	17.4	19.1	17.7
Akom	South	5	4.72	4.74	3.69	3.98	3.73	77.8	83.8	78.8	15.4	16.6	15.6
Ebolowa	South	5	4.84	4.85	3.78	4.08	3.82	77.8	84.1	78.8	15.7	17.0	15.9
Kribi	South	5	4.85	4.87	3.75	4.10	3.80	76.9	84.2	78.0	15.6	17.1	15.8
Buea	South West	6	4.00	4.01	3.13	3.28	3.15	77.8	81.4	78.3	13.1	13.1	13.1
Fontem	South West	10	4.35	4.39	3.46	3.62	3.46	78.6	82.2	78.6	14.4	15.1	14.4
Kumba	South West	6	4.85	4.87	3.73	4.11	3.78	76.5	84.4	77.7	15.5	17.1	15.8
Mamfe	South West	8	4.96	5.00	3.82	4.22	3.88	76.4	84.4	77.6	15.9	17.6	16.2
Mundemba	South West	7	4.40	4.42	3.37	3.71	3.41	76.1	83.9	77.1	14.0	15.5	14.2
Muyuka	South West	6	4.73	4.75	3.65	3.98	3.69	76.8	83.9	77.8	15.2	16.6	15.4
Nguti	South West	8	4.94	4.97	3.84	4.21	3.90	77.2	84.5	78.4	16.0	17.5	16.2
Baffousam	West	9	5.63	5.69	4.46	4.83	4.53	78.2	84.8	79.5	18.6	20.1	18.9

analysis undertaken in this paper therefore considered annual electricity generation between 1053 and 1764 kWh/kW$_p$.

Performance ratio

The performance ratio (PR) indicates the overall effect of losses on a PV array's normal power output and depends on its temperature, incomplete utilisation of incident solar radiation and system component inefficiencies or failures. The PR of a PV system indicates how close it approaches ideal performance during real operation and allows comparison of PV systems independent of location, tilt angle, orientation and their nominal rated power capacity [17,18]. Performance ratio is defined by the following equation [19,20]:

$$\mathrm{PR} = \frac{E_{AC}}{G_m \eta_{STC}} \quad (1)$$

It is seen in Table 3 that the PR for c-Si PV modules varied between 74.0% in Mokolo (Far North Region) and 78.8% in Kumbo (North West Region). For a-Si PV modules, the PR varied between 81.4% in Buea (South West Region) and 85.4% in Banyo (Adamawa Region) while for CIS PV modules the PR varied between 75.8% in Mokolo (Far North Region) and 79.7% in Kumbo (North West Region). It is seen that c-Si and CIS PV modules have higher PR in locations with low annual average ambient air temperature because of their negative temperature coefficient. c-Si PV modules have higher temperature coefficients than CIS PV modules so this results in lower PR under high ambient temperatures. a-Si has the highest PR in all locations due to their low temperature coefficient compared to that of c-Si and CIS PV modules.

Capacity factor

The capacity factor (CF) or capacity utilisation factor (CUF) is a means used to present the energy delivered by an electric power generating system. If the system delivers full rated power continuously, its CF would be unity. CF is defined as the ratio of the actual annual energy output to the amount of energy the PV system would generate if it operated at full rated power ($P_{PV,rated}$) for 24 h per day for a year and is given as [21]:

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$$CF = \frac{E_{AC}}{P_{PV,rated} \times 8760} \quad (2)$$

Table 3 shows that the CF for c-Si, a-Si and CIS PV modules had lowest values of 13.1%, 13.6% and 13.1% in Buea (South West Region) and highest values of 19.7%, 21.9% and 19.7% in Mora (Far North Region), respectively. The CF is highest in the North, Far North and Adamawa regions while it is lowest in the South and South West regions.

Economic analysis

The economic analysis undertaken in this paper consists of evaluating the simple payback periods and levelised costs of electricity generation from PV systems in Cameroon. It is assumed that the normalised electricity output from the PV systems would vary between 1053 and 1764 kWh/kW$_p$/yr depending on the location where they are installed. Annual electricity output is assumed to decrease by 0.5% over the service life of the PV system. The installed costs of the PV systems are considered to vary between 1500 and 2500 €/kW$_p$. The analyses are based on grid connected commercial and industrial consumers with annual electricity demand greater than 800 kWh with electricity purchase cost of 15.09 €c/kWh.

It is assumed that the PV systems will be installed in premises with electricity loads that coincide with generation from PV systems. As a consequence, all the electricity generated by the PV systems would be used on-site with shortfalls imported from the grid. The PV systems are assumed to have a useful service life of 30 years with annual operation and maintenance cost of 2% of the initial investment. 5% and 10% discount rates are used to compute the levelised cost of electricity generation. A summary of the parameters used in the economic analyses are shown in Table 4.

Table 4
Parameters used in the economic analysis.

Parameter	Value	Unit
Annual electric energy generation	1053–1764	kWh/kW$_p$/yr
Capital cost	1500–2500	€/kW$_p$
Electricity price	0.1509	€/kWh
System life	30	Years
Annual O&M percentage of capital cost	2	%
Discount rate	5 and 10	%
Annual PV output degradation	0.5	%

Simple payback period

The simple payback period is the period of time required for the profit or other benefits of an investment to equal the cost of the investment. For an investment in PV systems it would represent the time it takes for the cumulative annual investment to equal the initial investment. Fig. 2 shows the simple payback period against capital cost for PV systems installed in locations with annual electricity generation of 1053 and 1764 kWh/kW$_p$. It is seen that the simple payback period would vary between 5.6 and 9.4 years, 7.5 and 12.6 years, and 9.4 and 15.7 years for an installed cost of 1500, 2000 and 2500 €/kW$_p$, respectively in locations with annual electricity generation of 1764 and 1053 kWh/kW$_p$.

Levelised cost of electricity

Levelised cost of electricity (LCoE) is the most transparent consensus measure and remains a widely used tool for comparing the unit costs of different technologies over their economic life in modelling and policy discussions. It corresponds to the cost of an investor assuming the certainty of production costs and the stability of electricity prices. Thus, if the electricity price is equal to the levelised average lifetime costs, an investor would precisely breakeven on the project. The discount rate reflects the return on capital for an investor in the absence of specific market or technology risks. The discount rate and electricity price are assumed constant during the lifetime of the project under consideration while all electricity generated is assumed to be sold at the LCoE. LCoE is expressed as [22]:

$$LCoE = \frac{CAPEX + \sum_{n=1}^{N} OPEX_n (1+d)^{-n}}{\sum_{n=1}^{N} G_n (1+d)^{-n}} \quad (3)$$

Fig. 3 shows the LCoE generation against capital costs for location with 1053 and 1764 kWh/kW$_p$/yr annual electricity generation, at 5% and 10% discount rates. It is seen that for a PV system

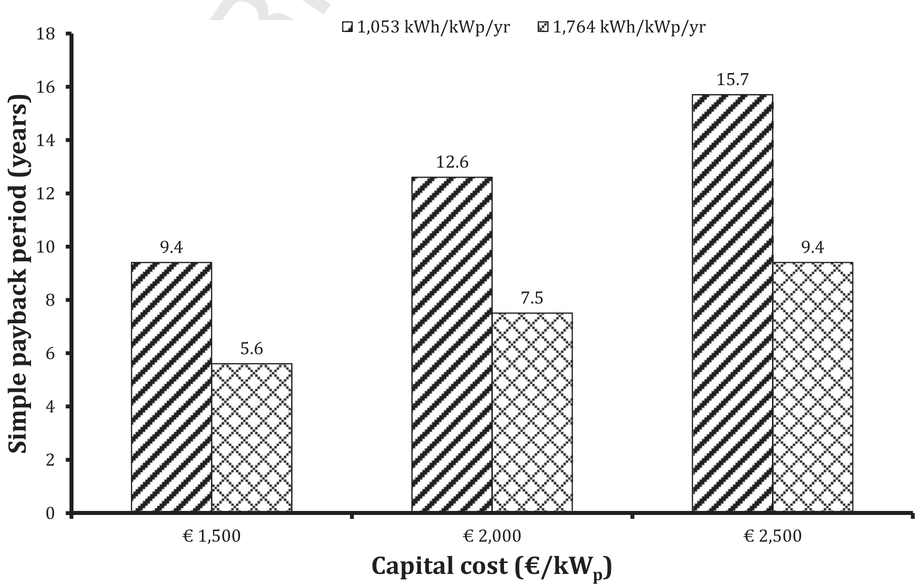

Fig. 2. Simple payback against capital cost for different annual electricity generation.

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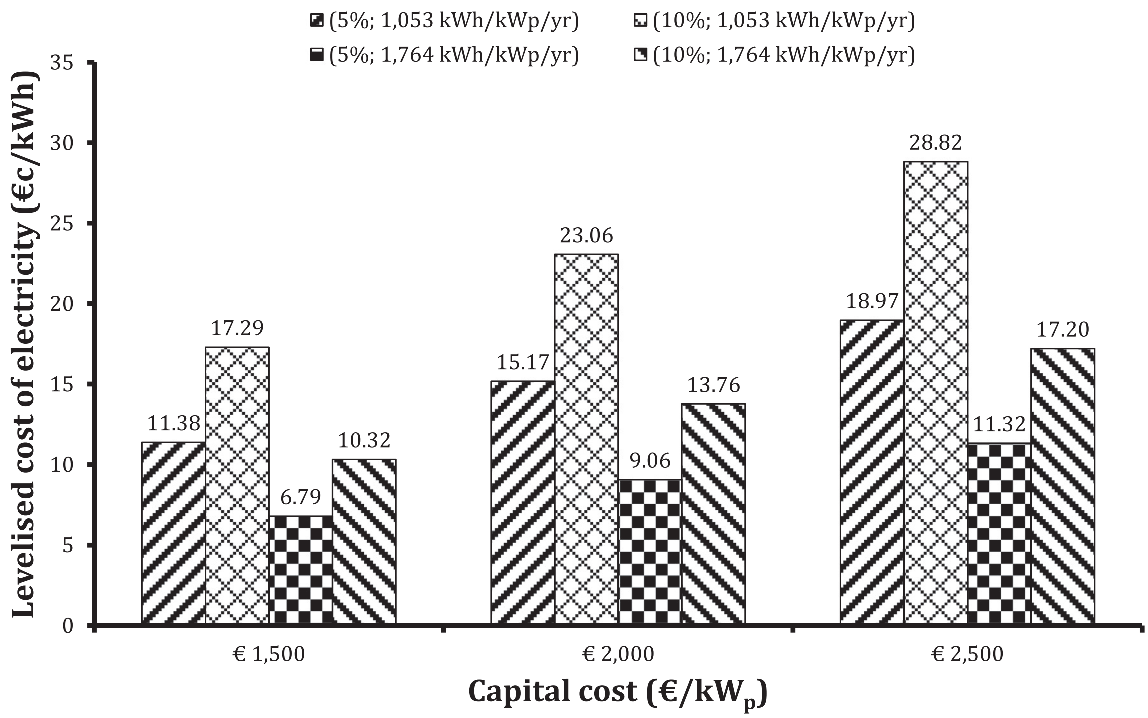

Fig. 3. Levelised cost of electricity generation against capital costs.

capital cost of 1500 €/kW$_p$ the LCoE generation would vary between 11.38 and 17.29 €c/kWh for 5% and 10% discount rates in locations with annual electricity generation of 1053 kWh/kW$_p$/yr. In locations with annual electricity generation of 1764 kWh/kW$_p$/yr the LCoE generation would vary between 6.79 and 10.32 €c/kWh for 5% and 10% discount rates. For a PV system capital cost of 2000 €/kW$_p$ the LCoE generation would vary between 15.17 and 23.06 €c/kWh for 5% and 10% discount rates in locations with annual electricity generation of 1053 kWh/kW$_p$/yr. In locations with annual electricity generation of 1764 kWh/kW$_p$/yr the LCoE generation would vary between 9.06 and 13.76 €c/kWh for 5% and 10% discount rates. Finally, for a PV system capital cost of 2500 €/kW$_p$ the LCoE generation would vary between 18.97 and 28.82 €c/kWh for 5% and 10% discount rates in locations with annual electricity generation of 1053 kWh/kW$_p$/yr. In locations with annual electricity generation of 1764 kWh/kW$_p$/yr the LCoE generation would vary between 11.32 and 17.20 €c/kWh for 5 and 10% discount rates.

Conclusion

Energy performance data of PV systems are of extreme importance to investors and project developers who are keen on setting up PV plants. The lack of reliable performance data for PV plants in locations such as Cameroon that are endowed with adequate solar resource has been a contributing factor towards the hesitance of both individuals, businesses, utility operators and independent power producers to invest in PV systems.

In this paper, the energy output, capacity factor and performance ratio of photovoltaic systems in 33 locations spread around ten regions in Cameroon were evaluated using monthly average daily global horizontal solar irradiation from long-term satellite-derived data available in Solar GIS software. Optimally inclined PV modules with crystalline silicon, amorphous silicon and copper indium selenide were considered in the study. For all 33 locations amorphous silicon PV modules had the highest energy output, performance ratio and capacity factor followed by cupper indium selenide and crystalline silicon.

The lowest average daily energy output was 3.13 kWh/kW$_p$ for c-Si PV modules installed in Buea (South West Region) while the highest average daily energy output was 5.25 kWh/kW$_p$ for a-Si PV modules installed in Mora (Far North Region). The PR varied between 74.0% for c-Si PV modules installed in Mokolo (Far North Region) and 85.4% for a-Si PV modules installed in Banyo (Adamawa Region). The lowest CF was 13.1% for c-Si and CIS PV modules in Buea (South West Region) while the highest CF was for a-Si PV modules installed in Mora (Far North Region).

The simple payback periods and levelised costs of electricity generation were computed for a range of capital costs, discount rates, normalised annual electricity generation and electricity tariff for consumers with annual electricity demand exceeding 800 kWh. Results from the economic evaluation revealed that a simple payback period of 5.6 years and levelised cost of electricity generation of 6.79 €c/kWh can be achieved in locations with annual electricity generation of 1764 kWh/kW$_p$ if the capital cost of the PV system is 1500 €/kW$_p$ at a discount rate of 5%. Alternatively, the simple payback period would be 15.7 years and the levelised cost of electricity generation 28.82 €c/kWh if the capital cost is 2500 €/kW$_p$ at a discount rate of 10%.

The return on investment would vary for different customers based on their location, investment cost, cost of capital (discount rate) and electricity tariff. With the levelised cost of electricity generation from PV competing favourably against the cost of grid supplied electricity under certain scenarios, the government of Cameroon should consider facilitating the deployment of PV in commercial buildings with loads that match PV generation. Such policies could include: exempting PV related equipment from custom duties until the market matures, providing low interest loans for the purchase of PV equipment, and providing capital cost grants in the form of tax breaks.

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