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Evaluation of field data and simulation results of a photovoltaic system in countries with high solar radiation

Akinola Adeyinka BABATUNDE, Serkan ABBASOĞLU*
Department of Energy Systems Engineering, Faculty of Engineering, Cyprus International University, Lefkoşa, Northern Cyprus

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Abstract: The objective of this study is to examine the conformity of different simulation tools in analyzing the performance of photovoltaic (PV) systems in countries with high solar radiation. Primarily an installed system was evaluated and the results were compared with the simulation results of 3 globally known PV software tools: pvPlanner, PVsyst, and Homer. The parameters evaluated in this study are energy production, specific yield, performance ratio, and capacity factor. Detailed explanations are presented for monthly, seasonal, and annual variation of installed system data and simulation results. Northern Cyprus is selected as a case study due to high solar radiation and duration values. The total annual energy production of the installed 5.76 kW system amounts to 12,216 kWh for the year studied. All the simulation tools appear to underestimate the installed system's energy production and the variances observed are 5.3%, 9.3%, and 7.5% for pvPlanner, PVsyst, and Homer, respectively. Energy production in summer was observed to be about twice the production in winter. The percentage shares with respect to energy production are 34%, 28%, 22%, and 16% in summer, spring, autumn, and winter, respectively. The performance ratio of the system is 80.8%. However, the average performance ratio of the 3 simulators was found to be 78.6%. PVsyst modeled a performance ratio with the least deviation from the system with 79.2%. The specific yield and capacity factor of the installed system are 2121 kWh/kW$_p$ and 25.06%, respectively. The average specific yield value and average capacity factor of the 3 simulators are nearly 7% lower than the measured data of the installed system. Different factors led to the difference between real-world application and simulation results. These are discussed in this study in detail.

Key words: Solar photovoltaics, energy production, performance ratio, specific yield, capacity factor, simulation tools

1. Introduction

Solar energy has received much attention in recent times; it is the energy from sunlight and, due to the abundance of sunlight, solar energy is thought to be a promising renewable energy source for the future. Solar energy is free of carbon emissions; hence, it has little or no hazardous impact on the environment and human health. Solar radiation can be converted into useful energy directly by using various technologies. When absorbed in solar collectors, it can provide hot water or space heating. Buildings can be structured with solar features that contribute to space heating and lighting requirements. Mirrors can be used to concentrate solar energy to provide heat for generating electricity in solar thermal electric power plants for commercial applications. Solar radiation can also be converted directly into electricity using photovoltaic (PV) systems. A PV system is a solar energy system that produces electricity when light shines on a module. In 2012, it was recorded that 31.1 GW of solar PV capacity

*Correspondence: sabbas@ciu.edu.tr

was installed around the world while global PV capacity was above 100 GW; studies have also shown that additional 100 GW PV systems will be installed worldwide by 2015 (http://www.greentechmedia.com/research). According to a report by the International Energy Agency (IEA), very few countries could boast of solar capacity of 100 MW or more in 2006; presently, about 30 countries are on that list and the IEA projects that this number will more than double by 2018 (http://www.iea.org/Textbase/npsum/MTrenew2013SUM.pdf). The same report also states that roughly 60% of global PV energy is currently manufactured in China compared to a decade ago, when China produced almost no PV energy. The US Department of Energy confirmed that the current module cost for solar PV varies from $5.5 to $10 per watt (http://www.nrel.gov/docs/fy13osti/56776.pdf). According to the National Renewable Energy Laboratory (NREL), the price of electricity for solar PV ranges from $0.15 to $0.59 per kWh (http://www.nrel.gov/docs/fy13osti/56806.pdf). These prices are dependent on location and government solar policies of such locations.

Nicosia, the capital of Northern Cyprus (NC), is known to have abundant sunlight; it has an average of 300 sunny days in a year, an average 11 daily sunny hours, and average annual solar radiation of 5.2 kW/m^2 daily [1]. This positions NC as a fertile location for conversion of solar energy to electricity and other applications. The fuel source (sunlight) is free, abundant, and widely distributed, available to every country across the globe. The world's current power usage is about 16 TW; it has been projected that the future usage will be about 60 TW, and the solar resources from the sun are over 165,000 TW. PV technology makes use of characteristics of certain semiconductors to directly convert solar radiation to direct current (DC) electricity. PV systems utilize wafers made of crystalline silicon, which respond to sunlight and produce a small direct current upon contact with light. These PV cells or solar cells can be combined into larger-sized arrangements called modules, while the modules arranged or combined together systematically are referred to as arrays; they have minimized emissions and produce large amounts of electrical power with no moving parts or noise. The components of a PV system can be arranged in many ways to design PV systems for different situations, but the most common configuration is the utility connected system, which is found in commercial and residential buildings [2].

This study focuses on the measurement and analysis of single-axis tracking PV system field data/parameters with respect to the meteorological conditions of Nicosia, validation and comparison of the PV system field measurements with the literature and 3 different simulation tools results, variance analysis, and further prediction of the best-case PV system performance using the PV simulation software tools.

2. Methodology

Evaluation of the performance of a single-axis 5.76 kW tracking PV system in Nicosia was carried out; comparison of the evaluated data with the results obtained from 3 globally known PV simulation software tools was also done. The simulation tools deployed were pvPlanner, PVsyst, and Homer. The 4 performance indicators studied were energy production, performance ratio, specific yield, and capacity factor. To further increase the credibility of this study, the results were validated with studies in the literature. The AC energy was measured from the system energy meter; energy production values for the winter and summer months were analyzed. The system energy production was then compared to the energy production simulated by each of the 3 PV software tools. Theoretically, energy production is calculated as shown in Eq. (1).

$$\text{Energy production (kWh)} = \text{Power} \times \text{time (h)} \tag{1}$$

The second parameter of interest is the specific yield; it is the net energy output divided by the nameplate DC power at the standard test condition (STC) of an installed PV array. It represents the number of hours the PV array would need to operate at its rated power or peak rating to provide the same energy. The units are hours or kWh/kW$_p$. The specific yield normalizes the energy produced with respect to the system size [3] and can be calculated theoretically from Eq. (2).

$$\text{Specific yield} = \frac{\text{AC energy output (kWh)}}{\text{Nameplate or DC rated power on PV module (kWp)}} \tag{2}$$

Thirdly, the performance ratio (PR) of a given PV system, which is defined as the energy output injected into the grid divided by the nameplate DC energy obtained under STC of the PV array [4], was evaluated. Theoretically, PR is calculated using Eq. (3).

$$PR = \frac{\text{Actual AC energy reading of plant output (kWh)}}{\text{Calculated nominal plant output (kWh)}} \tag{3}$$

The actual plant output is read from the export grid meter. Nominal power output (NPO) is calculated using Eq. (4).

$$NPO = \frac{\text{Incident solar radiation on PV system}}{\text{Irradiance } \times \text{area} \times \text{efficiency of PV modules}} \tag{4}$$

The last parameter presented in this study is the capacity factor (CF); it is sometimes referred to as capacity utilization factor. It does not have a unit and can be calculated from Eq. (5).

$$CF = \frac{\text{Energy measured (kWh)}}{365 \times 24\,(h) \times \text{installed capacity of the plant}} \tag{5}$$

2.1. System description

The installed PV system at Cyprus Solar Technology (CYS) is located in Nicosia. Figures 1 and 2 give the diagram of the 5.76 kW PV power system. It is tilted at 30° at 35.2°N and 33.4°E. A full description of the system is given in Table 1. The system module conversion efficiency is 15.1%. This indicates that only 151 Wh/m^2 of the 1000 Wh/m^2 (the STC power density) is converted by the PV module to useful DC electrical energy.

Figure 1. The 5.76 kW solar power system at CYS.

Figure 2. The 5.76 kW solar power system at CYS.

2.2. Meteorological conditions of Nicosia

Nicosia, the capital of NC, is located at 35.2°N, 33.4°E. "Solar irradiation in Cyprus (a typical example of an island in the Mediterranean sunbelt) is one of the highest in Europe, with more than 300 days of the year considered as having sunny weather and an annual irradiation of around 2000 kWh/m^2 on a tilted surface of 27.58°" [5]. The average solar radiation received in Cyprus, based on historical data collected by the various meteorological stations on the island, is estimated at 7.0 kWh/m^2 daily in summer and 3.0 kWh/m^2 daily in winter months [6].

Table 1. CYS PV system description.

Description	Specification	Description	Specification
Manufacturer	Mage Powertech Plus	Tracking	Single axis
Solar module type	Polycrystalline silicon cell	Inverter	2 × SMA SB3000 HF
Nominal power (Pnom)	240 W_p	Voltage at Pnom	29.57 V
Short circuit current (I_{sc})	8.76 A	Current at Pnom	8.2 A
Open circuit voltage (V_{oc})	37.35 V	Module efficiency	15.1%

2.3. PV simulation software

Various versions of PV simulation tools exist based on either improvement processes or specific applications. The characteristics of the simulation tools used are listed in Table 2.

Table 2. Simulation tools characteristics.

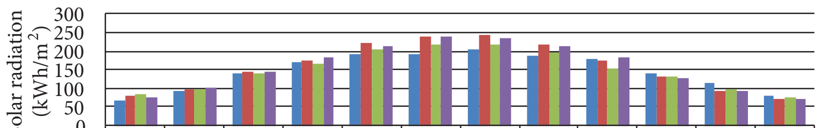
	pvPlanner	PVsyst	Homer
Version assessed	Not applicable	5.63	2.81
Commercially licensed	Yes	Yes	Yes
Meteo-data input	15-min time series data	1 year of hourly data	1 year of hourly data
Irradiance model (or plane of array)	Geo-model solar	Hay and Davis model or Perez et al.	HDKR model (Hay, Davis, Klucher, and Reindl)
Array performance model	-	One diode equivalent circuit model (modeled for thin film)	Linear irradiance model with temperature correction

(Source: Sandia National Laboratory and various PV software websites.)

3. Results and discussion

The PV simulators modeled their results with slightly different radiation and temperature data from the measured data. The global-in-plane radiations for CYS, pvPlanner, and PVsyst are 2565 kWh/m^2, 2580 kWh/m^2, and 2377 kWh/m^2, respectively. Figure 3 shows the monthly global horizontal radiation (GHI) for Nicosia in comparison with the simulators. It can be seen that, among the PV simulators, pvPlanner has the data set with the highest annual GHI (1892 kWh/m^2), followed by HOMER with 1881 kWh/m^2. The measured GHI of Nicosia is 1754 kWh/m^2.

Nicosia's measured annual average ambient temperature is 20.4 °C for the period of this study. HOMER does not model ambient temperature. These variations in primary data affected the overall output results. Figure 4 presents the solar duration in hours for Nicosia. HOMER did not model daily or monthly solar duration; however, the annual solar duration was given as 4300 h. This is 28% higher than the measured annual solar duration of Nicosia, which is 3159 h. pvPlanner and PVsyst did not model daily, monthly, or annual solar duration. The average measured daily solar radiation for Nicosia is 8.8 h, while the maximum solar duration is 12.5 h in July and the minimum is 4.2 h in January. It is observed that during the summer period, Nicosia experiences longer solar radiation hours, with shorter duration in the winter.

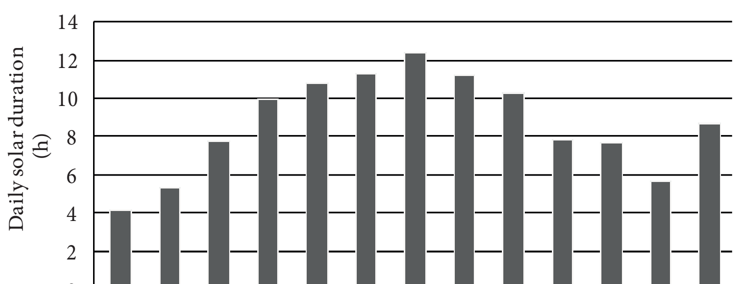


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CYS	66	92	140	172	192	192	203	186	178	140	112	80
pvPlanner	80	97	146	174	220	239	245	219	176	131	92	73
PVSyst	86	96	141	166	203	216	216	194	153	130	99	77
Homer	77	102	144	184	213	238	235	213	184	129	92	72

Figure 3. Average monthly global horizontal radiation (kWh/m^2).

3.1. Energy production

The electrical energy production of a PV plant is an important measure of system performance. The highest energy production was witnessed during the summer season with total and average energy production of 4102 kWh and 1367 kWh, respectively. The total and average energy productions in winter at CYS are 1942 kWh and 637 kWh, respectively. The summer energy production was found to be nearly 20% higher than spring production, 50% higher than the autumn production, and 111% higher than winter production. The total annual energy production of the 5.76 kW PV system at CYS is 12,216 kWh; the system supplies 28% of its annual energy production in spring, 34% in summer, 22% in autumn, and 16% in winter (Figure 5).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Daily solar duration	4.2	5.4	7.8	10	10.9	11.4	12.5	11.3	10.4	7.9	7.7	5.8	8.8

Figure 4. Nicosia average daily solar duration in hours.

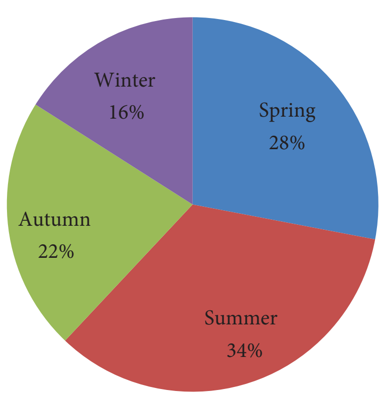


Figure 5. Fraction of annual PV energy produced by 5.78 kW system in NC.

Low energy production in winter is due to the low solar radiation and short solar duration values. On the other hand, the highest solar radiation and duration were measured during the summer period, which is the main reason for the high energy production during this period. Temperature plays a major role in the performance of PV modules; high temperatures lead to a drop in the performance of PV modules [7]. It was found that the average ambient temperature during summer was 28.4 °C, which is 56.5%, 26.2%, and 131% higher than average temperatures during autumn, spring, and winter, respectively. It was expected that due to the high temperature during the summer, there would be reduced energy production compared to spring and autumn with respective temperatures of 18.2 °C and 22.5 °C, but the high solar radiation and longer solar durations during this period outweighed the negative effect of temperature on the plane of the array. The annual average ambient temperature (20.4 °C) at CYS is equivalent to the ambient temperature of the best-case PV performance. Instead of the PV STC values (25 °C under 1000 W/m^2), nominal operating cell temperatures (NOCTs) of the PV module should be considered to find out the power output of the solar system. The NOCT is defined as the temperature reached by open circuited cells in a module under irradiance on the cell surface of 800 W/m^2, ambient temperature of 20 °C, and wind velocity of 1 m/s [8]. It was also observed that the rate of total and average energy production in summer was more than twice the energy production in winter. The ratio for radiation did not reflect the same ratio in energy production. This is most probably due to higher ratios in the ambient temperature during these seasons. Table 3 compares the annual electrical energy production at CYS with simulated results while Figure 6 compares the monthly energy production at CYS.

Table 3. Annual AC energy production of CYS and 3 simulators.

	CYS	pvPlanner	PVsyst	HOMER
Annual energy production (kWh)	12,216	11,573	11,083	11,304
Variance from actual production	-	5.3%	9.3%	7.5%

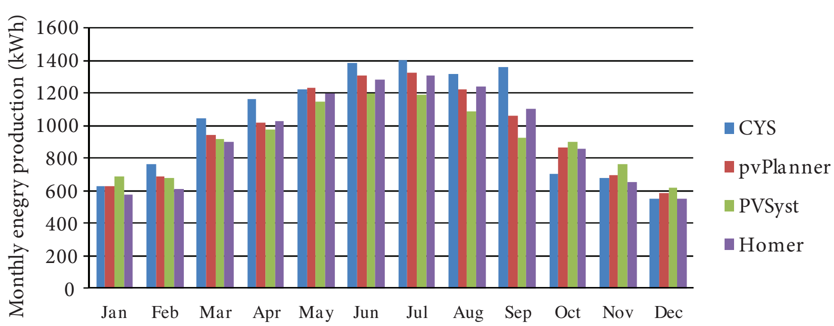


Figure 6. Monthly energy production (kWh).

Energy production obtained by pvPlanner shows the least variation of 5.3% from the CYS annual energy production with a total production of 11,573 kWh, followed by HOMER with variation of 7.5% and total energy production of 11,304 kWh. It appears that all the simulators underestimated the CYS annual energy production. The highest energy production deviation was observed with PVsyst. pvPlanner, PVsyst, and HOMER modeled 95%, 93%, and 91% of the annual energy production at CYS, respectively.

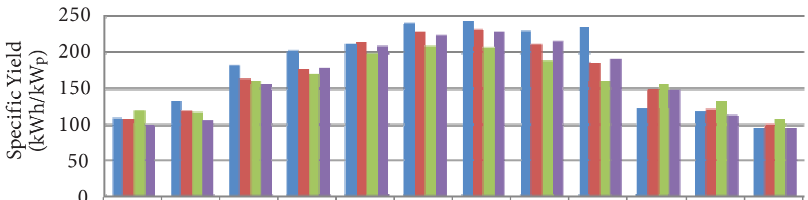
CYS monthly energy production did not match well with the monthly modeling results from all the simulation tools. The standard deviation of the 3 simulators' monthly energy production from the actual value is 10.7% for HOMER, 11.3% for pvPlanner, and 16.9% for PVsyst. When the average values were calculated, the results of the 3 PV simulation tools gave annual average energy production that amount to 11,320 kWh for the 5.76 kW PV system. The measured value from CYS is 7.3% higher. It was also found that the simulators' monthly AC energy production was lower than actual CYS values except for 3 months: October, November, and December. In practice, it is acceptable that the actual value of a PV system could be higher than the simulated or predicted values. Generally, the conservative nature of some mathematical models and algorithms of the software tools is capable of underestimating or overestimating the performance of PV systems. In addition, the environmental and operational conditions of the real-world system may not have been fully accounted for by the software tools. Solar radiation values at CYS have lower trends compared to the simulators but, most probably, other meteorological data such as solar duration or ambient temperature values have negative influence on the results of simulators and could be slightly different also [9,10]. Use of long-term meteorological data by the simulators is a meaningful reason for this difference because CYS values are instantaneous annual values for the period of this study. It is highly possible to have lower (or higher) solar radiation and ambient temperature with averaged long-term data used by the simulators compared to the instantaneous measured data during the study. Another possible reason for the variation in energy production could be the PV module peak capacity tolerance. Each module at CYS is rated 240 W and has a tolerance of 0/+5 W. Therefore, it is possible to obtain higher energy production values at higher solar radiation data during site applications. Since this may not have been accounted for by all the simulators, the fluctuations in the tolerance of the module might have led to daily or monthly increase in energy produced by CYS compared to the simulated energy by the software tools.

3.2. Specific yield

Specific yield is the ratio of net energy output of PV system by the nameplate DC power at STC of an installed PV array. Daily maximum yield of 243 kWh/kW$_p$ (8.1 h) was obtained in July at CYS. The lowest yield value was 96 kWh/kW$_p$ (3.2 h) daily, obtained in December. As expected, it was seen that the normalized yield was higher in summer with average yield of 237 kWh/kW$_p$, while the lowest average season specific yield was 112 kWh/kW$_p$ and was obtained during winter. This implies that the PV system daily average peak operating hours are 7.9 h (7.9 kWh/kW$_p$) in summer and 3.7 h (3.7 kWh/kW$_p$) in winter.

The average daily solar duration in summer and winter was found to be 11.7 h and 5.1 h, respectively. This implies that daily peak hours of operation are about 67% of the solar duration in summer and 72% in winter. The reason for the high percentage in winter can be traced to the effect of temperature. In winter the ambient temperature is low even if the solar radiation is high. This enhances the performance of the PV modules, and hence it is possible for peak operations with respect to available solar radiation and other factors. The specific yield is a derivation of the energy production; hence, it is thought that all the factors responsible for the monthly and seasonal energy production and variations also affect the specific yield.

Figures 7 and 8 show the monthly and annual specific yield obtained from CYS and the PV simulators. The 3 PV simulation tools all have their highest specific yield (or highest monthly operating hours) in summer, particularly June and July; this corresponds to the period with highest solar radiation in the measured values at CYS. The period of lowest specific yield for the 3 simulators also matches well with the CYS measurements. Solar radiation is a major contributing factor to specific yield, and so all the PV generators, including CYS, operated at maximum and minimum duration at their peak rating during periods of highest and lowest solar radiation, respectively. This study predicts an average specific yield of 1963 kWh/kW$_p$ for Nicosia from the results of the 3 simulation tools. A research study in Cyprus [11] showed that the installed fixed PV systems in Cyprus produced annual AC specific yields within the range of 1600–1700 kWh/kW$_p$; the study also showed that tracking systems in Cyprus generate AC energy yield of up to 2039 kWh/kW$_p$. Another study presented specific yield values for fixed-axis and 2-axes PV systems varying between 1821 kWh/kW$_p$ and 2311 kWh/kW$_p$ [12]. These results validate the measured results of the single-axis tracking PV system at CYS and also the results of the 3 simulators.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CYS	109	132	181	203	212	241	243	228	236	122	118	96
pvPlanner	108	119	163	176	214	227	230	211	184	150	121	101
PVSyst	120	117	160	169	199	208	206	189	160	156	132	108
Homer	100	106	156	178	208	223	227	215	192	148	113	96

Figure 7. Monthly specific yield (kWh/kW$_p$).

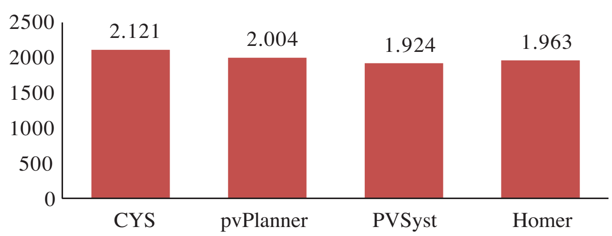


Figure 8. Annual specific yield (kWh/kW$_p$).

3.3. Performance ratio

PR is an important indicator of the performance of a PV system but does not quantify the amount of energy produced. When a PV system has low PR and is located at a good irradiation site, it has a tendency to produce more energy than a PV system with high PR but located at a lower irradiation site [4]. The higher the PR is, the more solar energy will be converted to electrical energy [13]. This study presents a spring performance ratio of 84.9% while the summer performance ratio is 80.4%.

Logically, the PR in summer would be expected to be higher than other seasons due to high solar radiation, but the PR value in this study for summer is lower than the value measured in spring. It was noted earlier in this section that the energy production in summer is higher than spring energy production. This can be due to the negative influence of higher temperature in summer. It was also implied in many studies in the literature that higher ambient temperature affects the performance of PV systems in a negative manner by lowering the system efficiency [14–16].

The annual performance ratio of CYS is 80.8%. At the time the measurements were taken, CYS systems had been installed for less than 2 years. According to the NREL, such newly installed PV systems are expected to have a minimum annual performance ratio of about 77%. Therefore, 80.8% is an acceptable PR value for CYS. Figure 9 compares the CYS performance ratio with the simulation tools. Contrary to the results of PR values at CYS during the summer period, all the PV simulators show considerable decrease in performance ratio, except HOMER. Generally, the variance in performance ratio from season to season is minimal for CYS and all the simulators. The average performance ratio from the simulation tools is 78.6%; this would represent the best case prediction for Nicosia, NC.

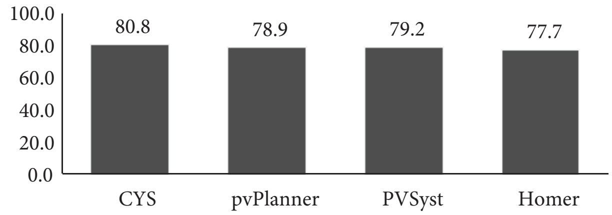


Figure 9. Annual PR of CYS and simulators (%).

An average of 12 out of 13 recently studied PV systems in another study [17,18] reveals that PR ranges from 79% to 85% under Cyprus's meteorological conditions. Therefore, measured results at CYS and also simulation results are parallel with the findings in these references.

The NREL reported that the standard performance ratio for a new PV system is expected to be a minimum of 77%, and, with time, the performance degrades 1% yearly (http://www.solarindustrymag.com/e107_plugins/content/content.php?content.4359). CYS is a new installation of less than 2 years of operation and its annual PR is 80.8%. Therefore, it is expected that in the next 20 years, the system performance ratio will be around 66.1%. According to the obtained results, all the simulators modeled performance ratios higher than the NREL recommendations.

3.4. Capacity factor

The CF values represented in Figure 10 were calculated theoretically using the formula provided in the previous section, except for HOMER which is the only PV simulation tool that modeled the CF. According to the literature, it is expected to have CF values between 20.8% and 26% for south-facing fixed (tilt angle 28°) and dual-axis tracking PV systems in Cyprus, respectively [10]. There are also other studies that reported a fixed PV system with CF of 19.4% and a dual-axis PV system of CF of 23.3% in Cyprus [17,18]. To the knowledge of the authors, there is no previous documentation or studies of the CF for a single-axis PV system in Cyprus. However, it can be deduced that a CF value higher than 19% and less than 26% is reasonable for a single-axis PV system. The single-axis tracking PV system (tilt angle of 30°) considered in this study has an annual CF of 25.06%. PVsyst, pvPlanner, and HOMER modeled CFs of 22.73%, 23.74%, and 23.19%, respectively. A best-case prediction for single-axis PV systems in Nicosia would be 23.22%, which represents the average of the 3 simulators' CF values.

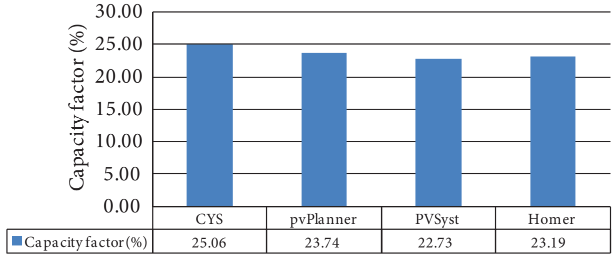


Figure 10. Capacity factors of CYS and 3 simulation tools.

4. Conclusion

This study provides the evaluation of the performance of a grid-tied, single-axis tracking 5.76 kW PV system located in Nicosia, the capital of NC. The energy production, specific yield, PR, and CF of the system were analyzed. Data measured from the installed system were compared with results obtained from 3 PV simulation tools, namely pvPlanner, PVsyst, and HOMER. The meteorological conditions of Nicosia were found to be suitable for PV systems operation. The solar radiation (an average global in-plane radiation of 2565 kWh/m^2, 2580 kWh/m^2, and 2377 kWh/m^2 for CYS, pvPlanner, and PVsyst, respectively) is in parallel with the values obtained in the previous studies on Cyprus and Germany. The high temperature of over 28 °C in summer and the subsequent heat generated was found to have an enormous negative effect on PV modules. The annual energy production, specific yield, PR, and CF of the system at CYS were found to be 12,216 kWh, 2121 kWh/kW$_p$, 80.8%, and 25.06%. These values are reasonable when compared with those from the literature.

All the modeling tools used in this study were found to be relatively accurate. In addition to the conservative nature of the simulators' mathematical algorithms, the difference in actual and simulated energy production can be traced to the use of meteorological data. This work predicts a best-case scenario performance for single-axis PV systems in Nicosia to be 11,320 kWh, 1963 kWh/kW$_p$, 78.6%, and 23.22% for the energy production, specific yield, PR, and CF, respectively.

Not all of the software tools deployed allow manual input of some data. Among the 3 simulators used in this study, only PVsyst allow for the flexibility of selection of various user inputs, thereby increasing the reliability of its results. A more reliable and fair comparison would be possible if all the data (solar radiation, ambient temperature, humidity, clearness index, etc.) measured at the system site were entered as inputs in the simulation tools. Generally, it is clearly observed that installation of PV systems in countries with high solar radiation values is feasible due to the high performance results according to the evaluation of a real-world application in Nicosia, NC. It can also be concluded that all 3 simulation tools present relatively correct outputs in countries with high solar radiation values.

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