A comparison of the performance of mono-Si and poly-Si photovoltaic modules operating under Kosovo climate condition

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The performance analysis and evaluation of a real grid-connected photovoltaic system operating under mild continental climate condition of Kosovo is conducted in this paper. The PV system is installed on a flat roof of the laboratory building at Faculty of Electrical and Computer Engineering. With fixed monocrystalline silicon (m-Si) and polycrystalline silicon (p-Si) module types with an installed capacity of 1.76 kWp and 2.16 kWp respectively, inclined at an angle of 45°C, facing south and through two solar inverters, the latter feds the low voltage distribution grid with electricity. Performance and meteorological data for each type of modules were collected and analyzed for the period between December 2014 to November 2015. The m-Si PV modules have shown higher performance compared with p-Si PV modules. Electricity production during the monitoring period was 1286.57 kWh/kWp from p-Si modules and 1328.21 kWh/kWp from m-Si modules. The annually average daily final yield (Y_f), the annual average value of performance ratio (PR) and system efficiency (η_{sys}), for the p-Si PV modules were found to be 3.53 kWh/kWp/day, 80% and 11.67% respectively. In addition, corresponding values for the m-Si modules were 3.64 kWh/kWp/day, 84% and 12.78% respectively. Furthermore, a comparative analysis of the performance of the photovoltaic system under study with other photovoltaic systems installed in various countries worldwide was carefully investigated and presented in this paper.

Keywords: Photovoltaics, Monocrystalline, Polycrystalline, Grid-connected, Final yield, Performance ratio

I. INTRODUCTION

A growing demand for energy, the significant increase in energy prices and the increasing depletion of fossil fuel reserves, coupled with the environmental damage caused by conventional thermal power plants have led to a world-wide focus on developing alternative means of electricity production. Kosovo is located in South-East Europe[1] which is known for its mild continental climate. Electricity generation in Kosovo is largely based on exhaustible fossil fuels such as lignite. Furthermore, about 97% of the total electricity production comes from thermal coal-fired power plants[2]. In Kosovo the highest value of solar radiation was recorded to be 1600 kWh/m^2/year[3]. Such values of solar radiation are relatively good and promising when compared to the values of solar radiation in other countries in Europe[4]. Indeed, this shows the Kosovo's favourable climatic conditions for penetration of renewable sources, especially of photovoltaic (PV) systems in the large scale. The conventional ways to produce energy do not only have a negative impact on the surrounding environment but in the society as a whole. Therefore, applying strategies to reduce the dependence on conventional energy sources is crucial to be undertaken in the level of the state. The latter can be indeed achieved through the integration of renewable energy sources in every energy sector. In recent years, a significant development of renewable energy technologies such as solar-based power plants with the major focus in photovoltaic systems was observed. PV systems usually utilize different technologies such as m-Si, p-Si, amorphous silicon (a-Si), and thin film technologies like copper indium diselenide (CIS), copper indium gallium selenide (CIGS) and cadmium tellureide (CdTe)[5]. However, the majority of the installed PV systems around the world have crystalline silicon technology[6]. Electricity production using photovoltaic (PV) systems is stable, reliable and have the potential to play an important role in CO_2 emissions mitigation[7]. Over the years, various studies have been conducted on the performance parameters of different PV systems installed in different geographical locations, with different climatic conditions[8–18]. Authors in[19] analysed the performance of a 171.36 kWp grid-connected photovoltaic park on the island of Crete. The performance ratio and various power losses were monitored and then carefully evaluated over a period of one year. In[20] the results from the assessment of the performance of four different roof-mounted PV systems in Abu Dhabi, UAE for a period of one year were presented. Such systems consist of m-Si and c-Si solar modules. The monthly average and annual performance parameters of the PV systems assessed include the total energy generated, final yield (YF), energy payback time (EPBT), capacity factor (CF) and CO_2 emission reduction. The compar-

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ison between the four systems shown that m-Si based PV systems resulted in higher monthly total average final yield than PV systems with c-Si modules. Authors in[21] monitored the performance of 2 kW grid-connected solar PV plant installed in Nis, Serbia. The global solar energy, ambient temperature, wind speed and generated electrical energy were the 2-year monitored parameters. Furthermore, Edalati et al.[22] compared the performance of mono- and poly-crystalline silicon PV modules used in a real 11.04 kWp grid-connected PV system in dry climatic condition for a period of one year. Results obtained from comparing data between m-Si and p-Si PV module technologies with the same efficiency and maximum power shown that p-Si modules produce more electricity than m-Si modules, especially in higher ambient and module temperatures. Therefore, authors suggest p-Si PV modules to be used in dry and warm regions. Micheli et al[23] presented the results from the comparison of the performance of a two grid-connected photovoltaic systems (17.94 kWp and 15.9 kWp installed capacity) with application of different module technology in Northern Italy. The calculated performance ratio was 89.1% for the first PV system, which was equipped with modules of mono crystalline silicon wafer surrounded by ultra-thin amorphous silicon layers, and 82.7% for the second PV system, which was equipped with mono crystalline silicon modules. An analysis of the performance of two grid-connected power plants with m-Si and a-Si under Western India climatic conditions was conducted by authors in[24]. Performance ratio of the m-Si modules ranges from 57.1% to 93.14% and for a-Si modules PR ranges from 53.72% to 87.64%. The a-Si modules found to have high capture losses as compared to the m-Si modules. Muhammad et al.[25] conducted a comparative performance evaluation of three commercially available photovoltaic modules (monocrystalline, polycrystalline, and amorphous silicon) in Taxila, Pakistan. The authors were able to conclude that output power of modules increases linearly with the increase of solar irradiance. The crystalline modules have shown high average output power while the amorphous Si modules have shown higher normalized output power in low irradiance condition. The average module efficiency of monocrystalline modules is higher than average module efficiency of other two modules. Outcomes of a 2.5-year investigation of defects occurred in multi-crystalline silicon modules of a 1 kWp PV system operating under western Himalayan climate condition was conducted in[26]. From the results obtained, authors were able to conclude that the main defects observed were 'junction failure', 'surface browning', 'hotspots' and 'snail trails' mainly caused by the climatic condition of the location where the PV system was installed and the use of improper material during the process of module manufacturing. The analysis was carried out using the visual inspection and infrared thermal imaging method. It is worthy to point out that several modules have experienced high level damage equal to 50% degradation during their operation in peak time resulting in the lower value of energy generated.

The objective of this study is to compare the performance of two PV modules technologies (m-Si and p-Si) operating under the same fluctuations of solar irradiance and mild continental climatic condition of Kosovo. To identify the more appropriate PV modules technology, a series of performances of these two PV modules technologies as part of the main grid-connected PV system installed in Pristina, Kosovo were consequently measured during twelve months.

II. THE PV SYSTEM

1. PV system description

The PV system under study is installed on the roof of Laboratory buildings at the Faculty of Electrical and Computer Engineering in Pristina (latitude 42.6667°N, longitude 21.1667°E) Kosovo. The region is characterized with a mild continental climate accompanied with warm summers and cold winters. An overall view of the PV system with the map of its geographic location is given in Fig. 1. In addition, the schematic block circuit diagram of the PV system is presented in Fig. 2. The modules are fixed, inclined at an angle of 45°, facing south and with no buildings or other structures around, which would possibly shade them and cause lower power output to be generated. It is important to highlight that the PV modules were not cleaned throughout the monitoring period. The studied system is composed of three main following components:

a. PV modules

b. Inverters

c. Data measuring and monitoring devices

FIG. 1: The map of geographic location of PV System and PV modules mounted in the roof of laboratory building at FECE

TABLE I: Electrical and mechanical properties of the PV modules

Parameter	Polycrystalline	Monocrystalline
Electrical proporties of the PV modules at STC[a]		
Maximum power P_{max} (Wp)	240	195
Voltage at maximum power point U_{mpp} (V)	29.75	36.8
Current at maximum power point I_{mpp} (A)	8.08	5.3
Open circuit voltage U_{OC}	37.4	45.4
Short circuit current I_{SC} (A)	8.6	5.67
Module temperature at NOCT[b] T_{NOCT} (°C)	47	45
Module efficiency	14.6	15.3
Mechanical properties of the PV modules		
Module length (mm)	1660	1580
Module Width (mm)	990	808
Operating temperature	-40°C to + 80°C	-40°C to + 80°C
Wight (kg)	22	15.5

[a] STC (Standard Test Conditions): irradiance 1000 W/m^2, ambient temperature 25°C and air mass 1.5
[b] NOCT: Irradiance 800 W/m^2, ambient temperature 20°C and wind speed 1m/s

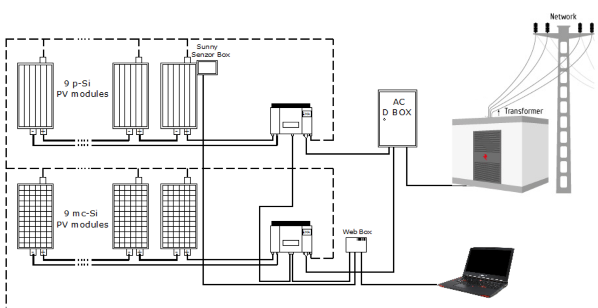


FIG. 2: Schematic block circuit diagram of the PV system

2. PV modules

The grid-connected PV array is composed of 18 modules, with an active surface area of 26.26 m^2. It is divided into 2 strings with 9 modules each, mounted in series. The installed capacity of p-Si and m-Si modules is 2.16 kWp and 1.76 kWp respectively. Regarding the type of PV modules, there are 9 PolySol 240 TE (IBC Solar, STC Power 240 Wp) polycrystalline silicon modules, and 9 MonoSol 195 DS (IBC Solar, STC Power 195 Wp) monocrystalline silicon modules. Physical characteristics in Standard Test Conditions, STC (T=25°C, I=1000 W/m^2 and AM 1.5) of both p-Si and m-Si PV modules are given in Table I.

3. Inverters

Based on the maximum power output generated from each type of PV modules, inverters are then selected from SMA Solar Technology AG, model Sunny Boy SB 2000 HF-30. These are single phase inverters with high-frequency transformer power of 2000W, and efficiency of 96.3%. Furthermore, it is tested that they can run at the ambient temperature from -25°C to 60°C. There is a display at the front of the inverters from which the values of the daily and total amounts of the power generated by the solar PV plant can be read. Technical data of the Sunny Boy 2000HF-30 inverter are given in Table II.

TABLE II: Electrical data of *Sunny Boy 2000 HF-30* inverter

Topology	HF transformer
Maximum DC power at cos$\varphi = 1$	2100 W
Nominal AC voltage	220V/230V/240V
Maximum input voltage	700 V
Maximum output current	11.4 A
AC power frequency	50Hz/60Hz
Power losses in night operation	≤1 W
Operating temperature range	-25°C to 60°C
Rated power at 230 V, 50 Hz	2000W
Maximum efficiency	96.3 %/ 95 %
Rated grid voltage	230 V

4. Measurement methodology of the electrical and meteorological parameters from the PV system

The PV system is fully monitored using a SMA Sunny WebBox data logger from which the data recorded from all the instruments in 15 minutes intervals is extracted. This device enables continuous recording of the PV system's electrical parameters (DC current and voltage, AC current and voltage, power at the output from the solar modules) as well as meteorological parameters such as solar radiation, ambient and module temperature. The measured values are stored as CSV or XML excel format to enable their further numeric and graphic processing analysis. The measured data from the devices are stored on a memory card inside the Sunny WebBox and are transmitted to a computer once a month. The solar radiation sensor had a measurement range of 0-1500 W/m^2, measurement accuracy of ±8% and a resolution of 1 W/m^2. The PV module's temperature sensor is a PT 100 platinum sensor with a measurement range from -20°C to +110°C, with an accuracy of ±0.5°C and a resolution of 0.1°C. The anemometer has a measurement range of 0.8-40 m/s and a measurement accuracy of ±0.5°C. The Sunny Sensor Box is installed outside facing southwards at an angle of 45° in relation to the horizontal surface, and measures global solar radiation and temperature. The inverter and ancillary equipment for the monitoring and data acquisition from the PV system on the FECE building in Pristina are shown in Fig. 3.

FIG. 3: Inverters and WebBox equipment for the monitoring and data acquisition of the PV system

III. PERFORMANCE OF THE PV SYSTEM

Detailed and comprehensive evaluation of the PV system performance parameters is crucial towards a proper and reliable operation of the system. PV system performance is an indicator of the quality of its design and functionality. The performance analysis is conducted based on the International Electrotechnical Commission (IEC) standards with the focus on IEC standard 61724[27]. The most common performance parameters that provide a base for comparing PV modules include final yield (Y_F), reference yield (Y_R), capacity factor (C_F) and performance ratio (P_R).

A. Energy Output

The total AC energy generated from a PV system can be defined as the daily (E_{Acd}) and monthly (E_{Acm}) energy generated by the system obtained as in[8,14,27–29]:

$$E_{ACd} = \sum_{t=1}^{24} E_{ACt} \quad and \quad E_{ACm} = \sum_{t=1}^{N} E_{ACd} \tag{1}$$

Where N is the number of days in a month.

B. System Yield

The system yield indicates the actual electric generation of the PV system in respect to its rated capacity. The array yield is defined as the energy output from the PV array over a defined period (day, month or year) divided by its rated power and is given as[8,17,19,30]:

$$Y_{A,d} = \frac{E_{DC,d}}{P_{PV,rated}} \tag{2}$$

The final yield is the total energy output from the inverter for a defined period (day, month or year). It indicates the number of full sun hours during which the PV system was able to operate. The annual final yield is given by the expression[8,14,16,29,30]:

$$Y_{F,a} = \frac{E_{AC,a}}{P_{PV,rated}} \tag{3}$$

Where $E_{AC,a}$, is the total annual AC energy output (kWh) and $P_{PV,rated}$ is the nominal power of the installed PV system under standard test conditions (STC). The corresponding values for the monthly and daily final yield are obtained using the ratio of the monthly and daily AC energy output (kWh) to the nominal PV system power, respectively.

The daily final yield ($Y_{F,d}$) and the monthly average final yield ($Y_{F,m}$) are given as described in[8,14,16,29,30]:

$$Y_{F,d} = \frac{E_{AC,d}}{P_{PV,rated}} \quad and \quad Y_{F,m} = \frac{1}{N}\sum_{d=1}^{N} Y_{F,d} \tag{4}$$

The reference yield (Y_R) is the ratio of the total in-plane solar insolation (kWh/m^2) to the module's reference in- plan irradiance G_0 (G_0= $1kW/m^2$)[8,14,16,29,30]. The unit of total in-plane radiation is kWh/m^2/day, therefore the unit of reference yield is h/d.

$$Y_R = \frac{H_t}{G_0} \tag{5}$$

C. Performance Ratio

The performance ratio represents the ratio between energy fed to the grid (final yield) to the energy that the system could have produced if it had been operating under its rated conditions (STC) of 1 kW/m^2 (reference yield)[8,18,21,29,31]. The performance ratio is also defined as the ratio between the final yield to the reference yield and represents the total losses in the PV system due to conversion process from DC to AC. Typical losses of a PV system include losses due to panel degradation (η_{deg}), temperature (η_{tem}), soiling (η_{solli}) and inverter (η_{inv}). The performance ratio can also be expressed as[8,19].

$$PR = \frac{Y_F}{Y_R} = \frac{E_{real}}{E_{ideal}} = \eta_{deg}\eta_{tem}\eta_{solli}\eta_{inv} \tag{6}$$

The PV system's efficiency is compared with the nominal efficiency of the photovoltaic generator under STC. The performance ratio is defined by the following equations as in[14,19]:

$$PR = \frac{Y_F}{Y_R} = \frac{E_{AC}G_{STC}}{H_T P_{DCSTC}} \tag{7}$$

D. Capacity Factor

The capacity factor (CF) represents the energy delivered by an electric power generating system. If the system delivers full rated power continuously, its CF will be unity. The capacity factor (CF) is defined as the ratio of the actual annual energy output to the amount of energy the PV system would generate if it had been operating at its rated power ($P_{PV,rated}$) for 24 h per day for a year and is given as[8,16,19]:

$$CF = \frac{Y_{Fa}}{24x365} = \frac{E_{AC,d}}{P_{PV,rated}8760} = \frac{H_t PR}{8760} \tag{8}$$

The CF for a grid-connected PV system is also given as[16]:

$$CF = \frac{h/day \quad of \quad ''peak \quad sun''}{24h/day} \tag{9}$$

E. PV module efficiency

The PV module efficiency represents the effective energy generated by the module with respect to the available radiation. The monthly average PV module efficiency is calculated as[16]:

$$\eta_{sys,m} = \frac{E_{DC}}{G_T A_a} x100\% \tag{10}$$

Where E_{DC} is monthly average daily total DC energy output.

F. System efficiency

A solar PV plant's energy efficiency denotes the relationship between the electrical energy generated by the solar PV system at a certain point in time and the solar energy falling on the system's solar modules at the same point in time. It is therefore possible to talk about hourly, daily, monthly and annual energy efficiency. The monthly system efficiency is calculated as[10]:

$$\eta_{sys,m} = \frac{E_{AC}}{G_T A_a} x100\% \tag{11}$$

where E_{AC} is the total amount of energy generated by the solar PV system and fed to the power grid over a certain period, G_T is the total amount of global solar energy falling during this time on one square metre of the solar PV system (Wh/m^2), and A_a is the total surface area of the solar modules (m^2).

G. Energy losses

Energy losses in the PV system occur from a variety of processes that take place in various parts of the system. These losses affect the performance of PV system and thereby justify why it is necessary to evaluate these losses using detailed performance monitoring data. The types of losses are array capture losses, system losses, cell temperature losses, soiling and degradation losses. Soiling and degradation losses are not discussed here.

H. Array capture losses

Array capture losses represent all the losses that occur during operation of the PV modules. They indicate how long the array would be required to operate at its nominal power to provide the losses. The array energy losses L_C from this system are obtained as the difference between the reference yield and the array's yield and is given as[8,19,29]:

$$L_c = Y_R - Y_A \tag{12}$$

The capture losses are constituents of the capture losses termed as thermal capture losses and miscellaneous capture loss. Thermal capture losses (L_{ct}) are associated with the thermal energy losses which occur due to increase in the module temperature of above 25 °C. It is given as the difference between the reference and the corrected reference yield[29]:

$$L_{ct} = Y_R - Y_{CR} \tag{13}$$

Miscellaneous capture losses occur due to multiple causes such as Joule effect in the wiring, diode loss, shading effects, low irradiance, snow, dust accumulation over the module, mismatch and losses due to maximum power point tracking process. This are given as the difference between corrected reference yield and array yield[29]:

$$L_{cm} = Y_{CR} - Y_A \tag{14}$$

I. System losses

System losses (L_S) are result of the inversion and are obtained as the difference between the array's yield and the final yield and given as[8,19,29]:

$$L_s = Y_A - Y_F \tag{15}$$

IV. RESULTS AND DISCUSSION

A. Meteorological data analysis

In order to investigate the behaviour of the PV system, the meteorological data recorded in the Sunny WebBox device of the PV system were analyzed and studied carefully. Such data include irradiance, ambient temperature, module temperature and wind speed. The latter were collected for the period between 1 December 2014 to 30 November 2015. The solar radiation is the principal parameter which plays a significant role towards a proper and reliable operation of PV module as well as in its performance. The monthly average variation of the total in-plane solar radiation which reaches PV modules' surface (45° tilted) through the monitored period is shown in Fig. 4. The monthly average solar radiation varies from a minimum of 35 kWh/m^2 in December to a maximum of 216 kWh/m^2 in July. As it can be seen from the Fig. 4, the solar radiation is higher during the spring, summer and autumn months (March, April, May, June, July, August, September, October and November) and lower in the winter months (January, February and December). The monthly variation of the daily average ambient and module temperature is shown in Fig. 5. The daily average ambient temperature varies from a minimum of 0.97°C in January to a maximum of 25.44°C in July. The daily average module temperature varies from a minimum of 1.02°C in January to a maximum of 28.36°C in July. In addition, the module temperature reached a maximum of 54.16°C at an irradiance of 714 W/m^2 and wind speed of 0.463 m/s. Furthermore, Fig. 5 shows the monthly variation of the daily average wind speed. The latter varies from a minimum of 0.66 m/s in November to a maximum of 1.25 m/s in March.

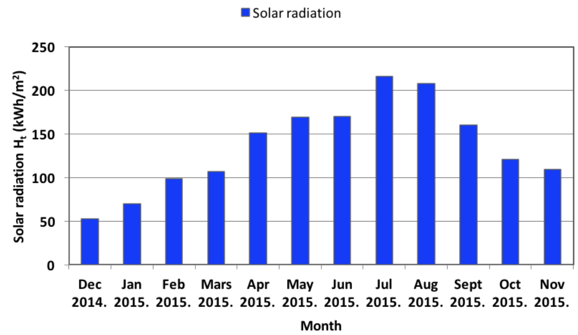


FIG. 4: Total in-plane solar radiation (H_t) falling on one square meter of a South-oriented surface, at the angle of 45° in relation to the horizontal surface.

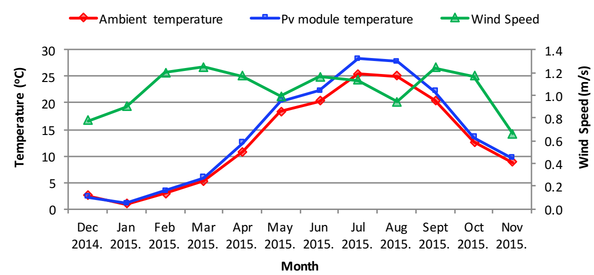


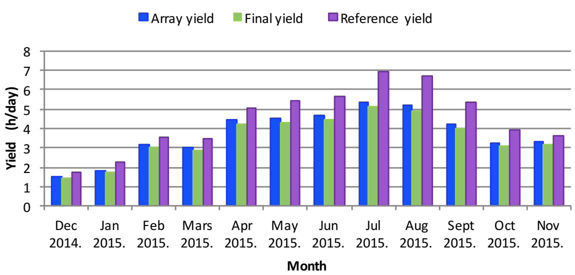
FIG. 5: Monthly variation of daily average ambient, module temperature and wind speed.

B. Performance evaluation results of PV system under study

1. Array reference and final yield

In order to assess the performance of the PV system configured as grid-connected, Eq. 2 3 4 5 are used for both the p-Si and m-Si modules. The daily average array yield, reference yield and final yield for each PV technology are shown in Fig. 6. The final yields give the energy produced with respect to system size, and it is a convenient way to compare the performance of PV systems with different sizes. It is expressed in hours/day. The reference yield represents the number of peak sun hours. It is a function of location, orientation and inclination of solar PV array. The daily average reference yield is directly proportional to the daily average radiation. From the results obtained it can be observed its variation from a minimum of 1.7 h/d to a maximum of 6.98 h/d. The daily average final yield for p-Si modules varied from a minimum of 1.419 h/d to a maximum of 5.093 h/d. On the other hand this value varied from a minimum of 1.470 h/d to a maximum of 5.220 h/d for m-Si modules. A higher annual output power was recorded from m-Si modules compared to the p-Si modules. The daily average array field varied from a minimum of 1.494

h/d to a maximum of 5.363 h/d for p-Si modules and from a minimum of 1.548 h/d to a maximum of 5.680 h/d for m-Si modules. Throughout the entire monitoring period, it was observed a slight difference between average array yield and final yield. The DC/AC conversion losses caused by the inverter are the reason behind this difference. As it can be seen from the Fig. 6, lower values of yields are observed during December and January due to the lower values of in-plane solar irradiation and bad weather accompanied with rain, snow and cloudy periods.



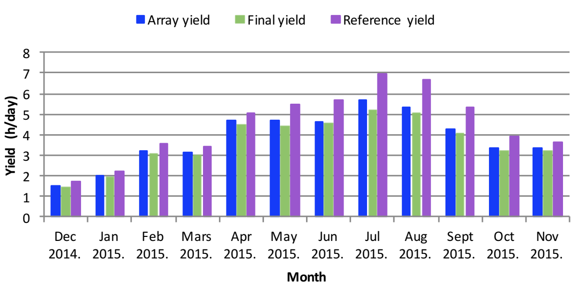


FIG. 6: Monthly variation of daily average array yield (Y_A), reference yield (Y_R) and final yield (Y_F) for the p-Si and m-Si modules respectively

2. Array capture losses

The electric power output from a PV system depends on incident solar radiation, cell temperature, title angle of modules, and load resistance. The manufacturer typically defines the specific electrical parameters of the PV module such as their open circuit voltage (V_{OC}), short circuit current (I_{SC}), maximum power, temperature coefficient of maximum power and nominal cell operating temperature of 25°C, according to STC. There are many sources which cause energy losses in PV system. Indeed, the losses strongly affect the performance of PV system. Some of the most common losses include: array capture losses, system losses, cell temperature losses, soiling and degradation losses. The capture losses are constituents of the capture losses termed as thermal capture losses and miscellaneous capture losses. Monthly variation of daily average final yield, reference yield, thermal capture losses, system losses, and miscellaneous capture losses, for the p-Si and m-Si modules are shown in Fig. 7. The monthly average daily value of useful energy for the p-Si modules was found to be 3.06 [kWh/day] in December and 11 [kWh/day] in July, with an annual average of 7.36 [kWh/day]. The corresponding values for the m- Si modules were 2.58 [kWh/day] in December and 9.16 [kWh/day] in July, with an annual average of 6.38 [kWh/day]. Thermal capture losses are the same for both m-Si and p-Si modules because their temperature coefficient of maximum power is the same. Highest thermal capture losses of 9.6 % of the reference yield are recorded in January when the cell operating temperatures were the lowest.

The negative values of a thermal capture losses, due to high temperatures during the summer indicate the positive effect of the temperature on the PV modules output power. The system losses for p-Si modules vary from a minimum of 0.075 h/d in December to a maximum of 0.27 h/d in July. Furthemore, the latter for the m-Si modules varies from a minimum of 0.078 h/d in December to a maximum of 0.46 h/d in July. The average of the annual system losses for the m-Si modules are higher compared to the p-Si modules due to their lower efficiency.

Thermal capture losses, system losses and miscellaneous capture losses which make up the overall energy losses in the PV system are highly effected from metrological condition such as ambient temperature, module temperature as well as wind speed on which the latter has been operating. From the results obtained it was concluded that the highest value of energy losses was recorded during July and August months when the ambient and module temperatures reached their maximum within monitored period. The lowest value of energy losses was estimated to be on January, when the ambient and module temperature were at their minimum. Regarding wind speed effect in the losses, not in all the cases the highest energy losses occurred during highest values of wind speed. However, in the case under study the highest value of energy losses was estimated during higher wind speed compared to the value of wind speed when the lowest energy losses were recorded. Consequently, we can conclude that wind speed has also impact in the PV system energy losses, but still the role of the module and ambient temperature in the losses is more fundamental when choosing the location of the installation of new PV systems. Furthermore, the role of the ambient and module temperature is of utter importance to be studied for the reasons mentioned above, since they do not only affect the energy losses but consequently lead to lower module and system efficiency.

3. Performance ratio

The performance ratio plays a significant role in the performance evaluation of PV system. It indicates the overall effect of losses on the array's rated output due to array temperature, less than full utilization of incident

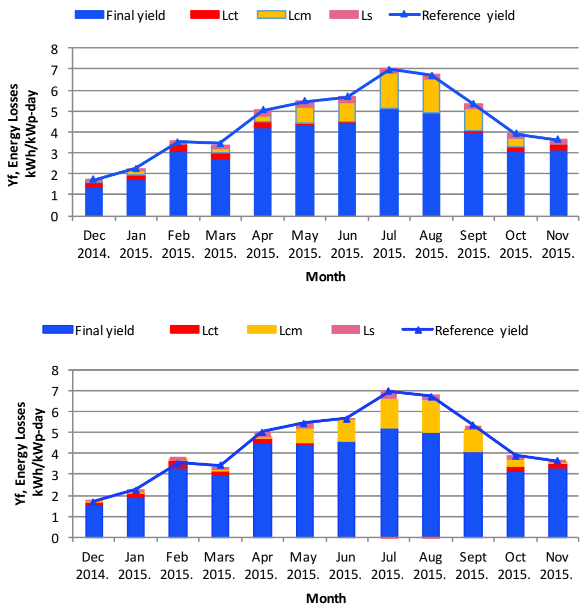


FIG. 7: Monthly variation of daily average thermal capture losses (L_{ct}) miscellaneous capture losses (L_{cm}), system losses (L_S) and final yield (Y_F) for p-Si and m-Si modules respectively.

solar radiation, and system components's inadequate efficiency or failure. Monthly variation of daily average performance ratio for p-Si and m-Si modules is presented in 8. The performance ratio for p-Si modules varied between 73% in July and August and 88% in November and February. The annual average performance ratio was 80%. The performance ratio for m-Si modules varied between 75% in July and August and 94% in February. While, the annual average performance ratio was recorded to be 84%. In general, monthly average value of performance ratio is lower during the summer months (when the ambient and module temperatures are higher) and higher during autumn and winter months (when the ambient and module temperatures are lower). From the results obtained, we were able to conclude that the annual average performance ratio of the m-Si PV modules is higher than that of p-Si PV modules as shown in Fig. 8. The values of performance ratio of PV system differ from those measured in STC due to the actual variation of the outdoor condition. The hourly average performance ratio of the PV system with the p-Si and m-Si modules for a day in May 2015 is shown in Fig. 9. From the Fig. 9, it can be deduced that the global solar irradiance has a significant impact on the performance ratio of both PV modules technology. In this case, the performance ratio of the modules decreases with the increase of global solar irradiance. During the observed hours between 8 am to 14 pm for a typical spring day, the performance ratio of p-Si modules and m-Si modules decreased by 33.3 and 28.2% respectively. During the same observation period, solar irradiance increased by 390 W/m^2.

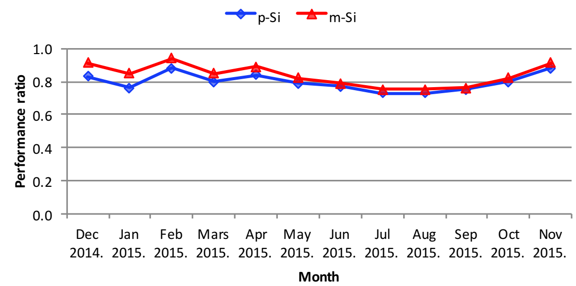


FIG. 8: Monthly average performance ratio of p-Si and m-Si PV modules

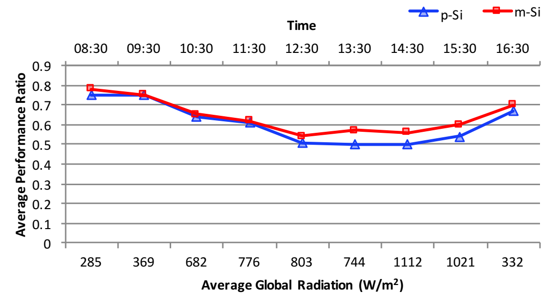


FIG. 9: Variation of hourly average Performance Ratio of the PV system with p-Si and m-Si modules from 8 am to 5 pm for the day 09.05.2015

4. System efficiency and power output

System efficiency and module efficiency of the PV system under study were calculated using Eq. 12 and Eq. 13. The results for these parameters for both m-Si and p-Si modules are shown in Fig. 10. As it can be seen, system efficiency is lower during July, August and September than in other months of the year. Low system efficiency was also observed in January due to the bad weather condition accompanied with snow and ice on the modules. Annual average system efficiency of p-Si and m-Si are 11.67 and 12.78% respectively. The module efficiency for p-Si modules varied between 11.26% in July and 13.49% in November and the annual average module efficiency was 12.30%. On the other hand, the module efficiency for m-Si modules varied between 12.05% in July and 14.35% in April, and the annual average module efficiency was recorded to be 13.30%.

The module efficiency of PV modules continuously changes from the value measured in STC due to the variation of the outdoor weather condition. The hourly average module efficiency of the p-Si and m-Si modules for

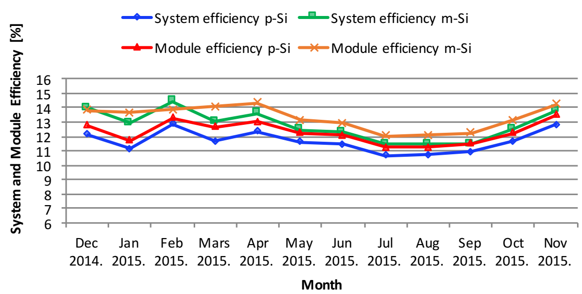


FIG. 10: Monthly average system efficiency and module efficiency of p-Si and m-Si PV modules

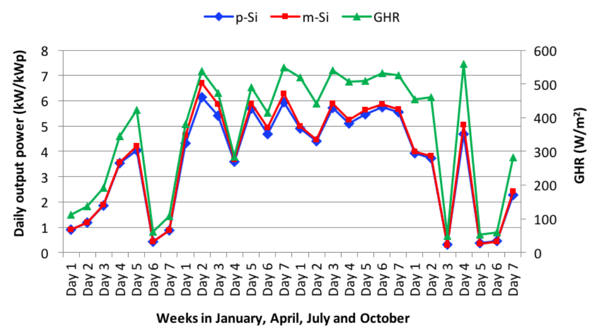


FIG. 12: Variation of daily average output power of day in different months

one day in May 2015 is shown in Fig. 11. As in the case of performance ratio, the module efficiency depends on the solar irradiation. In this context, the efficiency decreases as the solar radiation increases. For instance, the module efficiency for p-Si and m-Si decreased by 33.1 and 27.7% respectively while the solar irradiance increased by 390 W/m^2 during the observation period (Fig. 11).

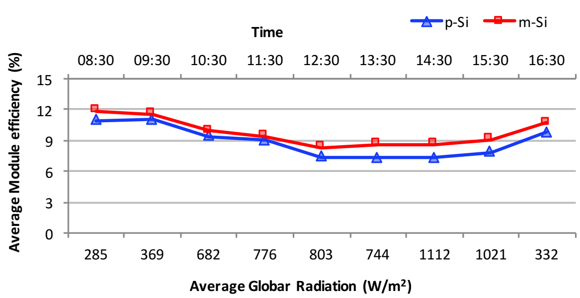


FIG. 11: Variation of hourly average module efficiency of p-Si and m-Si PV modules from 8 am to 5 pm for the day 09.05.2015

Daily average power output of the modules for the selected week throughout different months is shown in Fig. 12. Based on the obtained data, the average power output is more or less the same for both PV modules technologies at lower solar irradiance (below 150 W/m^2). On the other hand, the daily average power output from m-Si modules is higher than that of p-Si modules at higher solar irradiance (above 400 W/m^2).

A comparison of different existing solar PV systems installed in different locations around the world is given in Table III. PV system under study demonstrated higher performance ratio of the m-Si modules and p-Si modules compared with PV systems installed in other locations due to the favorable meteorological condition in Kosovo for the integration of PV systems (high values of solar radiation). In the studied PV system the annual average PR of the m-Si modules is higher than that of p-Si modules. In addition, it is higher than the ones reported in Iran, Ireland, India, and Spain. Furthermore, the annual average daily final yields of m-Si and p-Si modules in the PV system are 3.64 and 3.53 kW h/kWp/day respectively. These values are higher than those reported in Ireland, India, and Spain. Also, the performance ratio and system efficiency are higher than the ones reported in Ireland, India, and Spain.

PV system technology is completely a clean and zero-emission process used for generation of renewable energy. However, additional investigation regarding improvement of the PV module efficiency is crucial of further research. Higher values of performance ratio, capacity factor and system efficiency are recorded for m-Si PV modules than for p-Si PV modules. This is due to a higher manufacturing efficiency of m-Si PV modules. Consequently, the final yield of m-Si modules is estimated to be higher when compared to the final yield of p-Si modules. Regarding the losses, the m-Si modules have performed lower miscellaneous capture losses and system losses. Considering that crystalline PV modules are widely used in solar PV systems there is a big need for major improvements in the manufacturing process of the modules, which could possibly increase their efficiency and lead to an increase in the use of them mainly for electricity generation purposes. Furthermore, the advantages of grid-connected PV power systems are accompanied with many critical challenges. Overvoltages, the total harmonic distortion (THD) and other important issues related to the integration of these systems in the power system operation and planning are very important to be studied and analysed in detail. PV systems performance enhancement and their future increased participation in the overall electricity generation is indeed strong related to the effect they have in the power grid, environment and society.

V. CONCLUSION

The performance analysis of the grid-connected PV system installed on a flat roof of a laboratory building of Faculty of Electrical and Computer Engineering in Pristina, Kosovo is presented in this paper. The monitoring results are examined to analyse the behaviour

TABLE III: Comparison of the performance of PV Systems installed in different locations

Location	Module type	Final Yield (h/day)	Module Efficiency (%)	Performance ratio (%)	System efficiency (%)	References
Kerman, Iran	p-Si,m-Si	5.38, 5.24	14.3, 14.3	82.92, 80.81	//	[20]
Ballymena, Ireland	m-Si	1.7	10.0	62	9.0	[26]
Dublin, Ireland	m-Si	2.41	14.9	81.5	12.6	[4]
Gujart, India	m-Si	2.79-5.14	11.07	75.3	10.52	[22]
Jaen, Spain	p-Si	2.4	8.9	62.7	7.8	[27]
Pristina, Kosovo	p-Si, m-Si	3.53, 3.64	12.3, 13.3	80.0, 84.0	11.67, 12.78	Present Study

of PV system in the climatic conditions of North-East Kosovo. The operating performance of the latter composed of two types of PV modules technologies (p-Si modules and m-Si modules) was investigated based on final yield, performance ratio, and system efficiency. Electricity production during the monitoring period was 1286.57 kWh/kWp from p-Si modules and 1328.21 kWh/kWp from m-Si modules. The final yield of p-Si modules varied between 1.419 h/d in December and 5.093 h/d in July. The final yield for m-Si modules of PV system was higher and it varied between 1.470 h/d in December and 5.220 h/d in July. In terms of performance ratio, m-Si modules have shown higher performance than p-Si modules. In addition, the PR values varied between 75 and 91% (m-Si modules) and between 73 and 88% (p-Si modules). The influence of the ambient and module temperature is reflected in the performance ratio, capacity factor and system efficiency of the PV system. The data acquired in this study are useful for making comparisons with studies in other countries. In the light of everything presented here, it can be concluded that Kosovo is one of the truly favourable locations in Europe for the use of solar PV systems due to the high level of solar radiation. Although the main source of electricity production in Kosovo is lignite, indeed solar PV systems can play a vital role in the future in reshaping the power supply system towards a more sustainable, clean and reliable energy system.

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NOMENCLATURE

η Efficiency (%)
A_a PV modules surface
CF Capacity factor
$E_{AC,a}$ Total annual AC energy output (kWh
$E_{AC,d}$ Total daily generated energy (kWh)
$E_{AC,m}$ Total monthly generated energy (kWh)
G_0 Reference irradiance (kW/m^2)
G_{STC} Total solar radiation under standard test conditions (kW/m^2)
G_T Total in-plane solar radiation (kW/m^2)
H_T total in-plane solar insolation (kW/m^2)
L_C Capture losses (h/day)
L_S System losses (h/day)
L_T Cell temperature losses (h/day)
$P_{PV,rated}$ Nominal power of the installed PV array at standard test conditions (STC)
PR Performance ratio
PV Photovoltaic
STC Standard Test Conditions
$Y_{F,d}$ Daily final yield (kWh/KWp)
$Y_{F,m}$ Monthly final yield (kWh/KWp)
Y_R Reference yield (kWh/KWp)

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