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Performance analysis of different grid-connected solar photovoltaic (PV) system technologies with combined capacity of 20 kW located in humid tropical climate

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ABSTRACT

Objective: This study presents the outdoor performance of five solar photovoltaic (PV) systems with five different solar cell technologies (poly-crystalline (pc-Si)), mono-crystalline (mc-Si), Copper Indium disulfide (CIS) thin-film, Amorphous Silicon (a-Si), and Heterojunction Incorporating thin (HIT) film.

Methods: The PV systems are installed on rooftop of buildings at the Kwame Nkrumah University Science and Technology, Ghana. The systems' energy output in 2014, module temperature as well as environmental data were collected and analysed.

Results: The total annual energy delivered to the grid varies between 3133.2 kWh for CIS and 4572.1 kWh for pc-Si while the performance ratio varies from 48.84% (CIS) to 71.26% (for p-Si). The annual energy density ranges between 45.7 kWh/m^2 for CIS and 195.8 kWh/m^2 for HIT. The total actual energy delivered to the grid by all the systems in 2014 is 20.62 MWh.

Conclusions: The performance data shows, that, the CIS technology is least suitable while p-Si is the most suitable solar PV technology for the site considered, followed by a-Si, HIT and mc-Si respectively. If space is a constraint, then, the HIT based system is most suitable solar PV technology for this site and potentially, sites with similar climate.

Practice implications: The findings from this study are useful in identifying solar cell technologies that are appropriate for this location and provide useful information to policy makers and individuals about the performance of grid-tied PV system in Ghana.

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Introduction

Due to improved technology, reduction in photovoltaic (PV) cost and national and international climate change policies, solar energy is expected to contribute substantially to the future global energy mix. This contribution could be more significant for country like Ghana due to her geographical location. As a tropical country, Ghana has abundant solar energy resources. The daily solar irradiation ranges from 3.1 kWh/m^2 along the coastal region to 6.5 kWh/m^2 in the northern region. Both large- and small-scale development of solar energy conversion systems (especially solar PV systems) in Ghana can achieve three complementary goals, which are improved electricity access (both in rural and semi-urban areas), job creations and skill development, and offset greenhouse gas (GHG) emissions from thermal power plants.

In addition to solar energy resource (solar irradiation) and environmental factors, the performance of a PV system depends on the solar cell technology used for such system. This is mainly due to the solar cell efficiency, temperature coefficients (maximum power, open-circuit voltage and short-circuit current) and overall sensitivity to environmental conditions (such as ambient temperature, dust and shading) that are functions of solar cell technology. Even though, solar PV performance can be assessed using simulation softwares (tools), however, performance assessment of an actual PV system installation is the best way to determine the potential for solar PV power production in an area.

There are many studies on performance evaluation of solar PV installation installed outdoors globally. While some of these studies focus on one solar technology PV systems e.g., [1–11], others considered two or more technologies solar PV systems e.g., [12–17]. These studies show that solar PV performance at a given site is a function of the solar cell technologies. Nevertheless, to our knowledge, there is little information available (in open literature) on the actual operation and energy production from PV systems in sub-Saharan Africa, especially in Ghana. This paper presents performance measurements of five different commercially available solar PV technologies installed at the College of Engineering of the Kwame Nkrumah University of Science and Technology (KNUST) Kumasi, Ghana. The findings from this study can be helpful in identifying specific solar cell technology that is more appropriate for this location and locations with similar climate conditions as well as to provide useful information to policy makers and individual about the performance of grid-tied PV system in Ghana. Furthermore, the collected performance data can be used to validate PV performance model and numerical simulations.

Material and methods

PV systems and module technologies

Five small-scale PV systems with poly-crystalline Silicon (pc-Si), mono-crystalline Silicon (mc-Si), thin-film Copper Indium disulfide (CIS), Amorphous Silicon (a-Si), and Heterojunction Incorporating thin film (HIT) solar cell technologies are

Table 1 – Technical specifications of modules.

Cell-technologies	Amorphous Silicon	Mono crystalline Silicon	Polycrystalline Silicon	Heterojunction Incorporating thin (HIT) film	Copper Indium disulfide (CIS)
Model	Schott ASI100	Schott Solar GmbH Mono 190	Schott Solar GmbH POLY 225	Sanyo H250E01	Sulfurcell SCG50-HV-F
Module × string	10 × 4	7 × 3	9 × 2	8 × 2	9 × 9
Total number of modules	40	21	18	16	81
Number power per module (W)	100	190	225	250	50
Total module peak power (W)	4000	3990	4050	4000	4050
Voltage at nominal power (V)	30.7	36.4	29.8	34.9	36.8
Current at nominal power (A)	3.25	5.22	7.55	7.18	1.36
Open circuit voltage (V)	40.9	45.2	36.7	43.1	49.5
Open circuit current (A)	3.85	5.46	8.24	7.74	1.66
Maxi. system voltage (V)	1000	1000	1000	1000	1000
Temperature coefficient of open circuit voltage (%/°C)	−0.33	−0.33	−0.33	−0.01	−0.26
Temperature coefficient of short circuit current (%/°C)	0.08	0.03	0.04	0.03	0.04
Temperature coefficient power (%/°C)	−0.20	−0.44	−0.45	−0.30	−0.30
Total surface area of PV system (m^2)	58.9	28.1	30.6	22.6	68.6
Nominal power of PV-module (kW)	4.00	3.99	4.05	4.00	4.05
Module efficiency (%)	6.9	14.5	13.7	18.0	6.1
NOCT (°C)	49	46	47.2	46	47

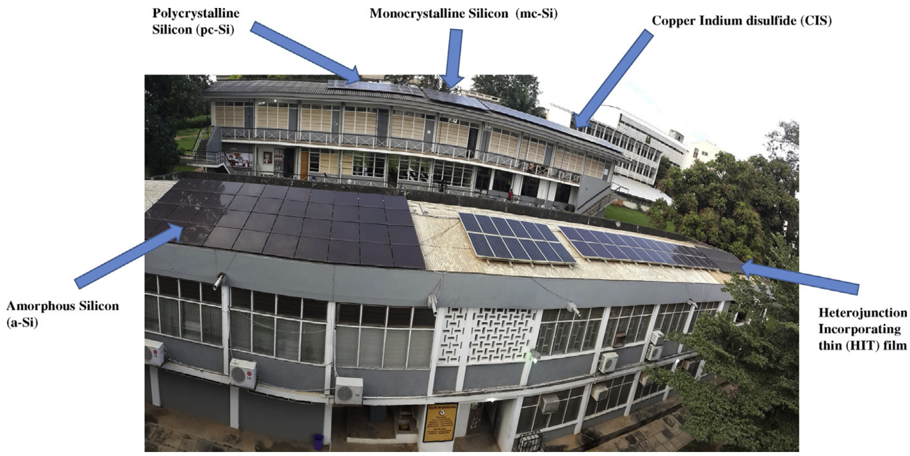

Fig. 1 – The photo of the installed five module technologies.

installed on rooftop of buildings at the College of Engineering, Kwame Nkrumah University of Science and Technology, Kumasi Ghana. Kumasi is located on the latitude 6° 40′ N and longitude 1° 37′ W, and elevation of 250 m above sea level. The installed capacity of each PV system is approximately 4.00 kWp. Table 1 shows the technical specifications of the modules installed. The World Bank Africa Renewable Energy Access program (AFREA) provided funds for these installations through a project titled: Capacity Upgrading for West African Partners in Renewable Energy Education Project. All the systems were installed in 2012.

The unshaded modules were mounted on an inclined buildings' rooftop with tilt angle of 5° orientated toward the equator ('south') as shown in Fig. 1. Each Solar PV technology is connected to the grid through a 4 kW SMA Sunny Boy DC-AC inverter (SB 3800). The five inverters communicate through a Bluetooth ad-hoc connection with a SMA Sunny Webbox, which interfaces and stores data from the Solar PV systems. The stored data is fed directly into the University local network dedicated servers and the SMA Sunny portal, which is an online monitoring system. Table 2 shows, respectively, the technical specifications of the SMA SB 3800 inverter.

Measurement procedures and data analysis

Detailed performance measurement of the systems started in March 2012 and still going on. The results presented in this study consist of the data recorded between January 1, 2014 and December 31, 2014. The parameters recorded include total module in-plane irradiation, ambient temperature, module temperature and final energy output. The acquired data were obtained by an integrated web server in the inverter, at five-minute intervals, from which the hourly, weekly, monthly and other derived performance parameters were determined. The in-plane radiation is measured by an amorphous silicon cell sensor. The measurement range of this cell is from 0 W/m^2 to 1500 W/m^2 with resolution of 1 W/m^2 and measurement accuracy of (+/−) 8% [18]. In addition, module temperature is measured using platinum sensor (PT100) with measurement accuracy of ±0.5 °C and resolution of 0.1 °C.

Table 2 – Selected technical specifications for Sunny Boy SB 3800 inverter.

Parameters	Value
Input data	
Nominal DC power (W)	4040
Maximum voltage (V)	500
MPP voltage range (V)	200–400
Start input voltage (V)	250
Maximum input current (A)	20
Power factor	1
Others	
European standard efficiency (%)	94.7
Maximum efficiency (%)	95.6

Performance indices

The performance of a grid connected PV system is usually examined using selected set of performance indices [6,9,11,19], however, the most important of these indices are final energy output, final energy yield and performance ratio. With these performance indices, the overall performance of the grid-tied PV system can be evaluated and performance of different PV installations can be compared. In addition to these indices, we also use energy density index to compare the performance of the five installations monitored in this study.

The final energy output is defined as the amount of alternating current (AC) power produced by the system over a given period. The total hourly, daily and monthly energy produced can be determined respectively from Ref. [6,9,11,19]:

$$E_{AC} = \sum_{t=1}^{N} E_{AC,t} \tag{1}$$

Where $E_{AC,t}$ is AC energy output at time t (depending on desired level of resolution t can be in minutes, hour, or day) and N is the number of observations in the data set.

The system yield can be classified into three types, which are array, final, and reference yields. The yields indicate the actual array operation relative to its rated capacity. For most situations, only the final and reference yields are normally considered. The final yield is defined as the energy output from the inverter (AC energy) normalized by the PV system's rated capacity. It indicates how many hours a day the PV system must operate at its rated power in order to produce the same amount of energy as was recorded. It is given as [6,9,11,19]:

$$Y_F = \frac{E_{AC}}{P_{PV,rated}} \ (\text{h/day}) \tag{2}$$

where Y_F is the array yield, E_{AC} is the AC energy output (kWh) and $P_{PV,rated}$ is the PV system rated capacity (kW). The reference yield is the ratio of the total in-plane solar radiation to the array reference irradiance (usually taken as 1 kW/m^2). It is a measure of theoretical maximum energy available at a specific location over a specified time period. It can be calculated from Ref. [6,9,11,19]:

$$Y_F = \frac{H_t}{G_R} \ (\text{h/day}) \tag{3}$$

where H_t (kWh/m^2)is the in-plane solar radiation and G_R (kW/m^2) is the reference irradiance.

The solar PV performance ratio (PR) measures the overall effect of losses on the rated output of the system. The PR of a PV indicates how close its performance approaches ideal performance during real life operation and allows comparison of PV systems independent of location, tilt angle, orientation and their nominal rated power capacity. It is given as:

$$PR = \frac{Y_F}{Y_R}(-) \tag{4}$$

In addition to the above indices, another index used in this study is energy density. The energy density, which is defined as the annual final energy output per array unit area, can be used to assess space requirement of a PV installation. It is expressed as:

$$E_D = \frac{E_{AC}}{A_m} \ (\text{kWh/m}^2) \tag{5}$$

where A_m (m^2) is module (array) total area.

Capacity factor

The capacity factor is defined as the ratio of AC energy produced by the PV system over a given period of time (usually one year) to the energy output that would have been generated if the system were operated at full capacity for the entire period. The annual capacity factor of the PV system is given as:

$$C_f = \frac{100 * Total\ annual\ energy\ output, E_{AC}}{P_{PV,rated} * 8760} \ (\%) \tag{6}$$

where C_f (%) is the capacity factor.

Power outage correction

For safety reason, grid-connected PV systems are normally designed such that they automatically disconnects from the grid when there is grid-outage. Even though, the PV system may be producing energy during the grid-outage period, this energy is considered as lost energy since is not used. We account for gaps in energy production by assuming that energy generated during normal operating hours is proportional to the electricity that would have been generated during the period when the system was down due to grid-outage. Based on this assumption, the system energy output during a given period (say a day) is then corrected as [11]:

$$E_{AC,est} = E_{AC,mea} * \left(\frac{T_{max}}{T_{max} - T_{missing}}\right) \ (\text{kwh}) \tag{7}$$

where $E_{AC,est}$ is the corrected electricity output, $E_{AC,mea}$ is the measured electricity output, T_{max} is total available time (in minutes) and $T_{missing}$ is total missing time (in minutes) within the measurement period. The duration of system outage (in hours) for each month is computed from the data gaps in the downloaded files.

Fig. 2 shows the total monthly grid-outage duration at the KNUST Kumasi in 2014. It can be observed that grid-outage occurrence varies between 3.08 h (in June) and 33.83 h (in December) with annual value of about 280 h. This annual value indicates that about 3.20% of the data were missing during the reporting period (that is, 2014). One of the reasons for this low grid outage period is that the College of Engineering (at the KNUST) has a stand-by generator, which is manually turned on when grid-outage occurs, particularly when academic activities are in progress. This gives the needed signal for the inverters to re-engage and hence, reduces the grid-outage impact on the PV production. However, for most residential and commercial premises without standby diesel generator in Kumasi (and any locations in Ghana), the grid-outage is generally higher and this will lead to more reduction in PV production in these areas.

Results and discussion

Daily module temperature

The module temperature is a function of combinations of environmental factors (solar radiation ambient temperature, wind speed and level of precipitation), module electrical parameters and installation methods (such as free standing, rooftop with (large) and without (flushed to the roof) gap). In the case of flushed-rooftop installations, roofing sheet material heat conductivity can also affect the module temperature.

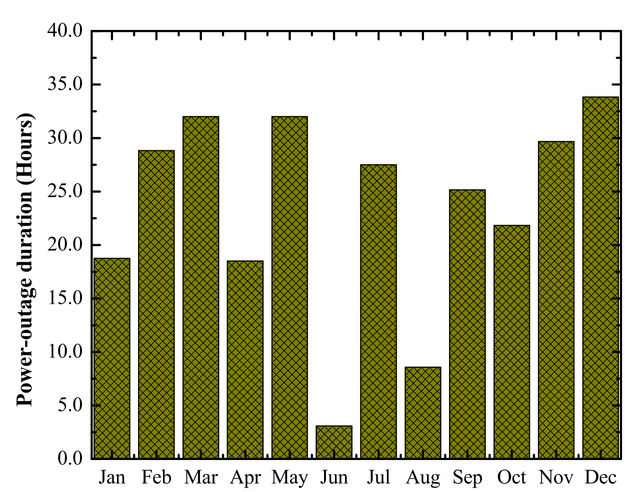

Fig. 2 – Monthly grid-outage duration at KNUST Kumasi Ghana in 2014.

Fig. 3 shows the daily modules temperatures for two selected days of the year (21 August and 21 November). These two months (on average) represent two distinct weather conditions in Kumasi Ghana, which are, respectively, raining season and harmattan (hot) season. The raining season is typically between May to September while harmattan/dry season months are from October to April. It can be observed from these figures that: (1) for a given module technology, the cell temperature depends on the time (or season) of the year, and (2) for a given day (and time), the cell module temperature varies with module technology. The maximum ambient measured temperature is 30.2 °C on 21 August while it is 38.1 °C on 21 November 2014. In comparison with harmattan month of November (which is characterized by high ambient temperature and solar radiation as well as less fluctuation in ambient conditions), August is characterized with cloudy and unstable weather conditions (due to precipitation) that give rise to relatively low ambient temperature and fluctuating solar radiation. This fluctuating condition leads to variability in module temperature as observed in Fig. 3a when compared with Fig. 3b. The maximum module temperatures on 21 August 2014 are 47.1 °C, 43.4 °C, 50.5 °C, 51.4 °C, and 44.6 °C respectively for mc-Si, pc-Si, HIT, CIS and a-Si based modules. Likewise, the maximum module temperatures are respectively for 61.3 °C, 59.0 °C, 57.7 °C, 70.7 °C, and 58.2 °C respectively for mc-Si, pc-Si, HIT, CIS and a-Si based modules on 21 November 2014.

Fig. 4 shows the daily power output from all the systems on 21 August and on 21 November 2014. The relationship between the module cell temperature (see Fig. 3) and power output can clearly be seen from these Figures. In general, CIS based system, produced less power (due to its relatively high module temperature) when compared with other systems.

Final energy output

Fig. 5 shows the total annual energy production by the PV systems. The total annual energy delivered to the grid over the monitored period varied between 3133 kWh for CIS thin film system and 4572 kWh polycrystalline silicon system with combined total output of 20.62 MWh. However, when the recorded data was corrected as previously discussed, the total annual energy production by each PV module technology is about 3.25% higher than recorded value with estimated combined output of 21.29 MWh. The average actual monthly final

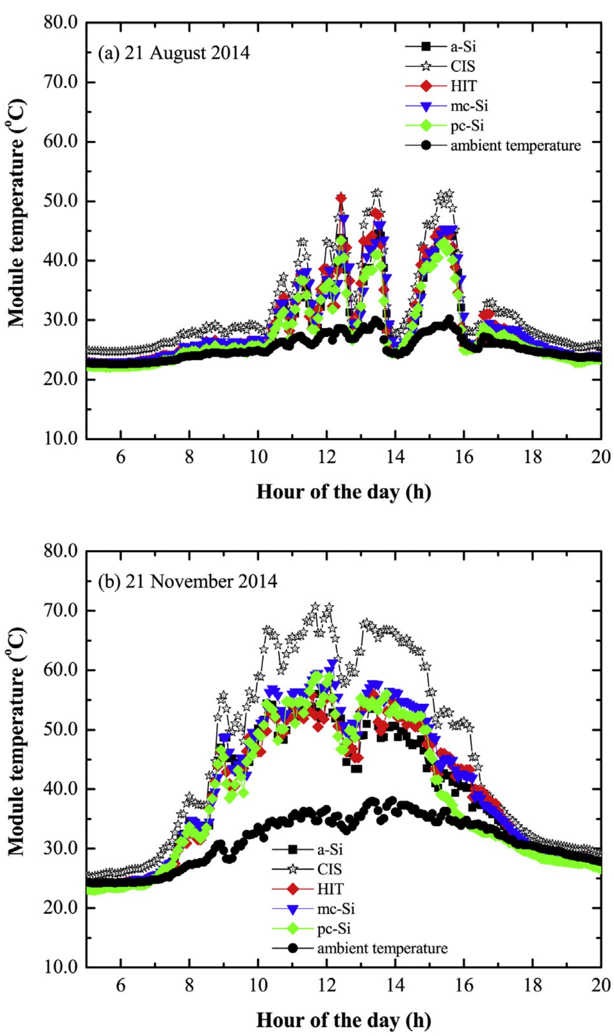

Fig. 3 – Daily module temperature on (a) 21 August 2014 and (b) 21 November 2014.

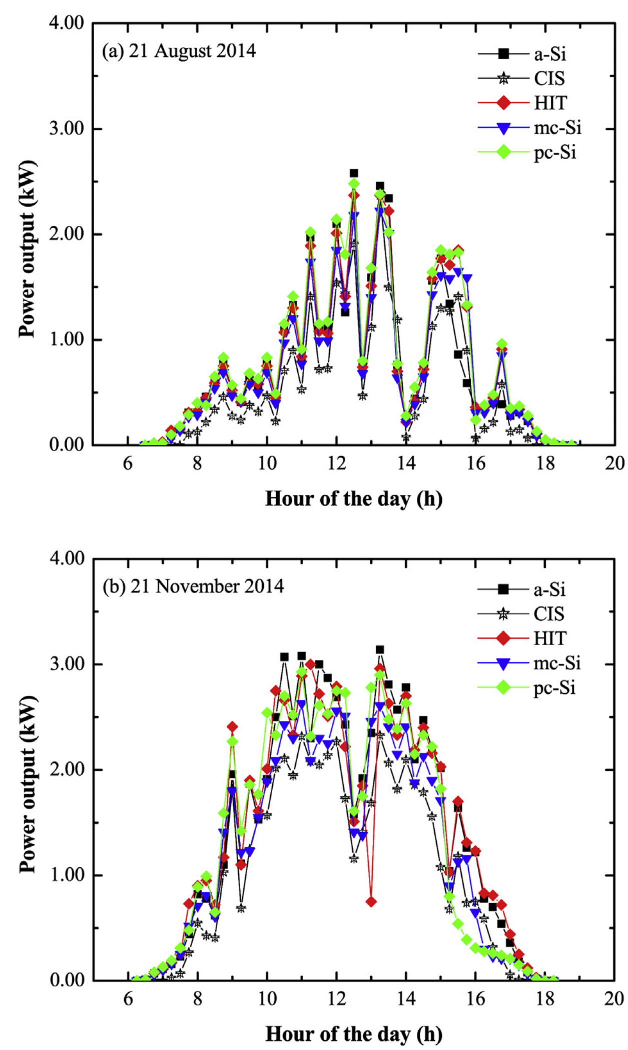

Fig. 4 – Daily power output on (a) 21 August 2014 and (b) 21 November 2014.

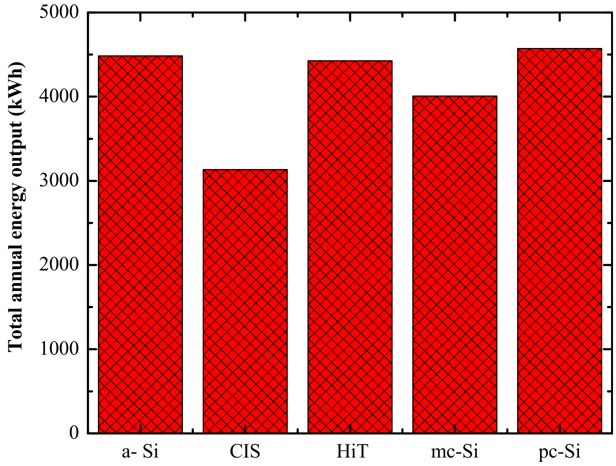

Fig. 5 – Actual annual energy generated (between January and December 2014) by the PV systems.

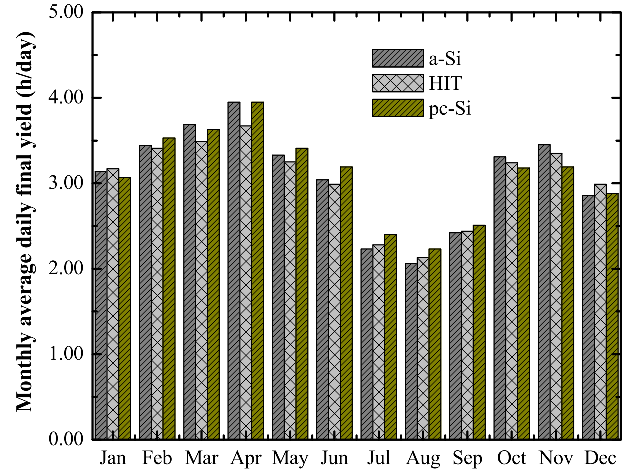

Fig. 7 – The monthly daily final yield for a-Si, HIT and pc-Si systems.

energy output of the systems are 374 kWh, 261 kWh, 369 kWh, 334 kWh and 381 kWh for a-Si, CIS, HIT, mc-Si and pc-Si, respectively. The annual specific final energy, defined as total final energy divided by installed peak capacity of a solar PV system, is estimated as 1121.3 kWh/kW$_p$, 773.5 kWh/kW$_p$, 1106.3 kWh/kW$_p$, 1004.5 kWh/kW$_p$ and 1128.9 kWh/kW$_p$ for a-Si, CIS, HIT, mc-Si and pc-Si, respectively.

The annual electricity consumption per capita is 396.1 kWh in Ghana [20] and with average household size of 4.4 [21,22] and hence, the monthly electricity consumption per household in Ghana is about 145.24 kWh. Assuming that a household installed one of the systems examined in this study on the rooftop of its building, the monthly output of the system can conveniently meet the electricity needs of this household and the excess electricity can be sold either to the utility company or to neighbours.

It can further be observed that the energy output from the a-Si system is similar to that of the pc-Si system. However, the pc-Si modules require less module area than a-Si modules for the same installed power capacity as result of its efficiency that is considerably less than that of pc-Si module (see Table 1). In the hot-season months of October to April, the total final energy produced by the a-Si system is about 1% more than pc-Si module while it is about 5% less during the wet-season months (May to September). This is in agreement with previous studies e.g., [13,14] that a-Si system produce relatively higher energy than pc-Si during summer (hot) months and less during the winter (wet) months. This observation is also consistent with expectation based on temperature coefficients for power these two modules technologies.

The annual specific energy, which is defined as annual final energy output divided by the system's installed capacity, is 1121 kWh/kW, 774 kWh/kW, 1106 kWh/kW, 1004 kWh/kW and 1129 kWh/kW for a-Si, CIS, HIT, mc-Si and pc-Si, respectively. The specific energy can be used to compare the performance of PV systems installed in the same climatic conditions. Therefore, based on energy output, a-Si and p-Si PV systems can be considered as best options and CIS as least suited option for this location.

Final yield, performance ratio (PR) and capacity factor

Fig. 6 shows the average daily annual final yield for all the systems. The final yield is observed to be lowest for the CIS

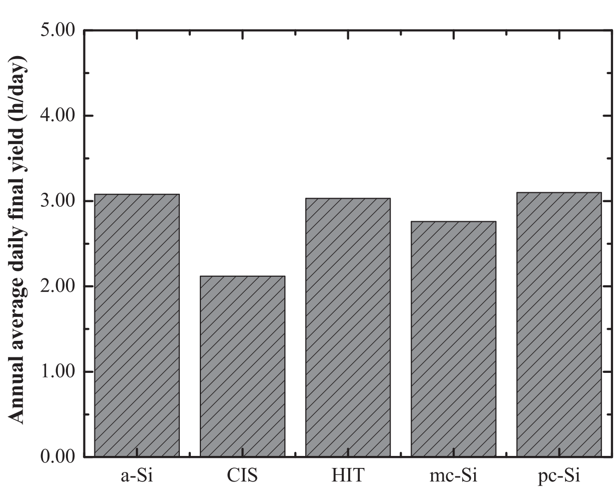

Fig. 6 – The average annual daily final yield.

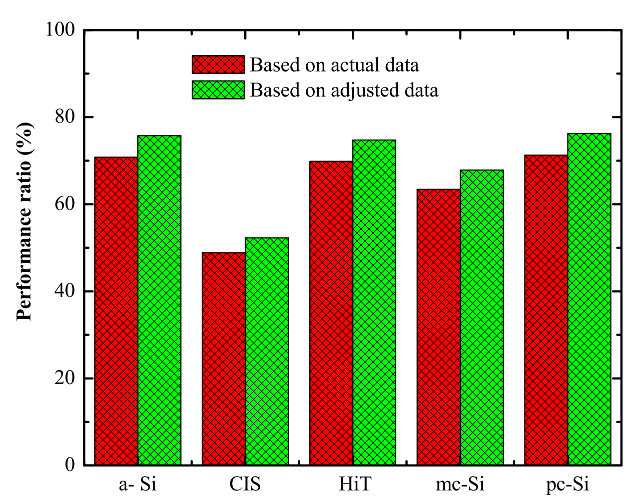

Fig. 8 – The annual performance ratio by the PV systems.

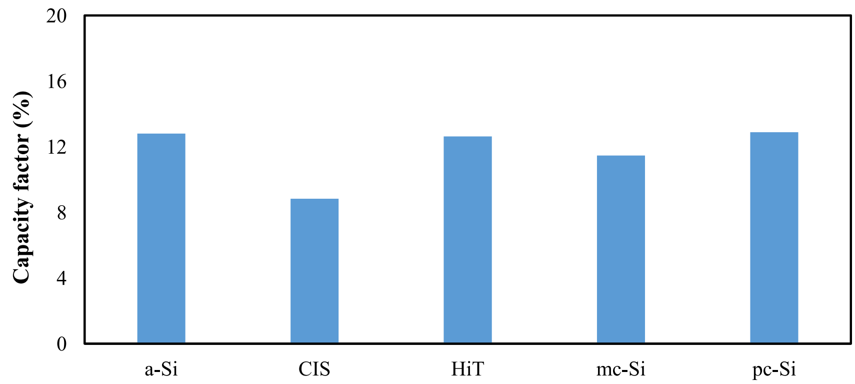

Fig. 9 – The PV systems annual capacity factor based on 2014 production data.

system (2.12 h/day) and highest for the pc-Si system. In addition, it is noted that there is no substantial difference between the final yield for a-Si (3.08 h/day) and pc-Si (3.10 h/day). The monthly average daily final yields for a-Si, HIT and pc-Si are shown in Fig. 7. It can be observed from this figure that the final yields for a-Si system are the almost the same or slightly higher than those of pc-Si system in January, March, April, October, November and December. These months (and February) are months with relatively high ambient temperature period in Kumasi. However, from May to September (relatively low ambient temperature period), the final yield is observed to be higher for pc-Si system than a-Si system.

The performance ratio measures the overall effect of losses on the rated output of the system. These losses can be classified as non-temperature related factors (e.g., inverter inefficiency, wiring, mismatch, soiling, system's availability and component failures, shading as well as system's age) and temperature related factor (as a result of module's temperature deviation from 25 °C in real operation). The *PR* of a PV system indicates how close its performance approaches ideal performance during real operation and allows comparison of PV systems independent of location, tilt angle, orientation and their nominal rated power capacity. Fig. 8 shows the performance ratio of the PV systems based on the actual recorded

Table 3 – Performance ratio of selected solar PV installations.

Source	Location	Module technology and performance ratio (PR)
Saleh et al. [23]	Tripoli, Libya	a-Si – 70%
Chumpolrat et al. [24]	Thailand	a-Si 65%–70%
Shukla et al. [25]	Bhopal, India	a-Si – 79.5% CdTe – 77.0% Copper indium selenide (CIS) – 73.1%
Humada et al. [26]	Malaysia	mc-Si – 59.92%–79.14% Copper indium selenide (CIS) – 63.8%–84.12%
Sharma and Chandel [9]	Khatkar-Kalan, India	pc-Si – 74%
Padmavathi and Daniel [8]	Karnataka State, India	mc-Si – 70%
Ghiani et al. [27]	Sardinia, Italy	mc-Si 83.20%, 87.3%
Tripathia et al. [28]	Gujarat, Western India.	mc-Si: 57.1%–93.14% a-Si: 53.72%–87.64%
Weber et al. [29]	Mexico City, Mexico	pc-Si 77.4%
Farhoodnea et al. [30]	Universiti Kebangsaan Malaysia	mc-Si 77.28%
Tahri et al. [31]	Algeria	Copper indium selenide – 79%
Mpholo et al. [32]	Lesotho	pc-Si – 70%
Al-Otaibi et al. [33]	Kuwait	CIGS – 76%
Okello et al. [34]	Nelson Mandela Metropolitan University (NMMU) South Africa	pc-Si 84.3%
Sasitharanuwat et al. [35]	Thailand	a-Si/pc-Si/HIT: 57%–79%
Sidi et al. [36]	Mauritania	a-Si: 63.59–73.56%
Tan et al. [37]	Malaysia	mc-Si: 77.85% HIT: 81.25% a-Si: 83.37%
Present study	Kumasi Ghana	HIT: 74.8%,
Present study	Kumasi Ghana	mc-Si: 67.9%
Present study	Kumasi Ghana	pc-Si: 76.3%
Present study	Kumasi Ghana	a-Si:75.8%
Present study	Kumasi Ghana	Copper Indium Disulfide (CIS*): 52.3%

and adjusted data. It can be observed that the performance ratio varies among the different types of PV module technologies. The unadjusted annual *PR* is 70.8%, 48.8%, 69.8%, 63.4% and 71.3% for a-Si, CIS, HIT, mc-Si and pc-Si, respectively. However, based on the estimated energy output to account for the grid-outage, the *PR* increased to 75.8%, 52.3%, 74.8%, 67.9% and 76.3% for a-Si, CIS, HIT, mc-Si and pc-Si, respectively (see Fig. 8).

The capacity factor of the installations was, respectively: 12.8%, 8.8%, 12.6%, 11.47% and 12.9% for a-Si, CIS, HIT, mc-Si and pc-Si (see Fig. 9). The technical performance of these installations, except for the CIS, compare favourably with those reported in the open literature (Table 3), although higher performance data has also been reported. The CIS technologies reported on in the literature are mainly Copper Indium Diselenide ($CuInSe_2$), whereas the technology analysed in this paper is Copper Indium disulfide ($CuInS_2$).

Energy density

Availability of adequate 'free' space is one of the issues facing development of renewable energy resources, especially solar energy for generating electricity on large-scale. For ground-installed PV system for example, there could conflict between land use for farming (crop and animals) and recreation parks, on one hand and, energy production on the other hand. In addition, in order to reduce the operating cost (such as lease payment for the land or space) for solar PV installations, there is need to minimise space requirement. Therefore, in addition to investment cost and potential energy output, energy density (defined as energy output per unit space area) of available technologies could be considered as one of the criteria to be used to make decision on which technology should be chosen for a site. Fig. 10 shows the annual energy density of the PV module technologies investigated in this study. The annual energy density of the systems varies between 45.7 kWh/m^2 for CIS system and 195.8 kWh/m^2 for HIT system. The energy densities for other systems are 58.5 kWh/m^2, 142.6 kWh/m^2 and 149.4 kWh/m^2 for a-Si, mc-Si and pc-Si, respectively. The low energy density for the thin film technologies (CIS and a-Si), in comparison with crystalline silicon based systems, is

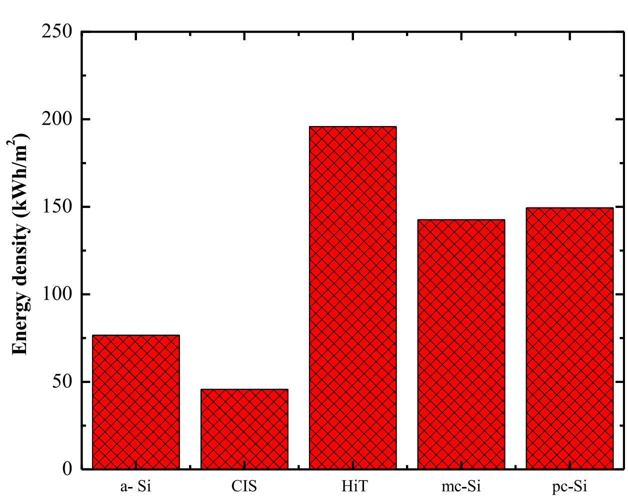

Fig. 10 – The PV systems annual energy density.

due to their generally low efficiency. Therefore, if space constraint is an issue, then the HIT based system is the most appropriate solar PV technology for this site and by an extension, for locations with climatic conditions similar to Kumasi in Ghana.

Conclusions

The comparative performance assessment of different five PV module technologies is investigated in this study based on their outdoor performance. The five small-scale PV systems are based on poly-crystalline Silicon (pc-Si), mono-crystalline Silicon (mc-Si), Copper Indium disulfide (CIS), Amorphous Silicon (a-Si), and Heterojunction Incorporating thin film (HIT) module technologies. The installed capacity of each PV system is approximately 4.00 kWp. The findings from this study can be summarised as follows:

- The combined total actual final energy output from all the systems is 20.62 MWh. However, when the recorded data to account for lost in production due to power outage, estimated combined final energy output increased to 21.29 MWh.
- The annual specific final energy is 1121.3 kWh/kW$_p$, 773.5 kWh/kW$_p$, 1106.3 kWh/kW$_p$, 1004.5 kWh/kW$_p$ and 1128.9 kWh/kW$_p$ for a-Si, CIS, HIT, mc-Si and pc-Si, respectively.
- The final yield is observed to be lowest for the CIS system (2.12 h/day) and highest for the pc-Si system (3.10 h/day).
- The annual performance ratio, based on the actual data (excluding the missing data due to power-outage), is 70.8%, 48.8%, 69.8%, 63.4% and 71.3% for a-Si, CIS, HIT, mc-Si and pc-Si based systems respectively.
- The annual actual energy density is 45.7 kWh/m^2, 58.5 kWh/m^2, 142.6 kWh/m^2, 149.4 kWh/m^2 and 195.8 kWh/m^2 for CIS, a-Si, mc-Si and pc-Si system HIT system, respectively.

Based on the technical performance of all the systems and space requirement, it can be concluded that the CIS PV technology is the least suitable while the HIT is the most suitable solar PV technology for the site considered. In order to improve the usability of solar PV grid-connected energy systems in Ghana and any locations with high rate of grid outage, it is suggested that this type of energy system should be designed in such a way that energy produce during outage period can be diverted to energy storage facility such hydrogen fuel and battery. Furthermore, due to generally high module temperature (about 70 °C) as observed in this study, combination of solar PV and solar water heating as a hybrid solar PV-thermal system can improve the usability of the solar energy resources at this site. This hybrid system will not only provide warm water, but can improve the energy yield (and hence, performance ratio) of the solar PV system.

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