

Performance analysis of grid-connected rooftop solar photovoltaic systems using different photovoltaic technologies: a case study in Romania

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Abstract— Solar energy is one of the most important unlimited renewable energy sources that is becoming an increasingly used alternative to generate cleaner electricity. The efficiency of solar photovoltaic technologies has improved considerably, especially in the last decade. This study investigates the performance of a 6-kW grid-connected residential rooftop photovoltaic systems that are using various photovoltaic modules technologies, namely monocrystalline silicon, polycrystalline silicon, heterojunction with intrinsic thin layer, thin film copper indium gallium selenide, cadmium telluride and amorphous silicon for a residence in Romania. The results highlight that thin film copper indium gallium selenide technology is the most suitable in terms of monthly average performance ratio, while monocrystalline silicon panel is the most appropriate option in terms of ratio between produced electricity and occupied area. The findings of this paper are valuable for the stakeholders in establishing the photovoltaic modules technologies that are suitable for the investigated location or other zones with similar climatic characteristics.

Keywords— Photovoltaics, Performance ratio, Romania, Solar energy, Photovoltaic technologies

I. INTRODUCTION

Global warming, mainly caused by carbon dioxide emissions resulted from burning fossil fuels for energy generation, represents one of the most important concerns for the humanity. Renewable energy sources can play a significant role in diminishing the carbon dioxide emissions, unlike fossil fuels, being an environmentally friendly alternative for energy production [1]. Globally, renewable energy deployment expanded considerably, in 2019, the renewable power capacity reaching about 2581 GW [2].

Solar energy has become one of the fastest growing renewable energy sources, the cost of generating electric energy from solar energy have decreased notably in the last decade [3-5].

Solar photovoltaic (PV) is the most deployed solar energy technology, converting sunlight to electric energy by employing PV cells manufactured from semiconductors [6-8].

The crystalline and thin film represent the main PV technologies that are currently commercially available. The crystalline PV technology accounts for more than 89% of the market share, especially due to mature technology that provide an increased efficiency at a competitive cost and reliability [9-10]. In the crystalline PV technology, silicon is the principal component used in the PV cells' production process. The main commercially types of silicon based crystalline solar cells are the following: monocrystalline silicon (m-Si), polycrystalline silicon (p-Si) and heterojunction with intrinsic thin layer (HIT). In the thin film PV technology, thin layers of different semiconductor materials are deposited usually on glass in the manufacturing process. The layer made of semiconductor materials has a thickness of less than ten micrometers, compared to the one encountered in the crystalline PV technology where the thickness is a few hundred micrometers [11-12]. Copper indium gallium selenide (CIGS), cadmium telluride (CdTe) and amorphous silicon (a-Si) are the principal commercially types of thin film solar cells [13-14]. Although currently the crystalline PV technology has the largest market share, in recent years the market share of thin film technology has grown due to advances in technology.

Cluj-Napoca is the capital of Cluj county, being located in Northwestern part of Romania. Its coordinates are latitude 46.7712 North and longitude 23.6236 East. Cluj-Napoca has a temperate continental climate with warm dry summers and cold winters. The city's historical climate has experienced average annual temperature around 8.2° C, receiving on average about 663 millimeters of precipitation annually. The annual sunshine duration is greater than 2000 hours. Cluj-Napoca is one of the largest cities in the country and, at the same time, one of the most populous in Romania, being one of the cities where a strong increase in grid-connected rooftop PV systems deployment have been recently registered.

Recent papers have investigated the performance of grid-connected PV systems using various PV technologies in several locations. Reference [15] used PVsyst software to investigate the performance of 8 kW grid-connected PV systems based on various PV technologies in Nanjing, China for a monsoon-influenced humid subtropical climate. The study revealed that

CdTe technology registered the highest monthly average performance ratio. Reference [16] evaluated the performance of principal PV technologies in Belem, Brazil for a tropical rainforest climate and found that the most appropriate relationship between produced electricity and occupied area was obtained by HIT technology. The performance of the systems was simulated using PVSOL software. Reference [17] investigated the performance of a 3 kW grid-connected PV system, based on m-Si PV modules, installed at Universiti Kebangsaan Malaysia campus and found that the average capacity factor of the system was 15.7 percent and the average monthly PV performance ratio was 77.28 percent. Reference [18] assessed the performance of a 5 MW grid-connected PV system, based on thin film a-Si PV modules, in Sivagangai, India and found that performance ratio was 89 percent and the difference between the energy forecasted by employing the RETScreen software and the monitored data was about 0.25 percent. Reference [19] presented the performance of PV systems based on several PV technologies in Kumasi, Ghana, and found that p-Si represents the most appropriate PV technology, while Copper Indium disulfide thin-film is the least proper for the investigated location.

In the literature, the performance of PV system has been assessed by using experimental evaluation and numerical simulation methods. The main benefits of the second methodology compared to the first are the low costs and the relatively short period of time in which the results are obtained [20-22]. This paper analyses the performance of grid-connected residential rooftop PV systems that are using six PV modules technologies for a residence located in Cluj-Napoca, Romania. To the best of our knowledge, there are no studies in the literature that evaluated the performance of PV systems based on different solar PV technologies in Romania.

Hereinafter this paper is organized as follows: the methodology is presented in the second section; the third section discloses the results, and the conclusions are presented in the fourth section.

II. METHODOLOGY

This investigation assesses the performance of 6 kW grid-connected rooftop PV systems, based on six PV technologies, of a residence, located in Cluj-Napoca, Romania.

The PVSOL premium 2021 software was employed for designing the PV installations and their electric energy production simulation. The distributed generation units have been modeled for a dwelling with gabled roof. Table 1 presents

the main specifications of the PV panels under standard testing conditions (STC) with solar irradiance of 1 kW per square meter, a PV panel temperature of 25 degree Celsius and an air mass of 1.5 [23].

In order to harness the solar radiation, the PV panels were oriented south, at an inclination of 27°. The meteorological data for Cluj-Napoca, indispensable for the hourly electricity production simulation, were acquired from the Meteornorm software.

The performance evaluation of grid-connected PV systems is one of the most suitable approach for identifying the PV power generation potential in a specific location [24]. The main performance parameters are energy output, energy yield and performance ratio [19]. Next, the formulation of the performance parameters is presented.

The daily, monthly, and yearly direct or alternating current energy can be determined as follows [15,25]:

$$E_{DC,d} = \sum_{i=1}^{24} E_{DC,h} \quad (1)$$

where: $E_{DC,d}$ represents the daily direct current energy output; i is the hour of the day; $E_{DC,h}$ represents the hourly direct current energy output.

$$E_{DC,m} = \sum_{j=1}^m E_{DC,d} \quad (2)$$

where: $E_{DC,m}$ is the monthly direct current energy output; j represents the day of the month; m is the number of days in the month.

$$E_{DC,a} = \sum_{k=1}^{12} E_{DC,m} \quad (3)$$

where: $E_{DC,a}$ represents the annually direct current energy output; k is the month of the year.

The array yield (Y_A) represents the ratio of direct current power output from a PV system over a particular period of time to the PV rated power [15]. Y_A can be calculated as follows [25]:

$$Y_A = \frac{E_{DC}}{P_{PV}} \quad (4)$$

where: E_{DC} represents the direct current energy output of the PV installation; P_{PV} is the peak power of PV installation.

TABLE I. THE MAIN SPECIFICATIONS OF THE PV PANELS

Characteristics	Type of modules					
	<i>m-Si</i>	<i>p-Si</i>	<i>HIT</i>	<i>CIGS</i>	<i>CdTe</i>	<i>a-Si</i>
Nominal power [W]	425	425	330	150	125	150
Number of PV modules	14	14	18	40	48	40
Efficiency [%]	19.84	19.24	19.7	14.2	17.4	9.7
Area [m ²]	2.1424	2.209148	1.67427	1.053768	0.72	1.54
Maximum power voltage [V]	41.39	39.7	58	63	90.7	64.7
Maximum power current [A]	10.27	10.71	5.7	2.38	1.39	2.32

The final yield (Y_F) represents the alternating current power output from the PV system over a given period normalized by the PV rated power of the PV installation [25]. Y_F can be determined as follows [15]:

$$Y_F = \frac{E_{AC}}{P_{PV}} \quad (5)$$

where: E_{AC} represents the alternating current energy output of the PV system.

The reference yield (Y_R) represents the ratio between in-plane solar radiation and the STC reference irradiance [15]. Y_R can be calculated as follows [25]:

$$Y_R = \frac{H_T}{H_{STC}} \quad (6)$$

where: H_T represents the in-plane solar radiation; H_{STC} is the STC reference irradiance.

The performance ratio (PR) highlights the losses resulting from the converting of direct current into alternating current [15]. PR represents the percentage ratio between Y_F and Y_R . PR can be determined as follows [26]:

$$PR = \frac{Y_F \cdot 100}{Y_R} \quad (7)$$

The capacity factor (CF) is defined as the percentage ratio of alternating current power generated by the PV installation over a particular period, normally one year, to the theoretically maximum energy output of the PV system [25]. The yearly CF can be calculated as follows [19]:

$$CF = \frac{E_{AC} \cdot 100}{P_{PV} \cdot 8760} \quad (8)$$

The energy density (ED) is a useful parameter for evaluating the space needed to install a PV system. ED is defined as the ratio of alternating current power generated by the PV system over a particular period, normally one year, to the PV array total area [19]. ED can be determined as follows [19]:

$$ED = \frac{E_{AC}}{A_a} \quad (9)$$

where: A_a represents the array total surface.

III. RESULTS

This section presents the results of performance parameters for the investigated PV panel technologies. Fig. 1 illustrates the electric energy produced by the PV installations after conversion to alternating current in the first year of operation.

Thus, based on electricity produced by the PV installations, CdTe PV system represents the best alternative, while CIGS is the least appropriate solution for the investigated location.

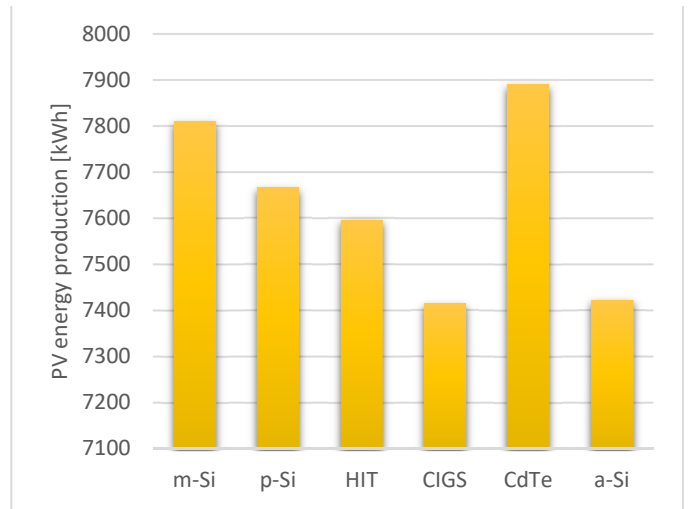


Fig. 1. Annual PV electric energy production

Fig. 2 shows the monthly average daily Y_A of the investigated PV panel technologies compared with the Y_R .

It can be noticed that the highest array yields were registered by PV system based on thin film CdTe PV modules in July, while the lowest values were obtained by distributed generation units based on thin film a-Si PV modules in December.

The monthly average daily Y_F of the examined PV module technologies compared with the Y_R are illustrated in Fig. 3.

It can be observed that the lowest final yields were attained by PV installation based on thin film CIGS PV panels in December, and the highest values were obtained by PV system based on thin film CdTe PV modules in July.

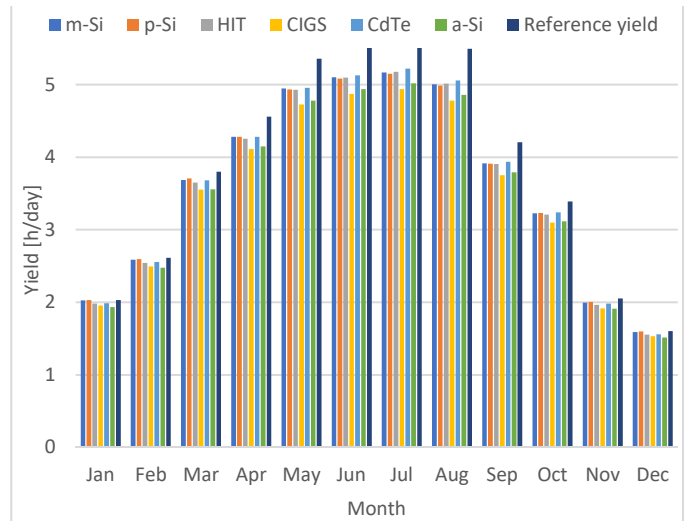


Fig. 2. Monthly average daily array yields

Fig. 4 illustrates the monthly average daily performance ratio of the explored PV panel technologies.

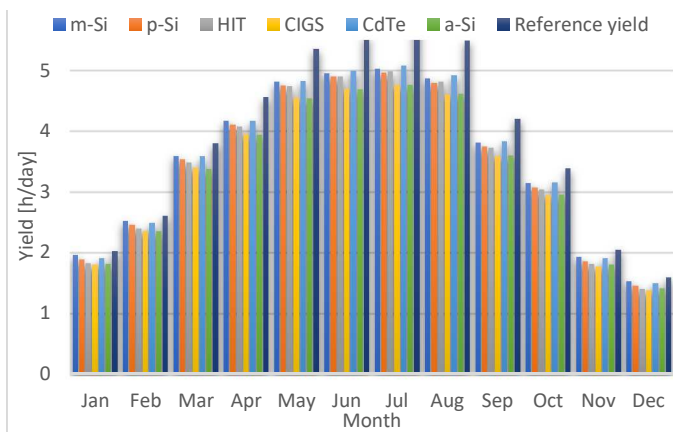


Fig. 3. Monthly average daily final yields

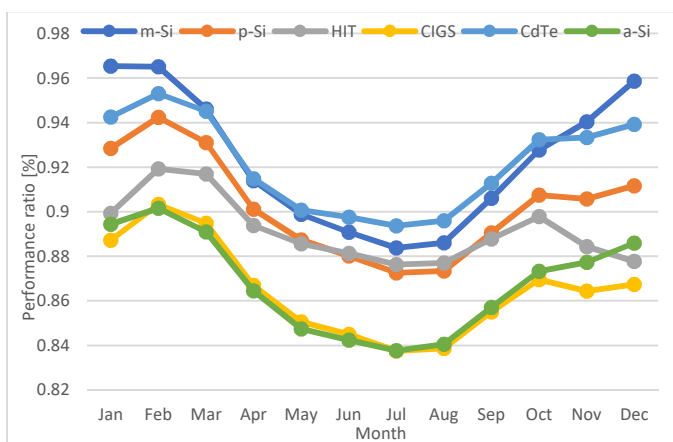


Fig. 4. Monthly average performance ratio

Although the highest annual performance ratio has been attained by PV system based on thin film CdTe PV modules with a value of over 91%, the distributed generation units based on m-Si PV modules registered the highest monthly average daily performance ratio in the winter months.

The annual capacity factor of the PV systems is shown in Fig. 5.

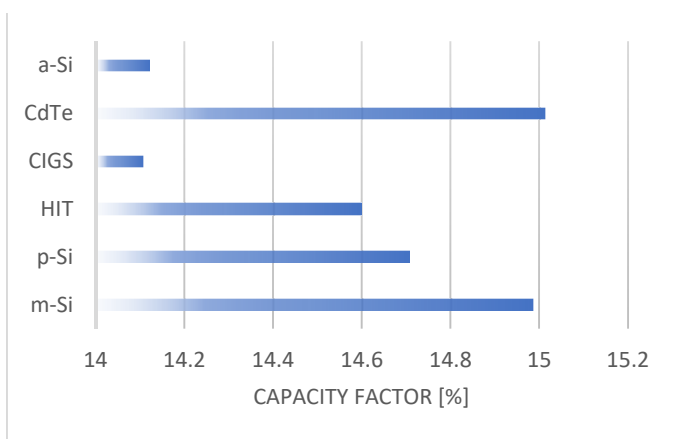


Fig. 5. The PV installations yearly capacity factor

It can be noticed that the distributed generation unit based on thin film CdTe PV modules generated at its maximum capacity the highest quantity of time, followed closely by the PV system based m-Si PV modules, while the lowest values were attained by the PV installation based on thin film CIGS PV panels.

Fig. 6 illustrates the yearly energy density of the PV panel technologies examined in this paper.

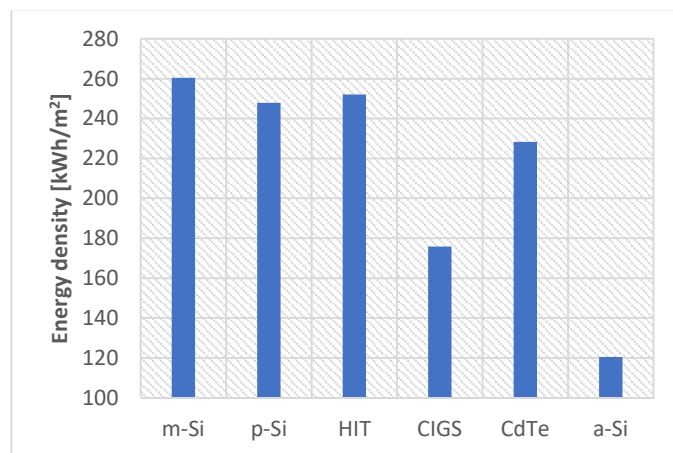


Fig. 6. The PV installations yearly energy density

As can be observed from Fig. 6, the yearly energy density differs depending on the type of solar PV panel technology. The energy density of the distributed generation units based on the crystalline silicon solar cell technologies is noticeable higher than that of the installations based on thin film technologies. The lowest energy density has been registered by the PV installation based on thin film a-Si PV modules, while the highest value has been obtained by the m-Si solar PV system.

IV. CONCLUSIONS

This study investigated the performance of grid-connected rooftop solar PV systems based on six PV panel technologies in the city of Cluj-Napoca, Romania. The PV installations, with an installed power of about 6 kW, were based on the main commercially available types of PV panels, namely m-Si, p-Si, HIT, CIGS, CdTe and a-Si. The PV systems electricity generation simulation has been conducted by using PVSOL software.

Although the m-Si and p-Si technologies displayed the best yields during the winter months, the PV system based on thin film CdTe PV modules exhibited slightly the highest yearly yields.

The CdTe technology revealed to be the most appropriate technology in terms of annual performance ratio, especially due to the high values of monthly average daily performance ratio in the summer months.

The PV installations based on the crystalline silicon solar cell technologies displayed the best yearly energy density. The m-Si represents the most suitable solar PV technology for the investigated location if the space required to deploy the PV system is limited. On the other hand, the thin film a-Si proved to be least suitable solar PV technology in terms of energy density.

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