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TECHNO-ECONOMIC FEASIBILITY OF DIFFERENT PHOTOVOLTAIC TECHNOLOGIES

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Abstract:
This study modeled monocrystalline (mono-Si), polycrystalline (poly-Si), and amorphous silicon (a-Si) Photovoltaic (PV) systems with a 300 kWp installed power using PVsyst software in Konya province, Turkey. The system's electricity generation was calculated and compared with different PV technologies. In addition, an economic analysis for a 25 year lifespan was made with the obtained data. The annual global horizontal radiation (G_I) and effective global irradiation (G_E) are found to be 2001.7 kWh/m² and 1949.6 kWh/m², respectively. The highest yearly total electricity production was obtained from mono-Si, with a value of 513.91 MWh. This value is 1.91% and 3.07% higher than poly-Si and a-Si, respectively. Since the Performance Ratio (PR) values are proportional to the generated electricity and incoming irradiation to the surface of the PV panels, it calculated 0.853, 0.847, and 0.830 for mono-Si, poly-Si, and a-Si, respectively. According to the basic payback method, the economic analysis showed that mono-Si and poly-Si pay off in about 5.8-5.9 years, while a-Si pays off in 9,1 years. A net profit of $1.5 million, $1.45 million, and $1.1 million was obtained from mono-Si, poly-Si, and a-Si, respectively. It was concluded that the ratio of income values to investment cost was 253%, 244.77%, and 126.6%, respectively. Therefore, it was concluded that mono-Si and poly-Si are economically quite feasible for small and medium-scale PV systems, but a-Si is still not feasible due to lower efficiency and higher costs.

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1. INTRODUCTION

The increase in energy consumption has also led to an increase in emissions and greenhouse gas effects. In addition, buildings account for 40% of energy consumption today. This consumption causes large emissions and brings significant environmental problems [1]. In the current situation, unless countries turn to renewable energy sources, the amount of CO_2 produced in these countries by 2030 will exceed the amount produced by the total OECD members [2]. In addition, the amount of CO_2 produced directly or indirectly causes global warming and creates a greenhouse gas effect in the atmosphere. For example, between 2005 and 2018, the global greenhouse gas effect increased by 23%, bringing environmental problems such as an increase in temperature [3]. For this reason, many countries are turning to renewable energy sources with nearly no emissions after installation.

In recent years, one of the trends in renewable energy sources is PV cells that can convert photons into electrical energy. The installed PV power was only 40 MW in Turkey in 2014, corresponding to 0.06% of the total installed power. In 2021, it reached 7816 MW with a total installed ratio of 7.83%, with a significant growth [4]. Some European

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countries and Turkey's PV installed capacities over the years are given in Fig.1. Since 1990, the transition rate to renewable energy has been increasing in developed and developing countries. The main reasons for these transitions are the development of technology, reduction of costs, renewable energy support policies of governments, climate change, and foreign dependency [5].

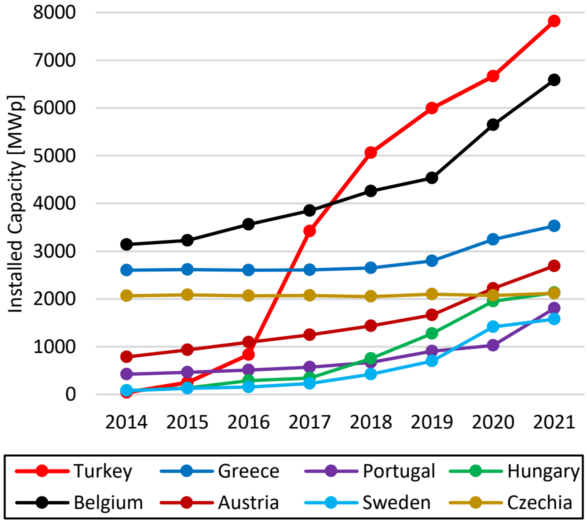

Fig. 1. PV installed power of various countries by years [4,6]

As shown in Fig.1, Turkey has made a big move, leaving many European countries behind. By 2021, Turkey ranks 7th in Europe in terms of installed power, although it started the PV system installation comparatively late [6]. The amount of irradiation coming to the panel surface of the PV cells and the sun exposure time directly affect the cell performance and electricity production [7,8]. Furthermore, the amount of energy obtained from PV systems depends on many parameters, such as the system's positioning, the material used, size, and the surrounding structures [9]. As seen in Fig.2, Turkey has more advantages than most European countries, with a yearly total of 1527.46 kWh/m² of irradiation and an average of 7.5 hours/day of sunshine [3].

The amount of solar radiation reaching cities in Turkey varies according to location. As seen from Fig.3, Konya, Turkey, is in a lovely position for PV system installation with irradiation of about 1610 kWh/m² and a sunshine duration of about 7.95 hours/day. Konya province has a high potential for solar energy systems due to their features, such as being very suitable for agriculture, receiving less precipitation, having low humidity, and being an industrial area. It also has a particular location named the Renewable Energy Resources Area (YEKA) in Karapınar district, where the lands are not suitable for agricultural practices but suitable for PV applications. This area, in particular, is well-suited for PV technology.

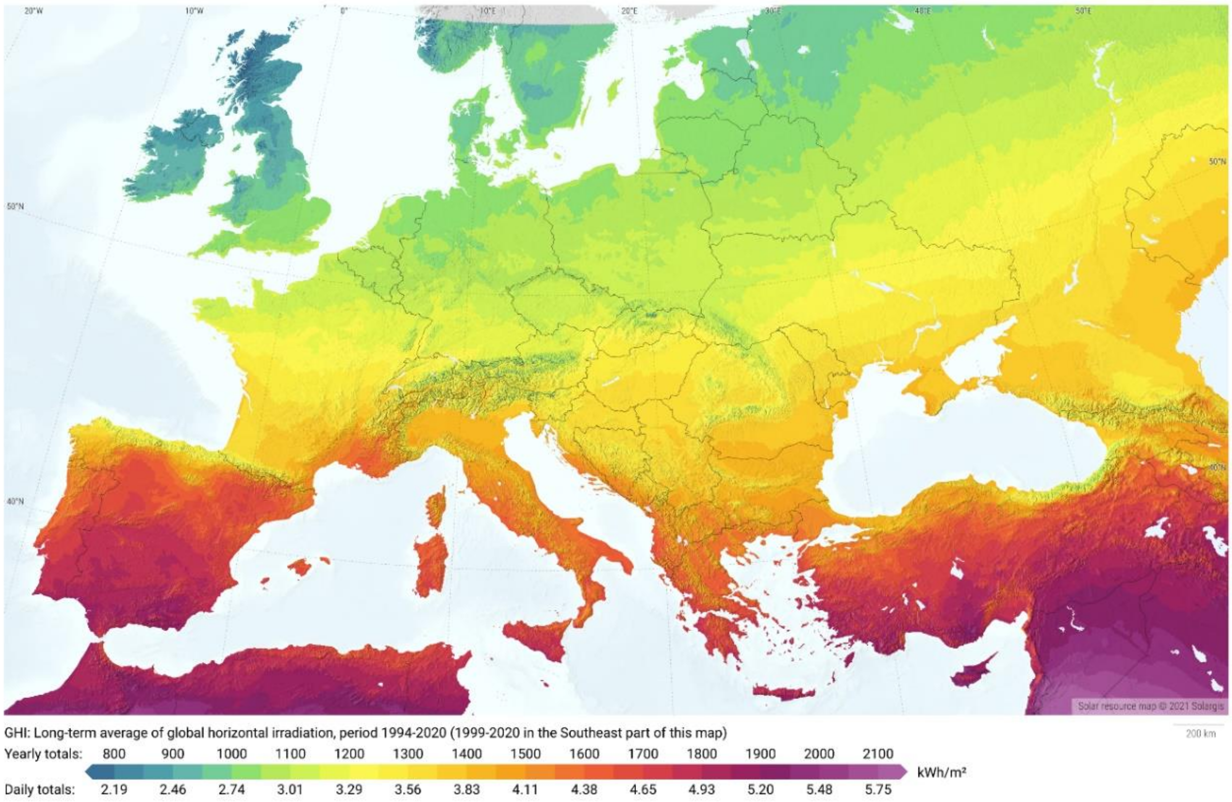

Fig. 2. Average annual solar radiation of Europe [10]

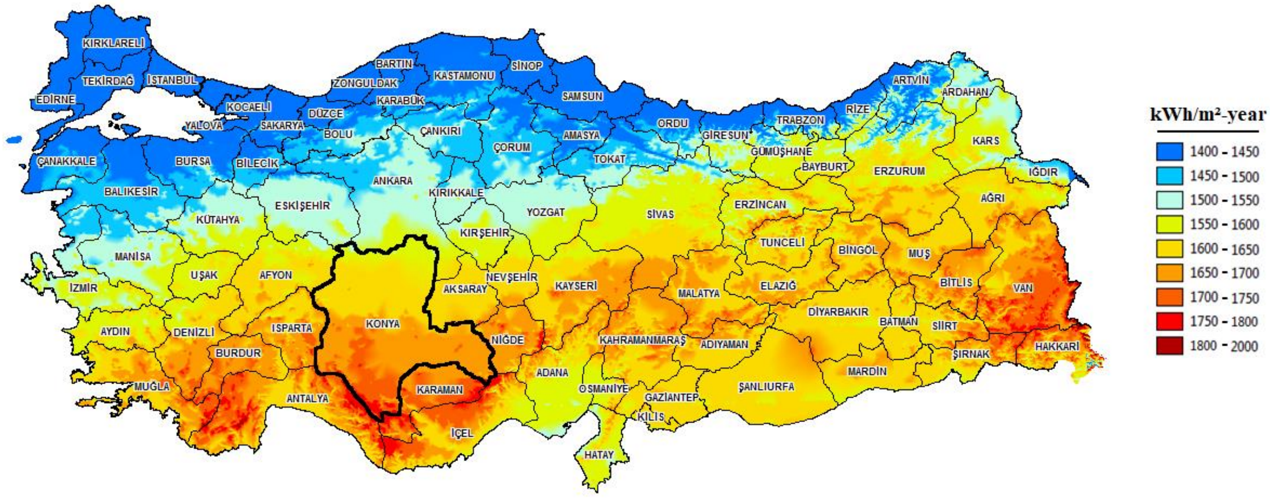

Fig. 3. Average annual solar radiation of Turkey [11]

PV cell efficiency is an indispensable parameter for system analysis. In 1953, efficiency was only 4.5% achieved in experiments on silicon-based PV cells in the Bell laboratory, while in 1954, an efficiency of 6% was achieved in experiments conducted in the same laboratory [12]. The efficiency of silicon-based (c-Si) and other cells increased year by year, as shown in Fig.4. The efficiency of mono-Si cells, among the c-Si cells, under laboratory conditions was about 15% in the 1950s, 17% in the 1970s it is today is around 28% [13].

The efficiency of a-Si cells ranges from 6% to 44.0% for multiple-junction manufacturing cells and 47.1% for several dies combined into a hybrid package. However, the most efficient cells are not always the most affordable; for instance, a 30% efficient multijunction cell made of unusual materials like gallium arsenide or indium selenide that is produced in small quantities could cost up to 100 times as much as an 8% efficient amorphous silicon cell that is produced in large quantities but only produces about four times higher output [14,15].

Although PV cell efficiency, especially multijunction systems, can reach efficiencies up to 50%, the production costs of these cells are very high, and it is not yet possible to use them economically in real applications. In addition, there is no clouding, shading, dusting, refraction, reflection etc., losses under laboratory conditions. Today, the most economically viable silicon-based cells are mono-Si and poly-Si cells, with efficiencies of around 25%, under laboratory conditions. On the other hand, multicrystalline Si solar cells with commercial availability have an energy conversion efficiency of 14–19%. Thin film technologies are also being developed, and the most suitable cell type to be used economically is a-Si, which has an efficiency of about 15% under laboratory conditions. In addition, the cost of production is as vital as cell efficiency in PV systems. It has become trendy to obtain electricity from PV systems. In addition, the price of electricity obtained from PV systems has been decreasing over the years [16]. The cost of PV modules was between $20-100/Wp in the 1970s [17], $3-3.5/Wp in the 2010s [18], $1.2-1.8/Wp in 2018 [19], and finally, $0.2-1/Wp in 2020, depending on the improvement of manufacturing technologies [20,21]. In addition to the module prices, other costs, such as land, labor, and construction, also affect the installation costs. System and module prices by year are given in Table 1.

Table 1. Current costs and projection of c-Si PV cells by years [21]

Year	Module costs (€/Wp)	System costs (€/Wp)
2010	2	3
2020	<1	2
2030	<0.5	1

With the development of technology, there has been a noticeable decrease in the prices of PV systems.

Today, PV system modeling can be done for many studies using computer systems. PVsyst, RETScreen, HOMER, TRNSYS, INSEL, and PV F-Chart are the leading software models for PV systems [22]. PVsyst has many advantages compared to other software, such as providing detailed results, location selection, detailed results, more parameters, a straightforward interface, and an extensive archive [23,24]. There are analysis studies for many countries using PVsyst software in the literature.

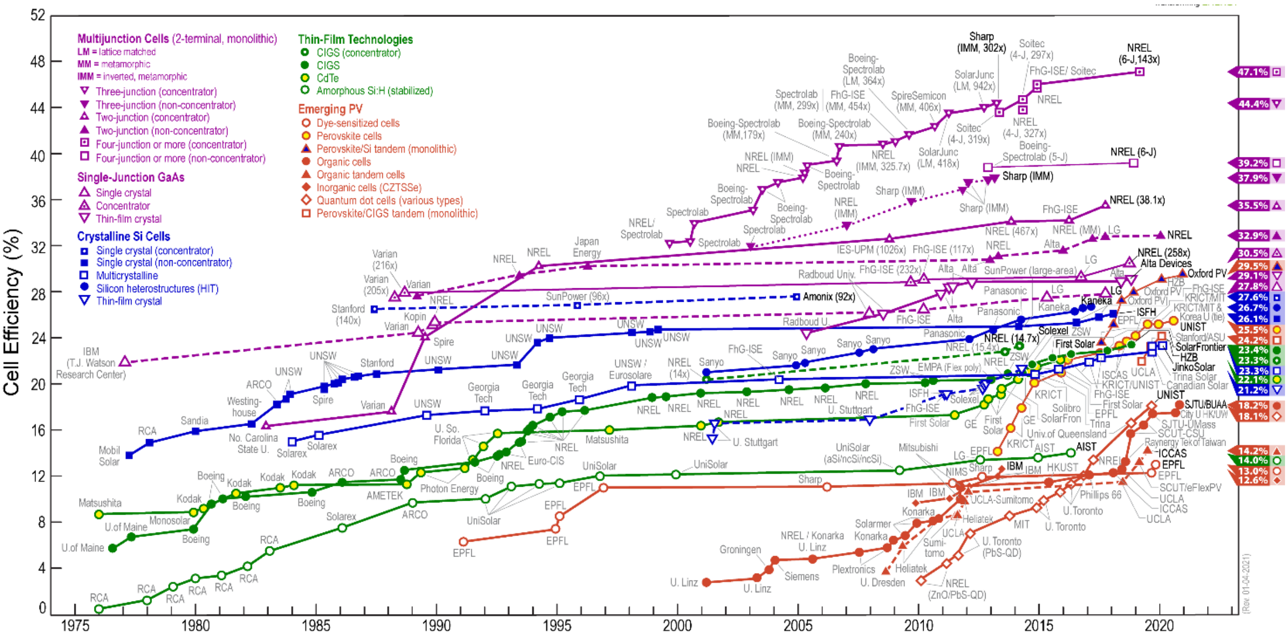

Fig. 4. Research solar cell energy conversion efficiencies reported since 1976 [13]

The same installed capacity systems of 1 MWp for four different regions of India were modeled using PVsyst. In modeling, more electricity was produced in the Tuticorin region, closer to the equator [25]. In a study conducted in Turkey, bifacial PV systems were modeled using PVsyst with three different grounds: asphalt, sandy and white ground. Obtained results were compared with monofacial systems. The highest electricity generation was obtained from bifacial PV systems with white ground [26]. In another study for Turkey, modeling was made using PVsyst for the roofs of houses in various directions. The highest electricity generation was obtained from the system modeled towards the South direction [27]. There are many studies, such as India [28], Poland [29], and Algeria [30], in the literature.

2. MATERIALS AND METHODS

In this study, a PV system with an installed power of 300 kWp is modeled on the roof application in Konya province, Turkey, with a latitude angle of 38.03 °N, determined by using the METEO 8.0 program, which is a part of the PVsyst software. In modeling, 35° tilt and 0° azimuth angles were used. Three different PV cells, mono-Si, poly-Si, and a-Si, were used within the modeling scope. The DXM5-36P-100 model belongs to the Sun Earth brand for mono-Si, the ESP 100W model belongs to the Einnova Solarline brand for Poly-Si, and the XR12-100 model belongs to the Xunlight Corporation brand for a-Si were used. 3010 modules of 100 Wp each, 35“ horizontal and 85“ vertical, were used in mono-Si and poly-Si panels. On the other hand, 3000 modules of 100 Wp each, 20 of which are horizontal and 100 are vertical, are used in the a-Si panel. Due to different companies and series, the surface areas of the mono-Si, poly-Si, and a-Si cells are 1978 m², 2058 m², and 4745 m², respectively. The inverter used in all modeling is Huawei Technologies SUN2000-100KTL-INM0-415VAC.

One parameter of the PVsyst software that gives essential information about the modeled system is the Performance Ratio (*PR).* The *PR* is obtained by dividing the electricity production (E_G) in a system with unit-installed power by the global horizontal radiation incident on the panel surface (G_I) as given in Eq. (1).

$$PR = \frac{E_G}{G_I \times P_{PV}} \tag{1}$$

Where, P_{pv} is the rated power of the system.

The economic analysis of PV systems must be well calculated before they are installed. Production of PV systems is a challenging and complex process. Many parameters, such as mining, transportation network structure, transmission, production, and processing, affect the energy production cost. The economic analysis of PV cells is also difficult to calculate since these parameters are many, and future events such as cloudiness and sunshine duration are not known precisely [31].

This first calculated value is the basic payback period (BPB). This value is calculated to determine how long the investment pays itself. First of all, the investment cost is determined. Afterward, expenses such as maintenance and taxes are added to this cost according to the years. With the electricity sales obtained, this investment cost decreases yearly, and profit is made after a certain period. In this way, the profit and loss values of the system are determined. The BPB formula is given in Eq (2) below.

$$BPB = \frac{INV_{base} - salvage\ value}{net\ annual\ cash\ flow} \quad (2)$$

However, due to inflation, money can lose value over the years, so calculations should be made at a specific discount rate. The net present value (NPV) at a given discount rate is calculated as in Eq.(3) [32].

$$NPV = \sum_{k=0}^{n} INV_{base} - \frac{SAVING_n - INV_n}{(1+i)^n} \quad (3)$$

Where, INV_{base} is the initial investment cost, $SAVING_n$ is the n^{th} year earnings, IVN_n is the n^{th} year expenses, and i is the discount rate. Another significant economic parameter is the Internal Rate of Return (IRR). The discount rate (i) that makes the NPV zero is calculated as in Eq. (4) [33].

$$\sum \frac{SAVING}{(1+i)^n} = \sum \frac{INV}{(1+i)^n} \quad (4)$$

The ratio of net profit from the system to the total investment is called Return on Investment (ROI), as given in Eq. (5). If this value is negative, the system is not feasible. Therefore, this value must be positive in the calculations before the system is installed.

$$ROI(\%) = \frac{net\ profit}{investment\ cost} \quad (5)$$

Economic analyses are made with simple procedures. However, the *ROI* needs to be calculated high because of possible unexpected problems encountered over the years.

3. RESULTS AND DISCUSSION

Total incoming radiation cannot be completely transformed into energy on the panel surface. Some radiation losses can occur, such as reflection, clouding etc. Irradiation that can be converted to energy is called Effective Global Irradiation (G_E). The monthly averages of G_E and G_I solar irradiations reaching the panel's surface, and their difference are given in Table 2. As seen, solar radiation rises throughout the spring and summer months and decreases again towards the winter. The highest G_I and G_E irradiation amounts are observed in August with values of 215.5 kWh/m² and 209.5 kWh/m², respectively, while the lowest G_I and G_E radiation amounts are observed in December with values of 103.7 kWh/m² and 101.4 kWh/m², respectively. However, due to the high irradiation in summer, the most significant difference between G_I and G_E is seen in July, with a value of 3.35%.

Table 2. Total G_I and G_E reaching the panel surface in Konya Province

Month	G_I (kWh/m²)	G_E (kWh/m²)	Difference (%)
1	112.5	110.3	1.99
2	125.0	122.3	2.21
3	163.6	159.9	2.31
4	177.9	173.0	2.83
5	200.2	194.1	3.14
6	200.2	193.8	3.30
7	209.9	203.1	3.35
8	215.5	209.5	2.86
9	202.2	197.2	2.54
10	165.9	162.4	2.16
11	125.1	122.5	2.12
12	103.7	101.4	2.27

It is known that solar irradiation and electricity production are directly proportional. Therefore, monthly electricity production for mono-Si, poly-Si, and a-Si cells is given in Table 3. As seen in Table 3, since the highest irradiation reached the panel surface in August, all PV systems also generated the highest electricity production values in August. Therefore, when these cells are compared, mono-Si cells produce the most electricity, with an annual production of 513.91 MWh. This value is 1.91% and 3.07% higher than the electricity generation values of poly-Si and a-Si cells, respectively.

Table 3. Annual average monthly electricity production of mono-Si, poly-Si, and a-Si cells in Konya, Turkey

Month	mono-Si (MWh)	poly-Si (MWh)	a-Si (MWh)
1	31.65	31.00	29.26
2	34.53	33.55	32.37
3	43.30	41.98	41.70
4	46.38	45.17	45.17
5	50.64	49.84	49.98
6	49.27	48.89	49.04
7	50.56	50.29	50.52
8	51.82	51.31	51.74
9	49.93	48.87	49.16
10	42.90	41.86	41.30
11	33.78	33.07	31.66
12	29.16	28.47	26.70

Compared to a-Si, mono-Si and poly-Si cells are more efficient and have nearly equal panel surface areas since their efficiency is relatively close. However, since the efficiency of the a-Si cell is less than other cells, it must have more surface area to have the same installed power. Therefore, the amount of radiation reaching the surface also increases. For this reason, since the amount of irradiation reaching the surface and PR is inversely proportional according to Eq. (1), the PR values of a-Si are less than other systems. Fig.5a, b, and c illustrate the monthly energy accumulations the systems recorded throughout the one-year simulation period, together with the instantaneous output power injected into the grid. While the mono-Si system can generate even 300 kW of energy in some days, poly-Si and a-Si systems can not reach 260 kW.

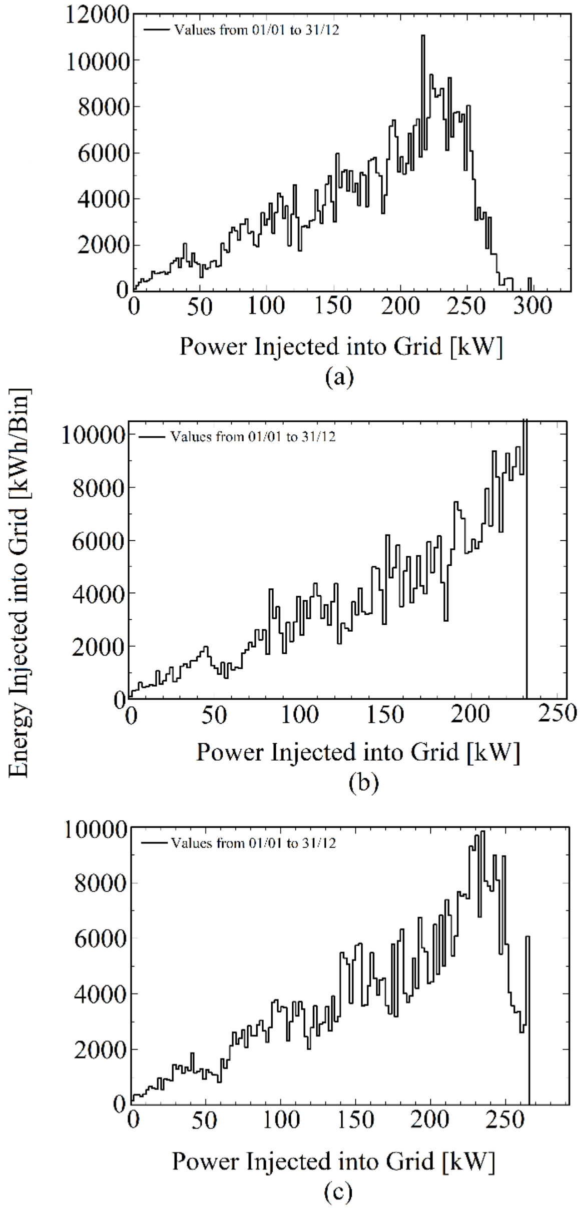

Fig. 5. The system output power distributions obtained from a) mono-Si, b) poly-Si, and c) a-Si PV panels

The *PR* values, the ratio of the electricity production obtained from the three PV technologies to the amount of irradiation coming to the panel surface, and calculated from Eq. (1), are given in Fig.6.

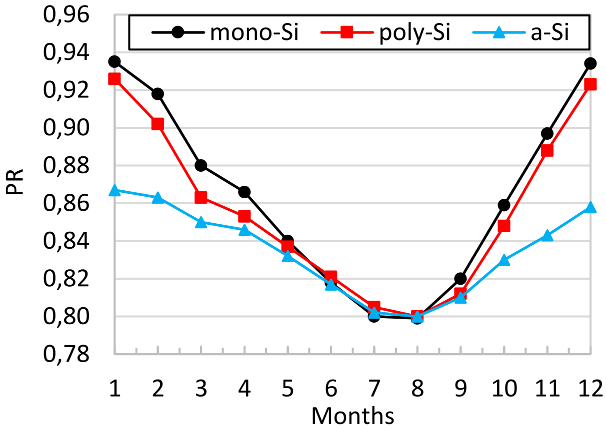

Fig. 6. Average monthly PR of the different systems

Due to the more surface area of a-Si, the amount of radiation coming to the panel surface is higher than other cells. Therefore, the PR value of a-Si is less than other cells. When annual values for all systems were compared, it was observed that the PR values decreased towards the summer months and increased towards the winter months. The highest annual PR value was obtained as 0.853 with mono-Si. In addition, while the difference between the PR values of the cells is lower in summer, the PR values of a-Si increase at a meager rate in winter compared to the other two cell technologies.

3.1 Economic Analysis

In this section, an economic analysis study was carried out with the electricity production values obtained from mono-Si, poly-Si, and a-Si. Some assumptions of the economic feasibility are given below.

- The systems will be built in the current year, and after construction, it will start generating electricity over 25 years lifespan.
- The installation cost for mono-Si and poly-Si is \$2.0/Wp, and for a-Si, it is \$3.0/Wp.
- The efficiency of all systems decreases by 0.5% every year compared to the previous year [34].
- The annual maintenance cost of the system taken as \$1500, which increases 15% each year in addition to the discount rate from the previous year.
- The electricity sales price is taken as 0.175 \$/kWh, which is assumed to increase by 5% each year, in addition to the discount rate.

- The discount rate is taken as 14.75% for Turkey [35].

At the end of 25 years, total income from electricity sales was calculated as \$1.5 million, \$1.44 million, and \$1.05 million.

NPV calculated by years using Eq. (2), and *i=14.75%* is given in Fig.7.

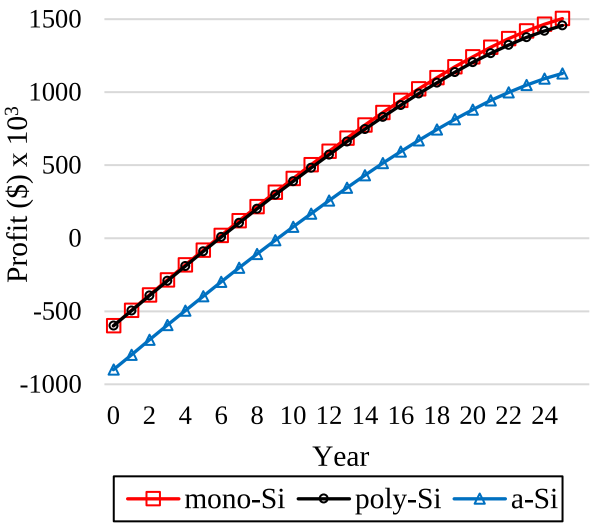

Fig. 7. NPV of the different projects by year

As expected, maximum profit was obtained from mono-Si. This value is approximately 3.29% and 33.67% higher than poly-Si and a-Si, respectively.

While mono-Si and poly-Si systems pay for themselves in approximately 5.8-5.9 years, a-Si pays off in approximately 9.0 years. Therefore, *ROI* values for mono-Si, poly-Si, and a-Si were calculated as 248.57%, 240.64%, and 123.97%, respectively, by Eq (5). These values mean the percentage of net profit obtained from the systems.

4. CONCLUSION

In this study, performance values of 3 different 300 kWp systems consisting of mono-Si, poly-Si, and a-Si were obtained using PVsyst, and an economic analysis was made. In addition, the values obtained from three different systems with different PV technologies are compared, and the results are listed below.

- Since it is installed in the same area, the amount of solar irradiation coming to the unit surface is the same.
- It was observed that G_I and G_E's reaching the panel surface increased towards the summer months and decreased towards the winter months. The highest G_I and G_E values were in July, with 209.9 kWh/m² and 203.1 kWh/m², respectively.
- The highest monthly electricity generation is calculated as 50.64 MWh, 49.84 MWh, and 49.98 MWh from mono-Si, poly-Si, and a-Si systems. The highest monthly electricity production was obtained from the mono-Si system in August, with a value of 51.82 MWh.
- The panel surface needed for 300 kWp installed capacity of mono-Si, poly-Si, and a-Si is calculated as 1978 m², 2058 m², and 4745 m², respectively.
- It is seen that PRs decrease towards the summer months and conversely increase towards the winter months.
- Annual highest PR values were obtained from mono-Si with a value of 0.935. This value is 0.71% and 2.77% greater than poly-Si and a-Si, respectively.
- For the economic analysis, the amount of electricity generated from mono-Si, poly-Si, and a-Si decreased to 142.55 MWh, 139.88 MWh, and 138.31 MWh in 2047, as the efficiency decreased by 0.5% every year for 25 years. It means that the system can lose up to 11.78% efficiency in its lifetime.
- It was concluded that the BBP of mono-Si, poly-Si, and a-Si is 5.80 years, 5.91 years, and 9.14 years, respectively.
- Although all systems have the same installed capacity, the mono-Si system occupies 1978 m², while the poly-Si and the a-Si occupy 4.04% and 139.88% more space than the mono-Si system, respectively.
- The profit values obtained from mono-Si, poly-Si, and a-Si were approximately \$1.5 million, \$1.44 million, and \$1.05 million, respectively, and the ratio of these values to the investment cost is 248.57%, 240.64%, and 123.97%, respectively.

Using mono-Si and poly-Si cells to set up such an extensive system is feasible. However, using a-Si is not recommended and not economically feasible due to the amount of electricity generation and its investment cost compared to the other technologies.

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