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The analysis of different PV power systems for the determination of optimal PV panels and system installation—A case study in Kahramanmaras, Turkey

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A B S T R A C T

The next century will witness a breakthrough in terms of renewable energy sources, particularly solar energy and its derivatives. This renewable and enormous energy source offers a solution to the energy problem all over the world. One of the areas in which solar energy is used is the photovoltaic (PV) systems. The main element of this sector, however, is the pure silicon technology. Because, most efficient PV cells are made of silicon and its degree of purity is very important. The most commonly used types of these materials for PV energy conversion are thin Film, mono-crystalline and poly-crystalline silicon, which are also known as silicon modules or panels. However, performances of these modules vary by region. This study focuses on analyzing different three-type PV panels and determining the optimal panel type for Kahramanmaras with three separate PV systems, each 3-kWp and grid-connected. Besides, this study is the first research project to consider all aspects to determine optimal PV power system in the region. To this aim, three different PV systems consisting of thin film, mono-crystalline and poly-crystalline silicon panels were installed. The amount of energy generated by each system, cost analysis, annual incomes, breakeven points, installation area occupied by the system and total weights of each system are evaluated for each panel type used in the installed system and potential energy to be generated by solar energy in the region was considered. Following energy generation which lasted one year and at the end of the 30-year operation period, it is concluded that poly-crystalline silicon panels are the most optimal panel for the region because it yields the highest annual incomes and the shortest breakeven point for the investors.

Contents

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1. Introduction

Due to an increase in energy demand and the limited amount of fossil fuels in the world, a lot of attention are to renewable energy sources nowadays. Both the limited amount of limited fossil fuels and their harmful effects on the environment increase the need for the most commonly used renewable energy sources such as solar and wind energy. Furthermore, these energy sources are more reliable, greener and more environment-friendly thanks to their low emission [1]. In addition, solar energy is used in a wide variety of sectors such as water heating, agriculture, water treatment, heat pumping, traffic signalization, mobile charging, and multi-purpose electricity generation systems [2–4].

Photovoltaic systems (PV) are made from semi conducting materials and convert photon energy into electricity. When sunlight reaches these materials, photons with a certain wavelength trigger electrons to flow through the materials to produce direct current (DC) electricity. Commercial PV materials include multi-crystalline silicon, mono-crystalline silicon, amorphous silicon, and thin film technologies, such as cadmium telluride (CdTe), and copper indium diselenide (CIS) [5].

Silicon (Si) based technology, which are considered the most developed technology, can be categorized as crystalline silicon and amorphous silicon and thin film, and crystalline silicon cells have different crystalline structures: single crystalline silicon, multi-crystalline silicon and ribbon cast multi-crystalline silicon [6,7]. A key feature of PV systems is their ability to provide direct and instantaneous conversion of solar energy into electricity without complicated mechanical parts or integration [8,9].

Crystalline Si thin films for solar cells are of great interest since Si is readily available, crystalline Si is a familiar semiconductor material, and Si solar cells demonstrate high conversion efficiency,

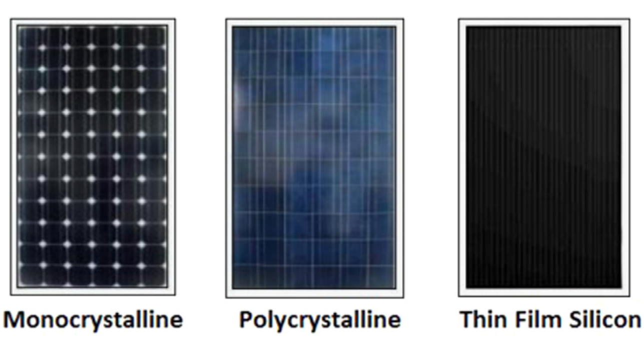

Fig. 1. Photovoltaic panel types.

which is close to 25% [10]. However, such efficiency is only possible by using high quality Si wafers and complex device processing. In order to produce cheap and efficient PV devices, research on a large number of different thin film technologies is in progress [11–14]. Pc-Si wafers can be fabricated over large areas. Plasma processing of lower-cost pc-Si is used to form a highly transmissive surface and to increase the light absorption. Known as reactive-ion etching, this process offers nearly 40% relative increase in absorption. The importance of texturing pc-Si to reach its full potential was considered [15,16]. 19.8% efficient textured pc-Si solar cells have been fabricated [17]. Bulk hydrogenation and nitride passivation of the cell surface have yielded good results. Despite a number of advantages of pc-Si, there is no significant difference between the costs of c-Si and pc-Si solar cells. Commercial pc-Si cells have efficiencies at 12–15%. Thin-film Si solar cells have the following important advantages compared to crystalline cells: (i) the thickness of Si can be drastically reduced to 50 lm; (ii) thin films can be deposited on low-cost substrates; (iii) thin films can be fabricated on module-sized substrates and in integrally interconnected structures. According to some calculations, the thickness of Si films can be reduced down to 1 μm [18,19]. General perspective view of some PV panels and classification of the silicon PVs are shown in Figs. 1 and 2, respectively.

As in the installation of other power systems, some important environmental or meteorological data such as ambient temperature, Sun radiation level, daily Sun duration and other climatic condition are required for the installation of a PV power system [20,21]. Because of its location between 36–42° North latitudes and 26–45° East longitudes, Turkey possesses a great potential in terms of solar energy [22,23]. In Turkey, annual average solar irradiation is 2640 h, which corresponds to 7.2 h per day. Therefore, annual average solar irradiation value reaches to 1311 kW h/m² [24]. Depending on the increase in the use of energy in the world, renewable energy has occupied an important position in recent years [25].

From past to present, PV systems for electricity generation via solar energy have been promising with their improvable efficiency [26]. Developments in nanotechnologies, such as organic semiconductor based solar cells to produce more efficient PV modules, at the same time, lead to decreases in the PV panel prices [27]. On the other hand, conductive and semi-conductive polymer materials with an efficiency of 12% became a new partner in the PV market [28], which means that it is needed to make an optimal plan for the installation PV power system anywhere [29].

In order to make an optimal plan for a PV power system, as compatibility between the equipments to be used in the power system is important, climatic conditions and geographic position

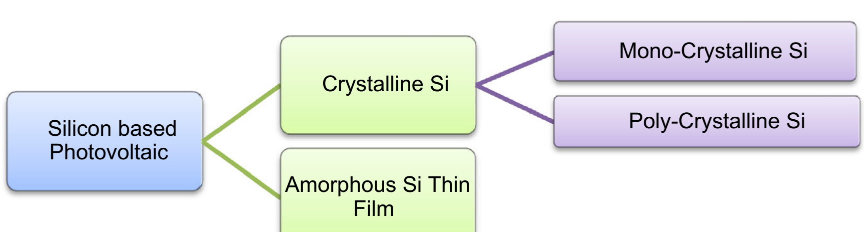

Fig. 2. Classification of the silicon PV panels.

of the region where the power system is to be installed are of vital importance. It is also important to decide the panel type to be used depending on the climatic conditions. Kahramanmaras is a rich region in terms of solar irradiation and thus photovoltaic investments become more and more popular in this city. In this respect, because no study has yet been carried out on this topic in Kahramanmaras, it is of vital importance to find out the most optimal panel type for Kahramanmaras and offer scientific data for future investors. Therefore, in this study, three different PV panel types were selected and analyzed in order to determine the optimal panel type for Kahramanmaras with three separate on grid PV system 3-kWp .The most commonly used panel types, thin film, mono-crystalline silicon and poly-crystalline silicon were employed in these PV power systems. These systems were analyzed in terms of annual incomes, the installation area occupied by the systems, total weights of system, the initial investment costs, the best breakeven points, and unit cost of the energy for 30-year operating period.

Fig. 3. Location of the selected region of Kahramanmaras by Google Earth.

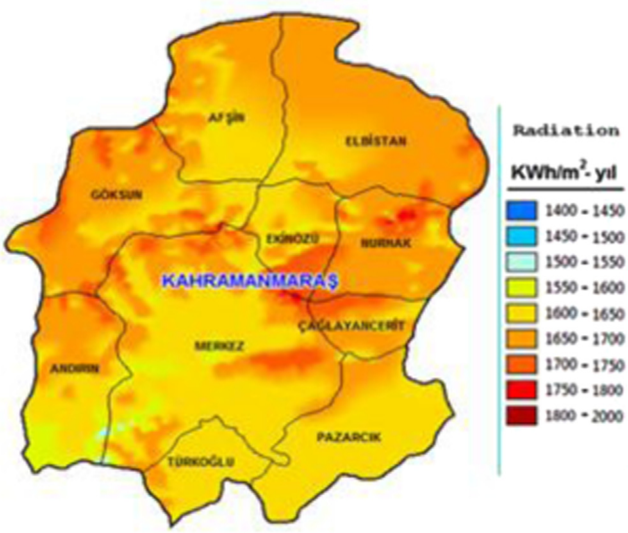

Fig. 4. Annual solar energy potential in Kahramanmaras.

1.1. Site description and solar potential in the region

1.1.1. Site description

Kahramanmaras, located at 37.5828 North and 36.9276 East, in Turkey, as shown in Fig. 3, possesses a high solar energy potential. The annual average radiation is around 1582.5 kW h/m^2. In Fig. 4, the variation of the annual average radiation is shown on the map [30].

1.1.2. Climatic conditions and solar energy potential in the region

Because the ambient temperature affects the efficiency of PV cells negatively, daily energy generated by the solar power system is shown in Fig. 5. On the other hand, since Kahramanmaras is located in the Mediterranean region, the weather is hot and dry with an average of 35 °C during summer, and it is cold and damp with temperatures ranging from 0–5 °C during winter. The highest temperature recorded was 45.2 °C on 30 July 2007, and the coldest temperature recorded was 9.6 °C below zero on 6 February 1997 [31]. In Fig. 6, average daily temperature profiles in recent years are given for maximum temperature and minimum temperature in August and January, respectively.

Meteorological data such as global irradiation, Sunshine duration, temperature and wind in the selected region is needed in order to design a PV solar power plant. In Table 1 are given data on these parameters. As shown in Table 1, Kahramanmaras is important in terms of solar energy generation because of its monthly average radiation value of 131.875 kW h/m^2, annual average temperature value of 16.405 °C and annual solar irradiation of 2874 h.

2. PV power system installation and design specifications

2.1. System description

Three PV panel types, thin film, mono-crystalline and poly-crystalline, were selected in order to determine the most optimal PV panel type to be used. Each part of the plant has a power of 3-kWp and it was installed with the same PV panel type. In all three systems, 10 panels were used to obtain required power. Power of each panel was 300-W and it had different output voltage and current based on the panel type. For each PV plant installation schema is shown in Fig. 7, where the system is operated as grid-

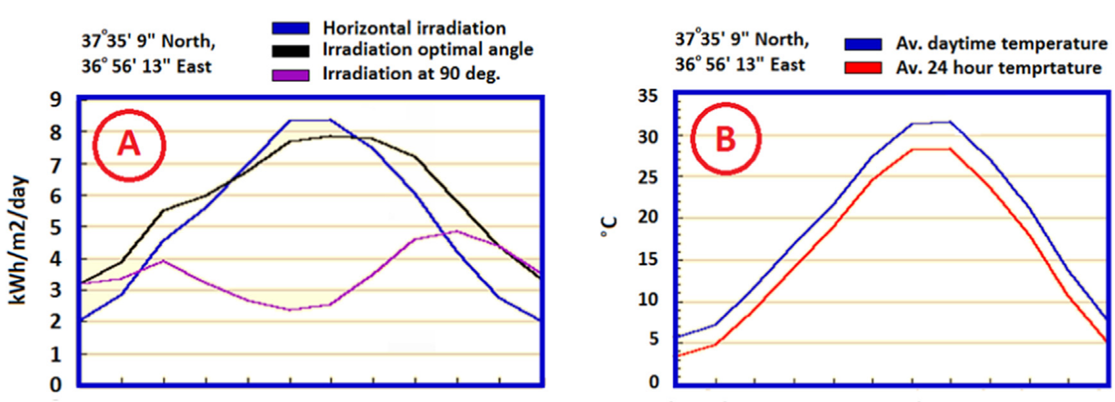

Fig. 5. (a) Daily sum of global irradiation and (b) yearly temperature variation in the region by PVGIS.

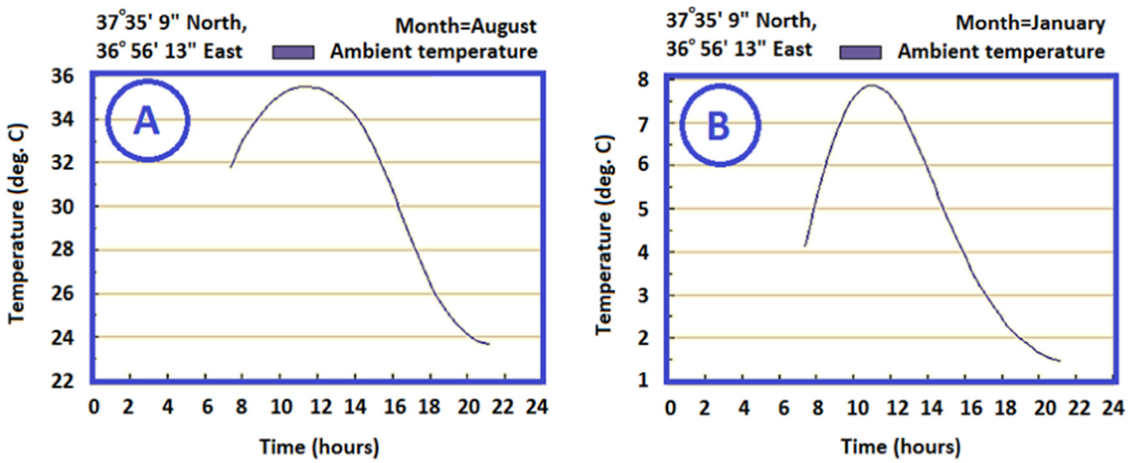

Fig. 6. Average daily temperature profile in the region for (a) August and (b) January, by PVGIS.

Table 1
Average daily meteorological data in the region [16].

Months	Radiation (kW h/m²)	Sunshine duration (h)	Temperature (°C)	Wind (m/s)
January	59.70	4.21	4.43	2.10
February	77.40	5.47	4.97	2.30
March	125.10	6.61	9.03	2.50
April	152.70	7.85	13.91	2.50
May	188.70	9.57	20.19	2.60
June	204.30	11.49	26.01	3.30
July	203.10	12.07	30.36	3.60
August	180.00	11.43	29.25	3.00
September	151.80	10.13	24.03	2.60
October	113.40	7.55	18.00	2.00
November	72.00	5.56	10.78	1.80
December	54.30	3.86	5.91	1.90

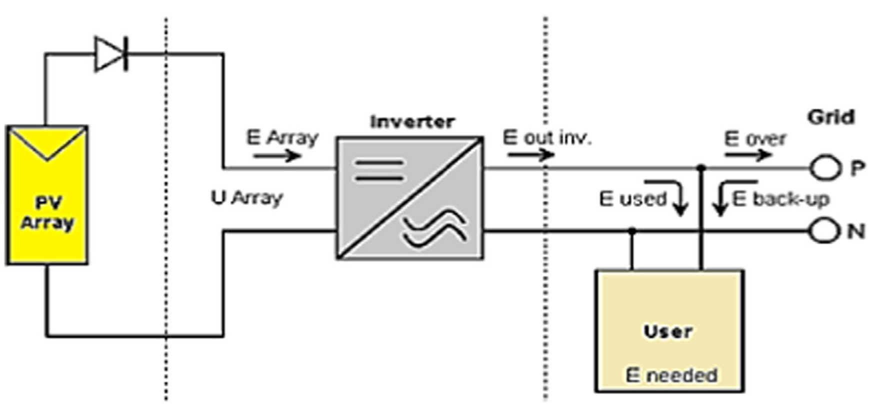

Fig. 7. Principle schema for installation of each power plant.

connected (on grid). Each plant employs an inverter independently. PV arrays of each plant are composed by output voltage to fit inverter input range. Output voltage is constant and keeps grid voltage.

2.2. Specifications of selected inverter and PV panels

Inverter model used in each plant is SB 3000HFUS-240 and its specifications are listed in Table 2. Recommended PV power of the selected inverter is 3.75-kW, nominal power of 3-kW, efficiency of 96.6%, and it can be operated in unity power factor.

The power plant consisting of thin film panels, called the first installation hereafter, was constructed in 5 × 2 array form, i.e. each parallel module was constructed by 5-serial connected panels. Output voltage of the array is 300-V and convenient for input of the inverter. The second installation was constructed by 10-unit mono-crystalline type panels, and all of the panels are connected in series with each other. Output voltage of this system for inverter input is equal to 371-V and it is convenient for the inverter input range, which is between 220-V and 480-V. The third installation was also constructed by 10-unit poly-crystalline type panels, and all of the panels are also connected in series with each other.

Table 2
Properties of inverters used in each PV power plant.

Inverter type: SB 3000HFUS-240				AC nominal power	3000 W
Input (DC)	Max. recommended PV power	3750 W	**Output (AC)**	Max. AC apparent power	3000 VA
	Max. DC power (@ cos $\varphi=1$)	3300 W		Nominal AC voltage	208 V
	Max. DC voltage	600 V		AC voltage range	183–229 V
	DC nominal voltage	480 V		AC grid frequency; range	50/60 Hz
	MPP voltage range	220–480 V		Max. output current	14.4 A
	Min. DC voltage/start voltage	220 V/220 V		Power factor (cos φ)	1
	Max. input current/per string	15 A/15 A		Harmonics	< 4%
	Max. efficiency	96.6%		Packing weight	25 kg
	Dimensions ($W/H/D$) in mm	348/727/183		Operating temperature range	–25 °C +45 °C

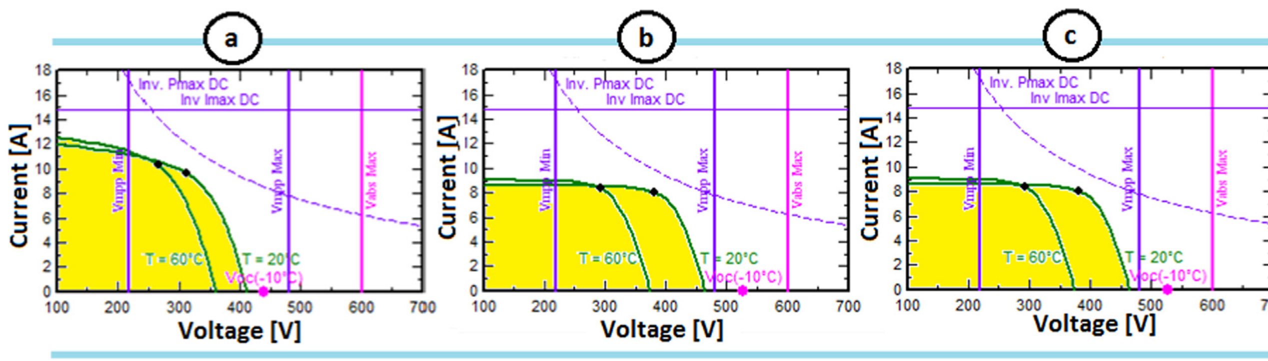

Fig. 8. Panel output specifications for voltage sizing, (a) thin films, (b) mono-crystallines, (c)poly-crystalline [30].

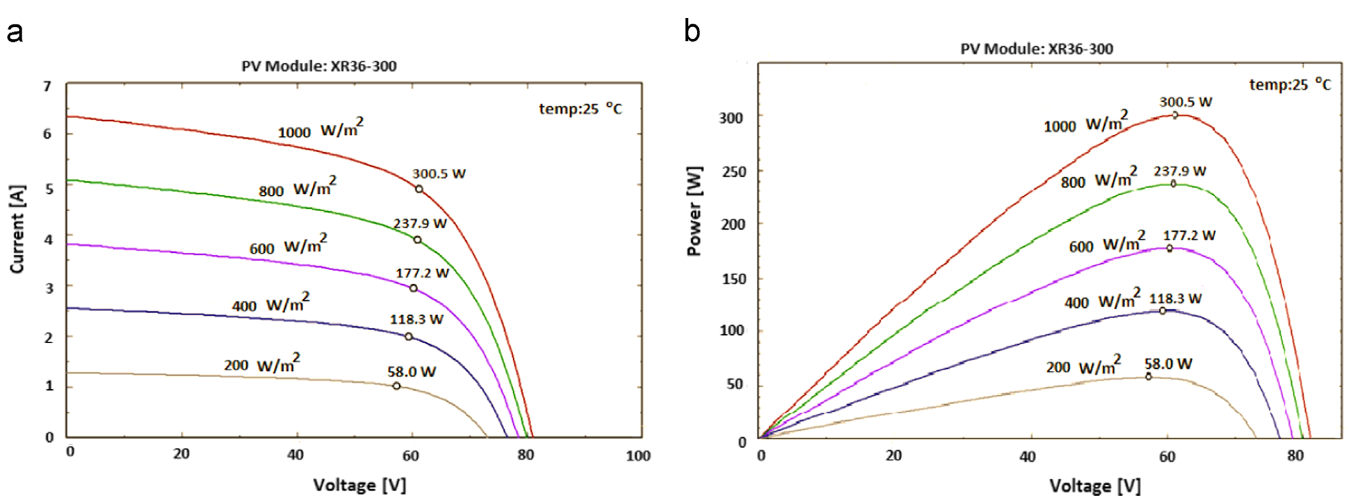

Fig. 9. Output characteristics of the used thin film panels: (a) *I–V* characteristics, (b) *P–V* characteristics.

Output voltage of this module was obtained as 361-V and it is also convenient for the inverter. Properties of the panel types used are listed in Table 2. The composition supported by manufacturers was used for array voltage sizing as shown in Fig. 8. Output characteristics of thin film, mono-crystalline and poly-crystalline are shown in Figs. 9–11, respectively (Table 3) [30].

2.3. Energy generated by the installed systems

This study aims to determine the optimal panel for the selected region. Therefore, monthly energy generated by different power plants must be analyzed. On the other hand, daily energy generated by all plants for the whole year must also be analyzed.

The solar energy generated by the systems were logged and graphed together for a whole year as shown in Fig. 12. The first installation constructed by thin film panels generated 5018.6-kW h, the second installation constructed by mono-crystalline panels generated 5036.6-kW h, and the third installation constructed by poly-crystalline panels generated 5195.1-kW h annually. Total amount of energy generated by three plants is around 15,250-kW h annually.

2.4. Discussion on harvested energy profile for three-plant

The system consisting of poly-crystalline panels generated energy more than the other two panels during winter when climatic conditions in the city are taken into consideration. However, total amount of energy generated by the system composed of thin film panels and mono-crystalline types are different from each other. Mono-crystalline panels generated more energy than thin films in October, November, December, January, February and March. On the other hand, , the energy generated by the

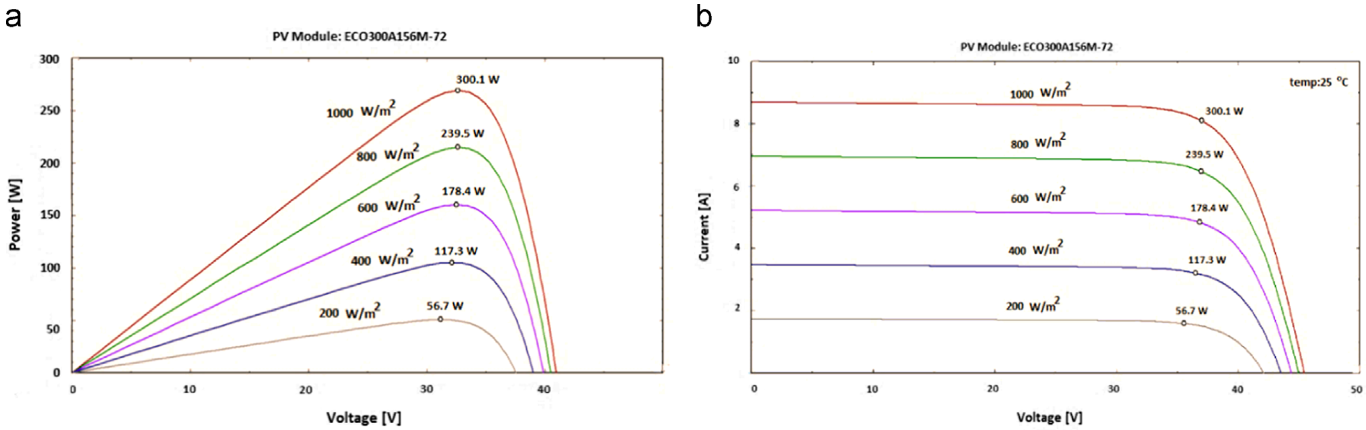

Fig. 10. Output characteristics of the used mono-crystalline type panels: (a) *I–V* characteristics and (b) *P–V* characteristics.

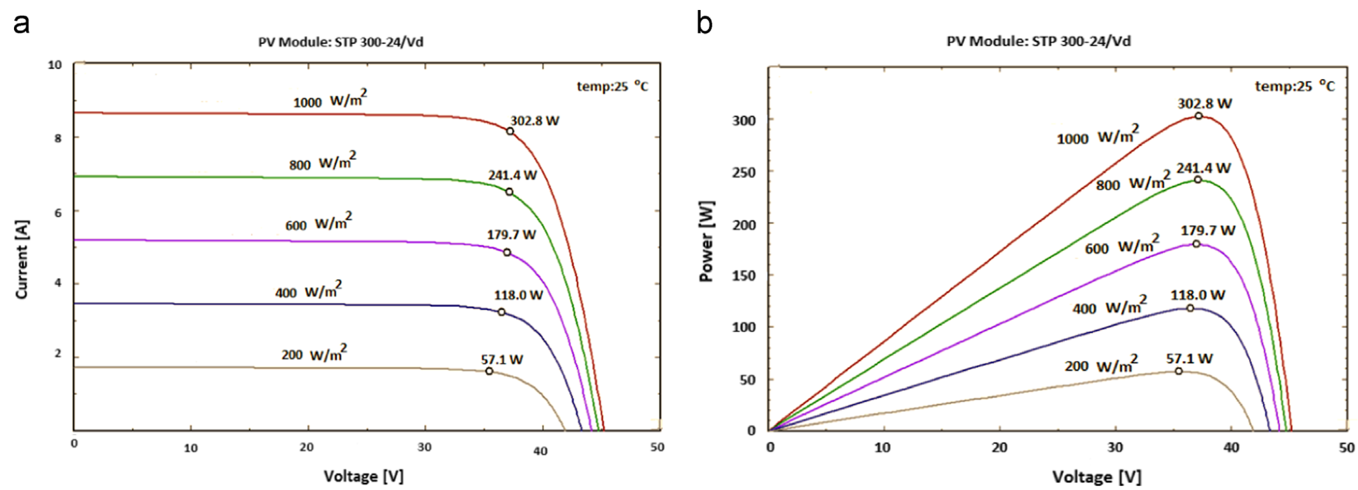

Fig. 11. Output characteristics of the used poly-crystalline type panels: (a) *I–V* characteristics and (b) *P–V* characteristics.

Table 3
Specifications of PV panels used in the power plants.

System ID	1	2	3
Trademark	Xunlight	EcoSolargy	Suntech
Model	XR36-300	ECO300A156M-72	STP 300-24/Vd
Solar cell	Thin film	Mono-crystalline	Poly-crystalline
Maximum power at STC (P_{max})	300 W	300 W	300 W
Optimum operating voltage (V_{mp})	60 V	37.12 V	36.1 V
Optimum operating current (I_{mp})	5.00 A	8.09 A	8.32 A
Open circuit voltage (V_{oc})	81.0 V	45.73 V	45.2 V
Short circuit current (I_{sc})	6.35 A	8.71 A	8.65 A
Module efficiency	6.54%	15.46%	15.5%
Length	5160 mm	1956 mm	1956 mm
Width	889 mm	992 mm	992 mm
Weight	12 kg	23 kg	27 kg

system consisting of thin film panels is more than the system constructed with mono-crystalline type panels in April, May, June, July, August and September.

The efficiency of PV energy conversion is much lower in some regions with high average ambient temperature compared to other places with low average ambient temperature. However, it can be concluded that the effect of the operating and ambient temperatures on thin film panels is less than mono-crystalline panels. Especially, while the efficiency of the mono-crystalline panels is high during winter, thin film panels are more productive during summer. On the other hand, according to the climatic condition of the city, all of the constructed systems generated energy on a daily basis. These systems can generate energy because of valuable radiation value in every season, even during winter season. Furthermore, more energy can be generated if the Sun tracking systems are used in the region [32–34]. Daily energy transferred to the grid versus global energy incidence is shown in a diagram in Fig. 13.

3. Cost analysis for three installed systems

Nearly 85% of the PV market concerns mono- and poly-crystalline silicon modules because of their high efficiency with respect to the others, as in reported in Refs. [35,36]. However,

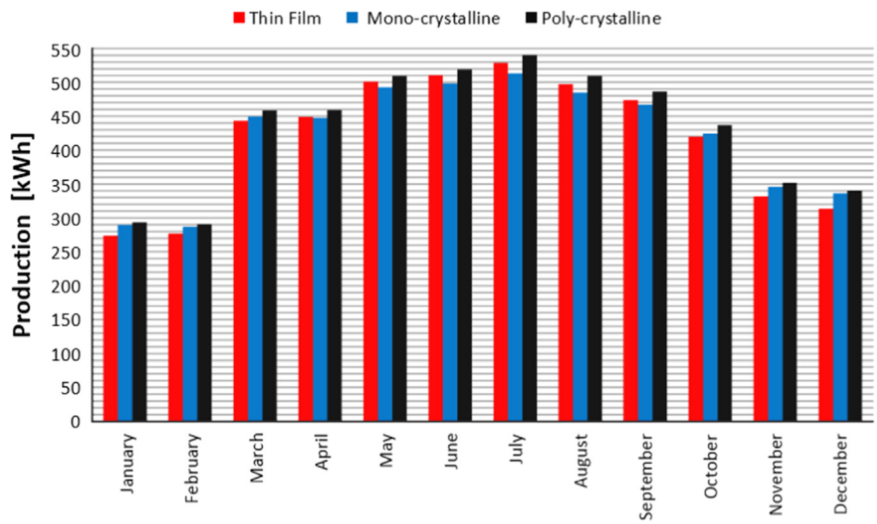

Fig. 12. Harvested energy profile from the three-plant all year round.

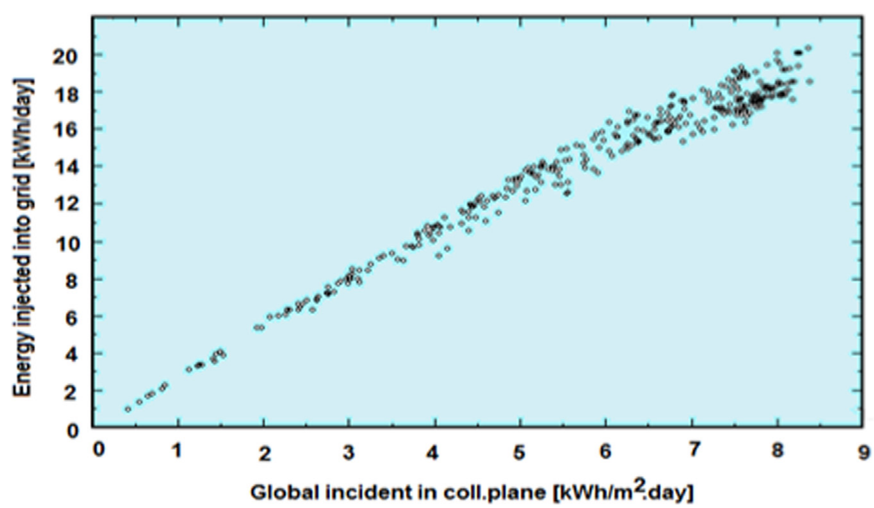

Fig. 13. Daily energy profile for the region, by PVsyst [30].

Table 4
Cost analysis for each system installed and their breakeven points.

	System-1			System-2			System-3		
Components	Thin film			Mono-crystalline			Poly-crystalline		
PV modules	138€	10	1.380€	142€	10	1.420€	145€	10	1.450€
Support equipment	50€	10	500€	50€	10	500€	50€	10	500€
Inverter	1.135 €	1	1.135€	1.135€	1	1.135€	1.135€	1	1.135€
Total	3.015€			3.055€			3.085€		
Taxes	241.2€			244€			247€		
Net initial investment cost	3.2562€			3.2994 €			3.3318€		
PV costs (€/W h)	0.460€			0.473€			0.483€		
System costs (€/W h)	1.085€			1.100€			1.111€		
Annual production time	2874 h			2874 h			2874 h		
Production [kW h] per year	5018.6			5036.6			5195.1		
Production [kW h] (for 30-year running)	150,558			151,098			155,853		
Fixed feed in tariff per kW h	0.11€			0.11€			0.11€		
Total yearly income	55,205€			55,403€			57,146€		
Total income (for 30-year running)	16.56138€			16.62078€			17.14383€		
The unit cost of energy for 30-year running	0.0216€			0.0218€			0.0214€		
Breakeven points	66,652-year			67,295-year			65,883-year		

according to the meteorologycal conditions of the installation area, an effective cost analysis can help to decide the most optimal panel type in the region. To this aim, taking the whole system installation into account, the cost analysis of each system together with annual incomes and their breakeven points for 30-year operation period is given in Table 4.

Consdering initial investment cost, the first system consisting of thin film panels is less expensive than the other two systems.

However, in terms of energy generation, this contributesless to the total annual energy generation. Total cost of the three systems is around €9887.

The inverters have a share of 37% in total cost of three systems. PV modules have a share of 47% and the rest of the expenses are for the other equipment as shown in Fig. 14. It must be emphasized that the fact that three independent inverters for three independent grid-connected systems led to an increase in the cost as in reported in Refs. [37–43].

On the other hand, although the cost of the system consisting of poly-crystalline type modules is more expensive compared to the other two systems, it is the most efficient system because its contribution to the total annual energy generation is the highest. First, the investment and maintenance costs of the panels are calculated. When the economic revenue of the electricity energy generated by the panel is equal to these costs after inflation rates, interest rates, the increase in electricity costs per unit, and temporal panel performance loss are taken into consideration, it is called breakeven point. Therefore, the nearest breakeven point among three-system is 6.5883-year and belongs to the system consisting of poly-crystalline type module as shown in Fig. 15. Thus, the unit cost of the energy generated by this system is lower than the two other system at the end of 30-year operating period as shown in Fig. 16 and reported in Refs. [44–54].

The systems consisting of poly-crystalline type modules is more productive than the two other systems in terms of annual income. A comparision study based on Table 4 is shown in Fig. 17.

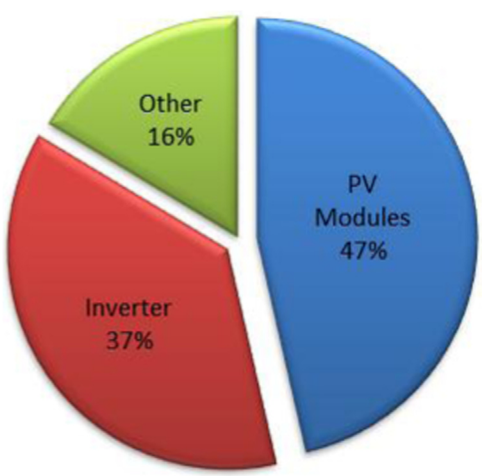

Fig. 14. The shares of the system components in total investment cost.

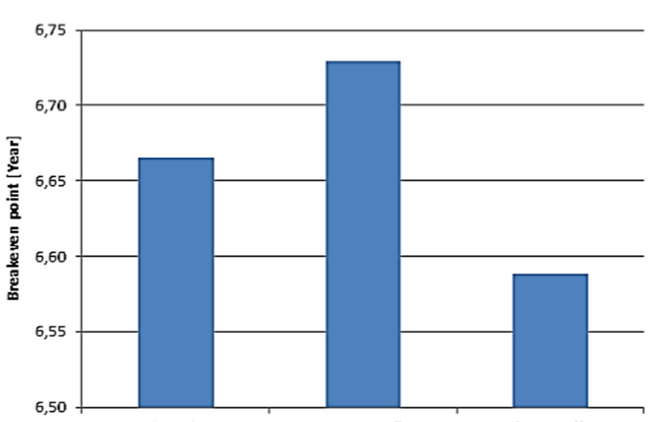

Fig. 15. Breakeven points of the installed systems.

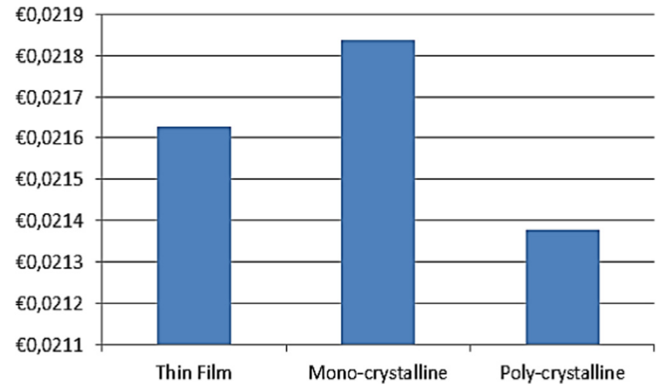

Fig. 16. The unit cost of the harvested energy for 30-year running.

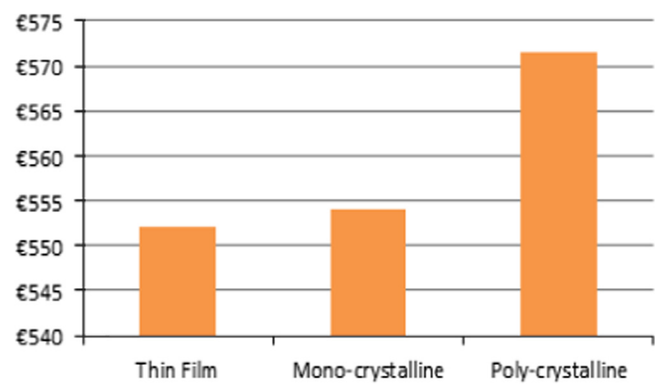

Fig. 17. Total yearly incomes for all three-system.

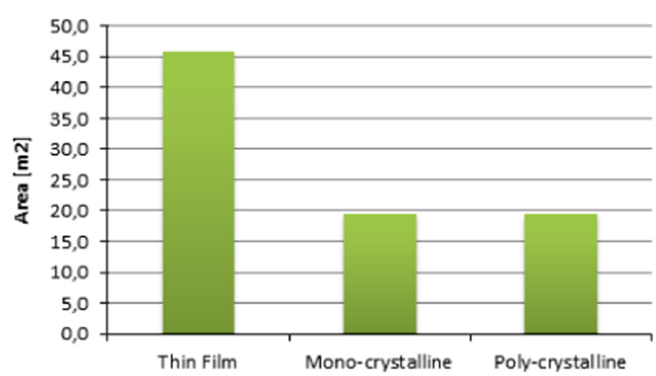

Fig. 18. Comparision of the areas occupied by each power system.

4. Analysis of the weights and the area occupied by the systems

While analyzing the cost of the PV power systems, the area occupied by the systems and their weights are also important. Irregardless of the fact that it is installed in an agricultural land or on a roof, their setups is of vital importance. The three systems in the present study were analyzed in terms of the area which they occupied and their weights. Although it generates the same amount of energy, the system consisting of thin films, occupies more area twice as much as the other two systems as shown in Fig. 18. Considering the area occupied, the cost of the land affects the initial investment cost in total and cost unit of the energy generated.

It is evident that the system consisting of poly-crystalline type PV module is heavier than the two other systems as shown in

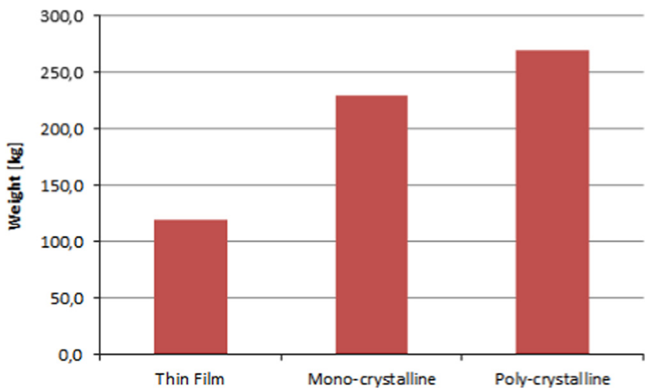

Fig. 19. Comparison of the weights for the installed systems.

Fig. 19. This is a drawback of the system when roof setup is taken into consideration. However, this is not a factor which directly affects the cost of the system if they are installed on the land.

5. Conclusion

Kahramanmaras province of Turkey displays a good performance in terms of electricity generated by the solar energy. However, no research on the optimal panel type to used has been carried out. Therefore, this study aims to determine the optimal PV panel type suitable for the selected region. There are some studies on photovoltaic panels in literature such as Gerbinet et al. [55] mostly examine silicon panel types and balance of system components. Akinyele et al. [56] presents a study on global progress in photovoltaic technologies and the scenario of development of solar module types. Kesler et al. [32], introduces an analysis of solar energy potential and data with seasonal variation for selected region. Also, the proposed study investigates photovoltaic panel comparison between thin film type panels and monocrystalline types. Unlike the other studies, to this aim, three different type panels were selected and three independent grid-connected PV power systems of 3-kWp were installed and realized as. In order to find the optimal PV panel for the selected region, the most important criterion for investors is the breakeven point of the systems. In this respect, the system consisting of poly-crystalline type PV panels is more suiatable for the region and more productive than the two other systems. However, the area occupied by the systems, especially available area on the roof and the cost of the installation on the land, is more important for the investors.

The effects ambient temperature on the efficiency of the panels were also evaluated. It is concluded that the panel consisting of thin film can compete with othe cities in this region with a high ambient temperature. On the other hand, they have an advantage in terms of the weight as far as roof installation is concerned. However, they occupy more area with respect to the other two systems. For an average solution in the region, mono-crystalline type panels can be selected to install because it occupies less area and it weighs less. We conclude that the system consisting of poly-crystalline is most optimal type for the region in terms of the shortest breakeven point for the investors.

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