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Optimal and Economic Evaluation of using a Two-axis Solar Tracking System in Photovoltaic Power Plants, a Case Study of “Tehran”, Iran

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Abstract

Photovoltaic systems are one of the types of solar power generation systems. One of the main issues for the construction of a photovoltaic power plant is to determine the type of solar panel installation structure to produce the maximum energy of the photovoltaic system. Most photovoltaic panels used around the world are at a fixed angle. To increase power generation, we can use solar Trackers that guide the panels in the direction of the sun, and with this technique, we can make the most of photovoltaic systems. In this paper, a 20 kW photovoltaic power plant is simulated to compare the power generation of a system with a fixed-angle panel and a system with a two-axis solar tracker. The purpose of this study is to determine to what extent more effective but more expensive tracking systems can be a suitable standard in future PV power plants in the country, it is also discussed the application of these systems when the area and number of modules are limited and this is if These cases have not been seen in previous studies. Simulations for the city of Tehran in Iran have been done with PVsyst software. The total energy produced annually by photovoltaic systems with two-axis solar trackers was more than the energy produced by fixed-angle panels. Also, the economic analysis of the power plant has been done with RETScreen software, which shows that the efficiency and output power of the solar system with a two-axis tracker has increased compared to the fixed system. Using solar tracking systems is complex and expensive, but we can have the same amount of energy with fewer solar modules than with fixed systems. Therefore, systems with two-axis trackers are more practical when using the minimum installation area required.

Keywords: Solar energy; Two-axis PV tracking; Photovoltaic power plants

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1.Introduction

The greenhouse effect of fossil fuels affects the environment and to reduce carbon emissions, many Countries have invested in renewable energy research, such as solar photovoltaic (PV) technologies [1]. To maximize the output power of photovoltaic panels, studies have been done [2]. With an increasing demand for renewable resources, the production of photovoltaic panels has greatly improved in recent years [3]. Today, photovoltaic cell technologies are one of the fastest growing [4].

Solar tracking systems use solar panels to receive the highest power, and at the maximum power point, they have the highest power [5]. The tracking

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technology is used to make better use of solar energy, and many Researchers have done extensive research compared to uniaxial and biaxial solar tracking systems [6]. The use of solar trackers in photovoltaic system is a method required to optimize energy production [7,8]. Öztürk et al [9] compared a Two-axis tracking system with a fixed plate in a photovoltaic system in Dozje, Turkey. Chen and Wang [10] proposed a Two-axis solar tracker based on a parallel mechanism. The results show that the proposed tracker reduces system complexity and power dissipation. Mirzaei and Mohiabadi [11] investigated the performance of three different tracking modes of the photovoltaic system in the dry climate of Rafsanjan in Iran. Batayneh et al [12] proposed a single-axis solar tracking system that is activated only three times a day on the azimuthal plane to track the sun. Researchers have done extensive research in this area, for example in [13] a fresnel solar lens focus with fixed focus has been proposed as a new type of solar focuser. In [14,15,16] photovoltaic power plants have been studied and analyzed with PVsyst software.

Satish et al [17] investigated the installation of a KW solar power plant on the grid using PVsyst software for Dubai (Ashwini in [18] for India). Soualmia and Chenni [19] modeled and simulated a 15 MW photovoltaic system in northeast Algeria without using solar trackers with PVsyst software. Ajgaonkar et al [20] designed an off-grid solar system and used an MPPT controller and a two-axis tracker to increase energy production. Kaddour et al [21] have simulated an independent photovoltaic system using PVsyst software and evaluated its annual energy. Kumar et al [22] analyzed the performance of solar energy systems with HOMER and PVsyst software for the northern region of India. Mukherjee and Razzak [23] have done an optimization and economic analysis of a 100 kW solar photovoltaic system in Bangladesh using RETScreen software. Shabaniverki [24] has designed and analyzed a photovoltaic solar power plant with PVsyst software and the results show that there are favorable conditions for the development of solar energy systems in the study area, however, the methods of improving the efficiency and efficiency of the system and its economic issues have not been investigated. Sanni and Mohammed [25] have done an economic analysis based on changing the power grid to a photovoltaic system in Nigeria with RETScreen software and the results show that the photovoltaic system and the relatively cheap cost are more economically beneficial. Ekhteraei Toosi and Sani [26] evaluated photovoltaic systems with fixed and single-axis Tracking using PVsyst software, but the economic issues of using the Tracking System and Two-axis Tracking were not investigated.

In [6,27], a model that expresses the effect of a two-axis tracker considering economic issues and compares the amount of energy produced by the system with the tracker in a different area in a fixed system has not been seen. This research is a step forward compared to previous studies. In this paper, the performance of a 20-kW photovoltaic power plant with a two-axis solar tracker is compared with a fixed solar panel system, and simulations and economic evaluation of the power plant are performed with PVsyst and RETScreen software.

PVsyst software is a highly detailed tool For the study, modeling, design, and analysis of PV systems and RETScreen software facilitates a numerical analysis for financial modeling of PV plants and enables the user to perform a feasibility study both technically and financially, For this reason, this two software have been used for simulation. It can be seen that the energy produced by the system with the two-axis tracker is increased and the tracking systems are more practical when using the minimum installation area.

In this section, the preliminaries are discussed, and in section 2, the types of solar tracking systems are studied. In section 3, a 20-kW solar power plant connected to the grid is simulated with PVsyst software. In section 4, the economic analysis of the power plant has been done with RETScreen software. Finally, in section 5, the conclusion is presented.

2. Solar Tracker

There are several ways to increase the efficiency of photovoltaic systems and many of them are dedicated to the use of solar tracking systems [28]. A solar tracker adds to the cost and complexity of the system [29].

2.1. Maximum power point tracking

Maximum power point tracking (MPPT) is critical to achieving optimal conditions in solar systems [30]. The maximum power point (MPP) of I-V curves intersects with the load line and if the intensity of the radiation on the solar cell increases, it becomes larger [2]. Figure 1 shows the voltage-current curve of a typical solar module.

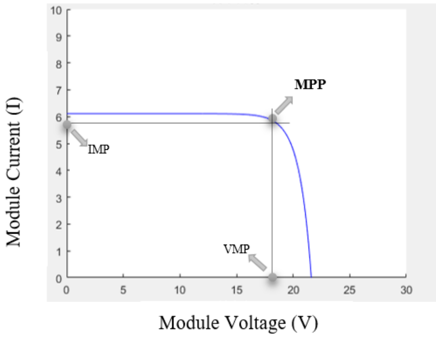


Figure 1. The Current-Voltage curve of a solar module with a resistance load [2]

There are many new techniques for MPPT in solar systems, including [31,32,33]:

1. Perturb and Observe (P&O)
2. Incremental conductance (INC)
3. Artificial Neural Network (ANN)
4. Fuzzy logic controller (FLC)

Among these techniques, P&O is widely used [34].

2.2. Types of solar trackers

Types of sun trackers examined Solar trackers can be divided into one-axis and two-axis tracking devices. Figure 2 shows the types of solar trackers. Tilt-roll (or polarity) are the most popular two-axis solar trackers [35].

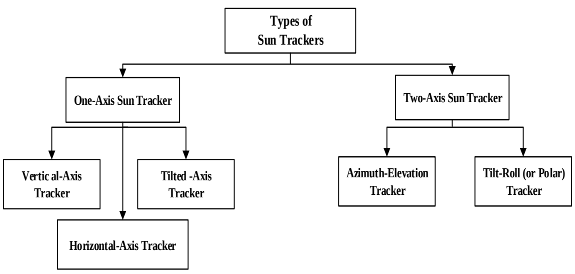


Figure 2. Classification of types of solar trackers [35]

In another classification based on the drive system, solar tracking systems are divided into two categories: passive and active [36]. In active systems, electrical devices, and mechanical devices are operating [37].

2.3. Two-axis solar tracking algorithm

Currently, two-axis tracker Solar panels are designed so that the panel moves to the point of maximum power every day [38]. A typical two-axis solar tracker can increase system efficiency by up to (30% -50%) compared to a fixed-angle solar system [39,40]. Using two-axis trackers, maximum sunlight is absorbed by photovoltaic panels, and maximum power is generated [41]. Systems with two-axis trackers have two axes of rotation [42]. The efficiency of the solar tracking system is shown in the following equation [43].

$$Gain_{tracking} = \frac{P_{Tracking} - P_{Fixed}}{P_{Fixed}} \quad (1)$$

Where $P_{tracking}$ is the total power on the solar tracking panel and P_{fixed} is the total power on the fixed panel. The two-axis solar tracker is shown in Figure 3 [44].

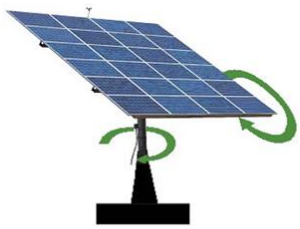


Figure 3. Two-axis solar tracker [43]

3. Simulation Results of a 20- kW Solar Power Plant and Discussions

The photovoltaic system includes a PV array, inverter, and components of the balance system, such as the charge controller, and energy storage system [44].

Figure 4 shows an overview of the photovoltaic system connected to the study network. In this paper, a 20-kW photovoltaic power plant connected to the grid in Tehran is simulated with PVsyst software. The conditions and equipment considered for the two power plants are the same except for their tracking algorithm. The tracking algorithm of the two systems periodically changes between the fixed and the biaxial tracker to investigate and compare the performances of the two systems (fixed and two-axis solar panels).

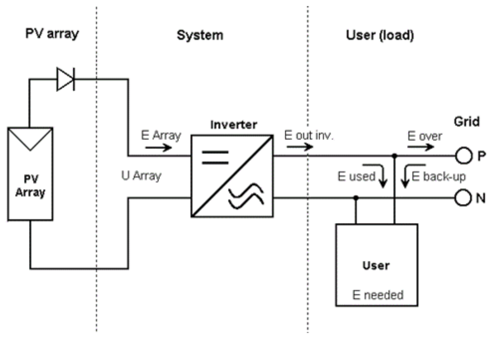


Figure 4. Schematic of 20- kW solar power plant

The geographical coordinates of the selected site (Tehran) are given in Table 1.

Table 1. Geographical coordinates of the study site [45]

Latitude	35.6800
longitude	51.3800
Altitude	1189
Time Zone	3.5

Climatic and weather information of Tehran city was obtained using the Meteonorm option in PVsyst software. The specifications of the panels used and the assumptions and simulation inputs are given in table 2.

Table 2. Amount of the inputs in the simulation

parameters	Amount
PV module model	Si-poly-YL250P-29b
Solar module power	250Wp
PV module manufacturer	Yingli Solar
Inverter model	Sunny Boy 5000 U-208
Inverter manufacturer	SMA
Total Power Plant	20 **kW**

The path of the sun is shown using PVsyst software in Figure 5. According to Figure 5, the path of the sun depends on its angle and movement of the sun.

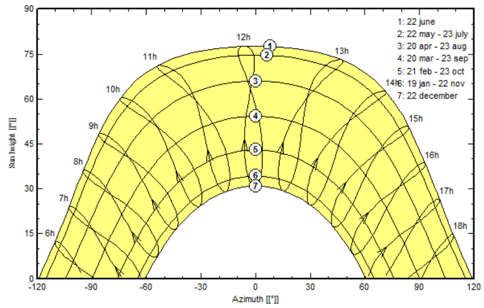


Figure 5. The path of the sun in the city of Tehran

Figure 6 shows the temperatures of Tehran separately for each month. Figure 7 shows the amount of horizontal diffuse irradiation (DiffHor) and horizontal global irradiation (GlobHor) in the city of Tehran. Climate information was obtained using the Meteonorm option in PVsyst software.

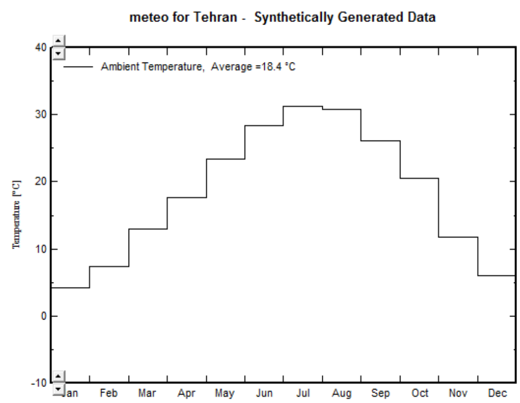


Figure 6. Temperature of Tehran by month

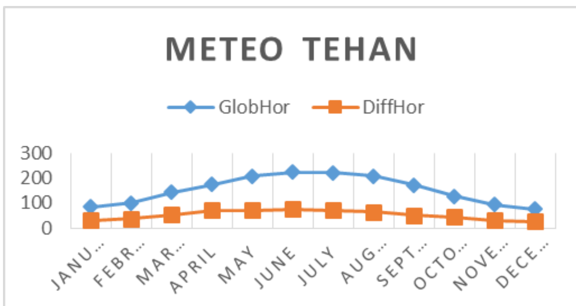


Figure 7. The amount of DiffHor and GlobHor in Tehran.

In the orientation section, the panels are facing south and the angle of the panels is adjusted to the ground (slope angle). In system S_1, the angle of the panels can be adjusted to 30 degrees to receive the maximum radiation in the solar module, and the angle of the panels in system S_2 varies during the day and night. Each tracking algorithm is presented separately in Figures 8 and 9. System S_1 is a fixed system and system S_2 is a two-axis tracking system.

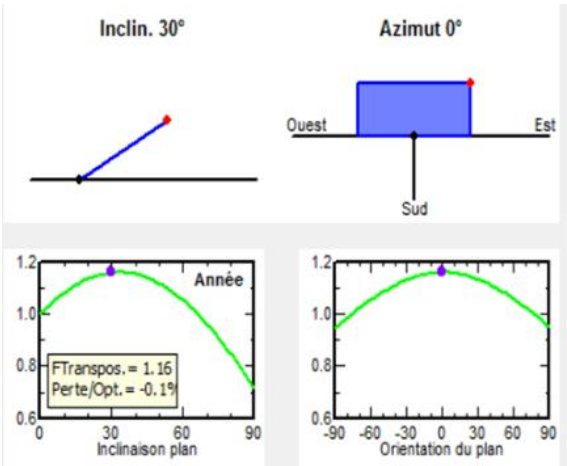


Figure 8. Algorithm and angle of PV panels in system S_1

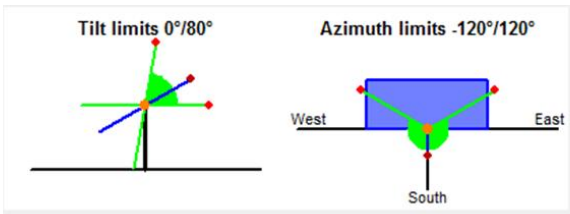
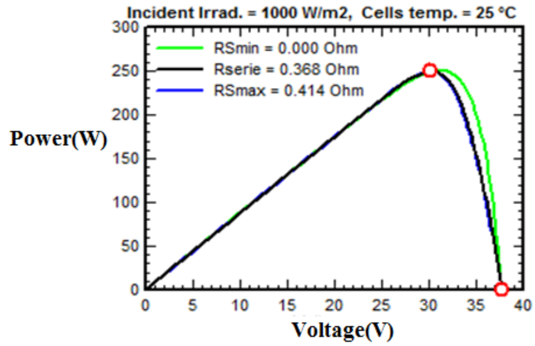


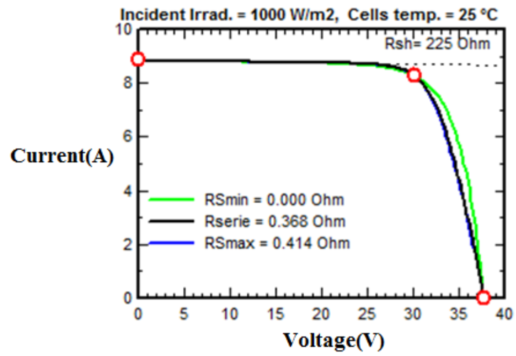
Figure 9. Two-axis tracking system algorithm of PV panels in system S_2

For both power plants S_1 and S_2, one type of panel and one type of inverter have been used. The characteristic P-V and I-V characteristic curves of the solar panels used in the systems are shown in Figure 10.

In this paper, the amount of energy injected into the grid in two modes of two-axis and fixed trackers in one year has been obtained with the help of PVsyst software and the results of two systems S_1 and S_2 are shown in the following figures and tables.



(a)



(b)

Figure 10. Characteristics curve of: (a) P-V, (b) I-V solar panels at 1000 w / m^2 and 25 ^oC temperature

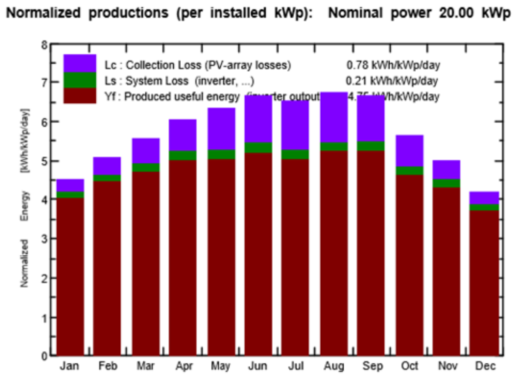
Table 3 shows the amount of energy generated and solar radiation information (temperature-horizontal radiation-scattered radiation) in a power plant with fixed panels (system S_1) in a year.

According to the results and tables, the energy generated in one year in the system without a tracker was 34.695 MWh, but in system S_2 with the two-axis tracker, the generated electricity was 47.835 MWh (i.e. about 37.87% more than a fixed panel).

According to the information obtained, the amount of energy generated in one year using the two-axis tracking system increased significantly. This conclusion can also be obtained with the help of diagrams obtained using PVsyst software. Figure 11 shows a graph of the energy produced each month for power plants S_1 and S_2. The corresponding normalized production per installed kWp for a 20KWp system tilted at 30° is shown in figure 11.

Table 3. System S_1 Balances and main results

	GlobHor Kwh/m²	DiffHor Kwh/m²	T-Amb ºC	GlobInc Kwh/m²	GlobEff Kwh/m²	E Array MWh	E-Grid MWh
January	85.7	31.50	4.19	139.3	133.7	2.612	2.505
February	99.6	37.71	7.33	142.0	137.4	2.622	2.513
March	142.6	54.27	12.98	172.6	166.1	3.071	2.939
April	173.2	71.80	17.66	180.9	172.9	3.155	3.022
May	208.2	72.06	23.41	195.5	186.6	3.299	3.155
June	222.1	75.87	28.38	199.4	190.1	3.292	3.149
July	220.5	71.23	31.32	202.6	193.7	3.292	3.147
August	207.0	63.85	30.82	209.1	200.7	3.407	3.264
September	171.0	51.02	26.17	199.2	192.1	3.311	3.172
October	128.2	45.51	20.45	174.5	168.5	3.022	2.900
November	94.1	32.02	11.73	149.5	144.8	2.717	2.607
December	76.8	27.42	6.05	129.8	125.7	2.422	2.321
Year	1828.0	634.26	18.44	2094.4	2012.4	36.222	34.695



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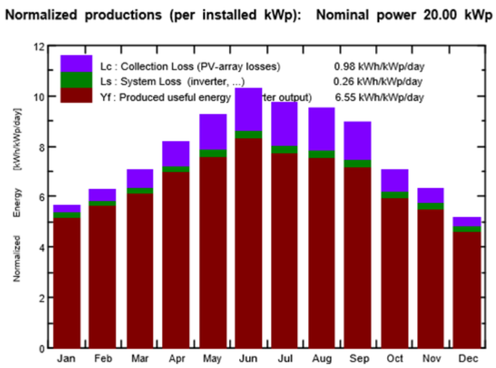


(b)

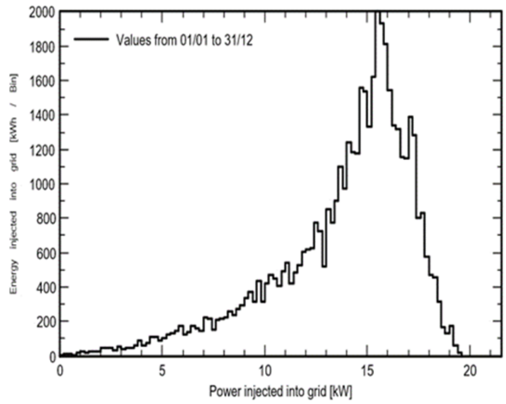
Figure 11. Normalized energy per month for power plants: (a) S1, (b) S2

Table 4 shows the amount of energy generated and solar radiation information (temperature-horizontal-radiation-scattered radiation) in a power plant with two-axis panels (system S2) in a year.

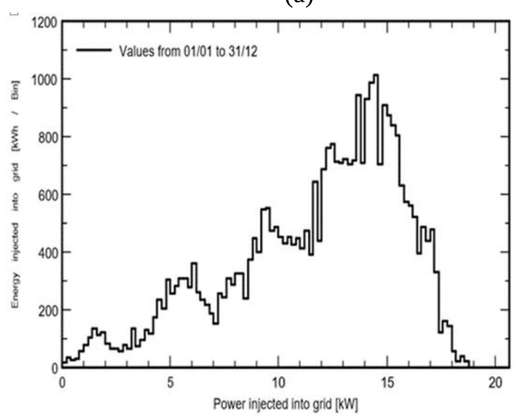
Table 4. System S2 Balances and main results

	GlobHor Kwh/m²	DiffHor Kwh/m²	T-Amb ºC	GlobInc Kwh/m²	GlobEff Kwh/m²	E Array MWh	E-Grid MWh
January	85.7	31.50	4.19	175.7	174.0	3.349	3.219
February	99.6	37.71	7.33	176.3	174.4	3.287	3.160
March	142.6	54.27	12.98	219.7	217.3	3.965	3.807
April	173.2	71.80	17.66	244.8	241.7	4.357	4.191
May	208.2	72.06	23.41	286.4	283.3	4.920	4.731
June	222.1	75.87	28.38	308.4	305.0	5.200	5.008
July	220.5	71.23	31.32	302.3	299.2	4.993	4.806
August	207.0	63.85	30.82	293.5	290.5	4.850	4.670
September	171.0	51.02	26.17	268.0	265.6	4.499	4.325
October	128.2	45.51	20.45	219.5	217.2	3.839	3.694
November	94.1	32.02	11.73	189.6	187.8	3.467	3.332
December	76.8	27.42	6.05	160.8	159.3	3.013	2.891
Year	1828.0	634.26	18.44	2845.0	2815.4	49.740	47.835

The output power distribution of systems S1 and S2 is shown in Figure 12.



(a)



(b)

Figure 12. The output power distribution of systems : (a) S_1, (b) S_2

4. Economic Analysis of the Solar Power Plant

The costs of setting up a solar energy system (fixed and with a two-axis tracker) are given in Table 5. It can be seen that the amount of electricity generated with a two-axis tracker is higher according to the required cost. In the simulation and analysis of this section, two cases are considered. At the first, the same area for a fixed solar panel system and two axes solar panel is considered.

The output power distribution of systems S1 and S2 is shown in Figure 12.

Table 5. Costs of setting up a fixed solar system with two-axis tracking (seller https://www.alibaba.com)

Row	parameter	amount		Fixed system cost ($)	Two-axis tracking system cost ($)
1	Solar panel	20(KW) No. modules= 80		6048	6048
2	Inverter	No. of inverters units= 4		1596	1596
3	Two-axis solar tracking system	_		0	8240
4	Aluminum structure of solar module	_		936	936
5	Cable, fuse and meter	_		761	761
6	The amount of land required	200 (m^2)		_	_
7	Annual production energy (MWh) (From Tables 2 and 3)	Fixed system	Two-axis tracking system	_	_
		34.695	47.837		
8	Total cost ($)	_		9341	17583

4.1. Economic criteria for project evaluation

- Net Present Value(NPV)

This criterion tries to find a balance between the investment payments and the income from the implementation of the investment by considering the time adjustment of the money. This interest is called the minimum attractive rate of return (MARR). The present value of a set of future cash flows can be calculated using the following equation [46]:

$$NPV = NCF + \frac{NCF_1}{(1+i)} + + ... + \frac{NCF_t}{(1+i)^t} \qquad (2)$$

Where
i= Discount Rate
t= Financial period
NCF= Net Cash Funds

- Internal Rate of Return(IRR)

IRR is a well-known criterion in the economic evaluation of projects. IRR is the discount rate based on which the net present value of the project becomes zero. If the project's NPV is positive, the IRR of that project is higher than the rate of return used for the investment [46,47].

- Payback Period(pp)

The period of net return of capital includes the period of net return of normal and movable capital. The meaning of period of net return of normal capital is the net cumulative cash flows of the project during the period of exploitation, and the meaning of the period of net return of movable capital is that the time value of money is taken into account in the calculation of PP and the calculations are made based on the Discounted data [46,47].

The annual maintenance costs are equal to one percent of the initial cost. The useful life of the solar power plant was considered to be 20 years, and the reason for this is the high temperature in some months of the year and the reduction of the useful life of the cells.

For a better analysis of the results, we draw a system Cumulative cash flow diagram in RetScreen software. The chart of return on capital (cumulative cash flows) taking into account the inflation rate of

12% and the discount rate of 18% are shown in Figures 13 and 14. According to the figure, we see that the time of return on investment is 4 years for a fixed system and close to 6 years for a solar tracking system.

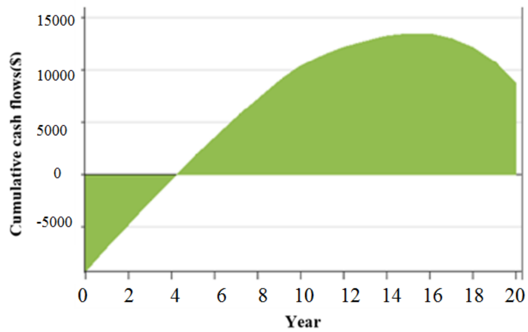


Figure 13. Capital return chart (cumulative cash flows) of a fixed solar power plant (S1 system) for 20 years

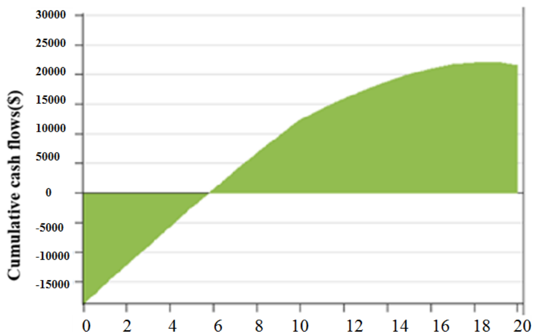


Figure 14. Capital return chart (cumulative cash flows) of a power plant with a two-axis solar tracker (S_2 system) for 20 years

The amount of energy generated for a system with a two-axis tracker is more than for a fixed system. If we want to unify the amount of energy generated for a fixed and two-axis system, we need more area and equipment.

As shown in Table 6, in a fixed system, to produce energy similar to a two-axis system, we need 80 meters more land and more equipment, and the total cost is without considering the cost of the added area, and according to the cost of the area need, a system with a two-axis tracker is more suitable for power generation.

The results show that the use of solar tracking systems is complex and expensive, but the annual energy production shows that tracked systems can have the same amount of energy and fewer solar modules than fixed systems.

Table 6. Costs of setting up a fixed solar energy system with the production capacity of a two-axis system (seller https://www.alibaba.com)

Row	parameter	amount	The cost of a fixed system with a production capacity equal to the system with a two-axis tracker ($)
1	Solar panel	28(KW) No. modules =117	8845
2	Inverter	No. of inverters units =3	1497
3	Two-axis solar tracking system	_	_
4	Aluminum structure of solar module	_	1263.6
5	Cable, fuse and meter	_	1027
6	The amount of land required	280(m^2)	_
7	Annual production energy	47.626 (MWh)	_
8	Total cost	_	12632.6$

5. Conclusions

In this paper, a 20 kW power plant connected to the grid in Tehran was designed using PVsyst software. The performance of the solar power plant was evaluated when the panels were without a tracking system (fixed) and when the system used a two-axis tracker. It was also shown that the energy generated in a year using a two-axis tracking system increased by 37.87%, which is satisfactory and will increase revenue and increase system efficiency and reduce losses in each part of the solar system. For an economic analysis of the system, the system cumulative cash flow diagram was drawn with RetScreen software for two modes of fixed panels and panels with the two-axis tracker. For the same energy generated in a fixed system, more area is required, therefore, it can be concluded that tracking systems are more practical when using the minimum installation area.

Acknowledgments

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Nomenclature

PV	Photovoltaic
MPPT	Maximum Power Point Tracker
GlobHor	Global Horizontal
DiffHor	Diffuse Horizontal Irradiation
T-Amb	Ambient Temperature
GlobInc	Global Incident in coll. plane
GlobEff	Efficiency Global,corr.for IAM and shadings
EArray	Efficiency energy at the output of the array
E-Grid	Energy injected into grid
NPV	Net Present Value
MARR	Minimum Attractive Rate of Return
NCF	Net Cash Funds
PP	Payback Period
IRR	Internal Rate of Return

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