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A comparative techno-economic assessment of manually adjustable tilt mechanisms and automatic solar trackers for behind-the-meter PV applications

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ABSTRACT

Many studies in the literature aim to increase the amount of solar radiation falling on photovoltaic (PV) panel surface to improve its performance. Most of these studies concentrate on solar tracking systems and few studies focus on manually adjustable tilt mechanisms. However, no studies in the literature compare these two methods techno-economically. Therefore, as its main contribution, this study makes a techno-economic comparison of solar trackers and manually adjustable tilt mechanisms. First, the electricity production of fixed-tilt, manually adjustable tilt mechanisms (monthly and seasonal adjustment), and automatic solar trackers (single-axis east-west (SA-EWT), single-axis south-north (SA-SNT), and dual-axis (DAT)) systems are technically analyzed for three provinces in Turkey with different solar characteristics. After that, the systems are compared economically and evaluated over levelized cost of electricity (LCoE), discounted payback period (DPBP), and internal rate of return (IRR). Finally, a detailed sensitivity analysis is made and the impact of changes in initial investment costs and real interest rates is examined. Eventually, the payback period of fixed-tilt systems is found to be 10.3–13.3 years in Turkey. Dual-axis solar trackers provide the highest electricity production increase (30.4–34.6%) compared to fixed-tilt but with the highest payback period (16.7–24 years) among all alternatives. Monthly manual tilt adjustment provides the most feasible solution by decreasing the payback period of fixed-tilt systems by around 8 months to 9.6–12.6 years and with an electricity production increase of 3.6–5%.

1. Introduction

1.1. Motivation and background

Over the last decade, photovoltaic (PV) investments have gained increased momentum due to falling module costs and raising environmental concerns. PV module prices, which were around 3 US $/W in 2010, decreased more than tenfold to 0.27 US $/W in 2020, making PV investments more feasible than ever [1]. During this period, the global installed PV capacity increased from 40.3 GW to 707.5 GW [2]. Meanwhile, the climate change continued to affect every country on every continent. Despite the efforts, the last decade was the warmest on record due to global warming which will likely fuel renewable energy investments in the 2020s [3]. At the end of 2020, the share of global solar PV capacity exceeded that of wind for the first time, becoming second in the total renewable mix after hydropower [4].

The feasibility of PV investments is affected not only by the investment cost but also by the amount of solar radiation falling on panel surface. Therefore, PV arrays are installed in areas with higher solar radiation whenever possible and optimally inclined to provide higher energy yield. Fixed-tilt systems cannot follow the changing position of the sun due to the sun trajectory. Thus, solar gain can either be increased by manual tilt adjusting or automatic solar tracking [5].

Solar tracking systems are mainly divided into two types, single-axis and dual-axis. Single-axis trackers have only one axis of rotation and pivot in horizontal or vertical planes. They are usually preferred at utility-scale projects. More widely used horizontal single-axis trackers are usually aligned with north/south axis to track the sun's trajectory from east to west [6]. Less common vertical single-axis trackers rotate from east to west and are more suitable to be used at the higher latitudes of northern and southern hemispheres [6]. Dual-axis trackers with two rotation axes, are mechanically more complex structures and require higher investment and maintenance but offer a wider range of tracking

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Nomenclature

List of symbols

h_s	Sunset hour angle
$H_{Total,t}$	The global (total) solar radiation on a tilted plane
H_{Total}	The global solar radiation on a horizontal plane
$H_{beam,t}$	Beam radiation on a tilted plane
H_{beam}	Beam radiation on a horizontal plane
$H_{diff,t}$	Diffuse radiation on a tilted plane
H_{diff}	Diffuse radiation on a horizontal plane
H_{ext}	Extra-terrestrial solar radiation
$H_{ref,t}$	Reflected radiation on a tilted plane
H_{ref}	Reflected radiation on a horizontal plane
H_{sc}	Solar constant
H_t^{STC}	Solar radiation under standard test conditions (STC)
K_T	Clearness index
$O\&M_t$	Operation and maintenance cost of the system
$P_t^{PV,prod}$	Power produced by PV panel
R^{PV}	The rated capacity of the PV system
R_b	The ratio of beam radiation on the tilted surface to that a horizontal plane
$T^{c,STC}$	Cell temperature under STC
T_t^c	Cell temperature
T_t^{out}	Ambient temperature
Z_s	Solar azimuth angle
a_p	Temperature power coefficient
$cash_t$	The net cash flow in time t
d^{PV}	PV panel derating factor
θ_z	Zenith angle
h	Hour angle
DL	Maximum sunlight duration
IC	The initial investment cost
L	The latitude of the selected provinces
N	Number of day starting from 1st January
T	System lifetime
Z	Surface azimuth angle
i	Real interest rate
i_n	Nominal interest rate
β	The tilt angle of a PV panel with a horizontal plane
δ	Solar declination
θ	Angle of incidence
ρ	Albedo constant

possibilities. Dual-axis trackers are more costly and usually more common among behind-the-meter applications or off-grid systems where supply must meet demand [7].

An alternative to solar trackers is manually adjustable tilt mechanisms. In this method, the tilt angle of arrays is manually and periodically adjusted by manpower such as semi-annual, seasonal, or monthly. While they may not be as effective as solar trackers in terms of energy gain, they can be more cost-effective as they do not rely on costly electric motors or hydraulic cylinders to change position. An example design of a manually adjustable tilt mechanism is demonstrated in Fig. 1 (adopted from [8]).

Today, manually adjustable tilt mechanisms can provide an electricity production increase of up to 8%, while single- and dual-axis trackers can increase production by 15–25% and 30–45%, respectively, compared to fixed-tilt [9,10]. On the other hand, despite the higher energy gain, dual-axis trackers require higher initial investment and maintenance costs whereas manually adjustable tilt mechanisms require negligibly low costs. The different cost parameters of these systems require a feasibility comparison. Therefore, this study makes a techno-economic comparison of solar trackers and manually adjustable tilt mechanisms for PV installations.

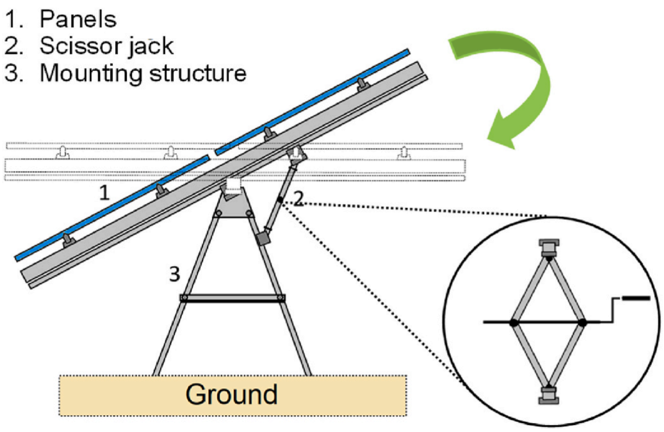

Fig. 1. Design of manually adjustable tilt mechanism.

1.2. *Literature review*

Many studies in the literature focus on obtaining the electrical energy that can be produced from PV systems in an optimal way. The early studies on this subject focused on determining the optimal tilt angle with respect to the correlation between the latitude of the region and the optimal tilt angle [11,12]. Apart from the relation between latitude and optimal tilt angle, there are also studies constructing correlations for optimal tilt angle using solar declination and latitude in a statistical way. Raptis et al. [13] investigated the amount of solar radiation on inclined surface taking into account the cloudiness effect and determined the optimum tilt angle to be 30° in Greece. Bakirci [12] constructed regression models based on solar declination for optimal tilt angles using the data of locations with different climatic characteristics for Turkey. Khorasanizadeh et al. [14] built up some models to determine the optimum tilt angles by statistically analyzing the diffuse radiation values for the city of Tabass in Iran. Le Roux [15] evaluated the influence of soiling and weather conditions in determining the optimum tilt angles for South Africa using data from several measuring stations. Jacobson and Jadhav [16] analyzed the data of sample locations selected from many countries with PVWatts software and estimated the optimum tilt angles worldwide.

Another way to increase the solar radiation falling on panel surface is to use manually adjustable tilt mechanisms. In this method, optimal tilt angles are determined depending on a region's solar radiation data, and then the tilt angle of panels are adjusted periodically such as monthly or seasonal. In the literature, many studies have been carried out in many places and regions with different climatic characteristics. Nageh et al. [17] investigated the energy gain of automatic and manual tracking systems for 12 provinces worldwide. Seasonal and monthly automatic tracking provided 1.59–7.24% more energy compared to fixed-tilt. Aksoy Tirmikci and Yavuz [18] found that monthly and seasonal manual tilt adjustment ensure 5.69% and 4.54% more solar radiation, respectively, in the province of Sakarya, Turkey. Liu [19] showed that changing the tilt angle two and three times a year provides 5.1–5.6% more energy than fixed-tilt in Liaoning, China. Garni et al. [20] determined that monthly tilt adjustment and seasonal tilt adjustment at unequal time intervals (fime times a year) provides 4.01% and 3.63% more electric energy yield in Saudi Arabia, respectively. Gonul et al. [21] determined that manually adjustable systems provide 3.21–5.30% more electricity production in Turkey, depending on the solar radiation of a location. Some other studies in the literature are summarized in Table 1.

Many studies analyze the energy that can be obtained from single- and dual-axis solar tracking systems [26–31]. Abdallah and Nijmeh [26] compared the electricity production of fixed-tilt systems and dual-axis trackers controlled by programmable logic controller (PLC), and found that the latter provided 41.34% more production on average. Maatallah et al. [27] showed that, in Tunisia, single-axis systems increased the electricity production by 10.34% in summer and 15% in winter solstices, whereas dual-axis systems provided increases of 30% and 44%. Quesada et al. [28] investigated the behavior of dual-axis tracking systems at high latitudes (Montreal, Canada) and found that their use on cloudy days was ineffective. Şenpınar and Cebeci [29] showed that the daily energy production from dual-axis tracking systems is %13.2 higher on average compared to fixed-tilt systems, and varying between 13 and 15% depending on the cloudiness. Abdallah and Badran [30] found that vertical single-axis tracking system provided 22% more electricity production compared to fixed-tilt in Jordan. Bahrami et al. [31] investigated the effect of latitude on the energy gain of different solar tracking systems for Europe and Africa and showed that dual-axis systems increased the production by 17.72–31.23% compared to fixed-tilt. The other studies in the literature about the energy gains of tracking systems are presented in Table 2.

The studies reviewed above only addressed the technical analysis and evaluated solar trackers in terms of energy gain. However, the most important factor that ensures the realization of an investment is its economic viability. Only very limited number of studies have examined solar trackers from this perspective. Garni et al. [41] conducted a techno-economic analysis of solar trackers. Vertical single-axis and dual-axis systems provided 20% and 34% higher power output than fixed-tilt, respectively. The vertical single-axis tracker had lower levelized cost of electricity (LCoE) and positive return on investment (ROI), which enhanced its viability for a utility-scale PV system. Rodriguez-Gallegos et al. [42] investigated the techno-economic performance of monofacial and bifacial PV panels for fixed, single- and dual-axis systems in ten countries. On average, LCoE of monofacial single- and dual-axis trackers were found to be 0.86 and 1.08 times the LCoE of fixed-tilt systems, respectively. Vaziri Rad et al. [43] carried out an environmental impact analysis of solar trackers in addition to their technical and economic analyzes. All three studies evaluated the feasibility of solar trackers on LCoE and other economic determinants such as discounted payback period (DPBP) and internal rate of return (IRR) are not considered. The summary of the economic performance of solar tracking systems is presented in Table 3.

1.3. *Content and contribution*

The papers reviewed above made valuable contributions to the literature. Yet, no study in the literature has compared manual tilt adjusting and automatic solar tracking both technically and economically. Although there are few studies in terms of technical performance comparison, the economic feasibility of these two methods has not been compared so far. Therefore, the main contributions of this study are twofold:

(1) The study makes a techno-economic comparison of manually adjustable tilt mechanisms and solar trackers for the first time in the literature.
(2) There are only a few studies on the economic analysis of solar trackers in the literature. The study contributes to filling this gap. Also, unlike other studies, it does not only evaluate the economic viability of solar trackers through LCoE but also discounted payback period (DPBP) and internal rate of return (IRR) to consider all economic determinants.

Table 1
Technical performance of manually adjustable tilt mechanisms in the literature.

Reference	Location	Energy gain (%)		Optimal tilt angle (°)
		Monthly	Seasonal	
Ullah et al. [22]	Lahore, Pakistan	7.25	6.09	31.5
Despotovic and Nedic [23]	Belgrade, Serbia	8.91	7.72	40.6
Kaddoura [10]	Saudi Arabia	7.74	6.38	19.3
Jafarkazemi and Saadabadi [24]	Abu Dhabi, UAE	5.71	4.75	22
Abdallah et al. [25]	Gaza & Jerusalem, Palestine	5.98	4.92	29

Table 2
Technical performance of solar tracking systems in the literature.

Reference	Location	Energy Gain (%)	
		Single-axis	Dual-axis
Lazaroiu et al. [32]	Romania	12.0–20.0	–
Chang [33]	Taiwan	18.7	–
Hammad et al. [34]	Jordan	–	31.3
Khilji and Munir [35]	UK	–	20.5
Ponce-Jara et al. [36]	Ecuador	–	19.6
Ghosh et al. [37]	Bangladesh	22.0	25.0
Helwa et al. [38]	Egypt	21.0	30.0
Okoye et al. [39]	Nigeria	26	30.9
Praliyev et al. [40]	Kazakhstan	28.9	33.1
Garni et al. [41]	Saudi Arabia	20.0	34.0

Table 3
Economic performance of solar tracking systems in the literature.

Reference	Location	LCoE (USD-cent/kWh)		
		Fixed-tilt	Single-axis	Dual-axis
Saudi Arabia	4.9	4.5–5.4	~5.2	
Rodriguez-Gallegos et al. [42]	China	2.8	2.3	3.0
	Japan	4.9	4.5	5.0
	Germany	6.8	5.9	6.8
	United Kingdom	8.2	7.1	8.3
	United States	4.7	3.9	4.6
Vaziri Rad et al. [43]	Iran	~2.6	~2.8	~2.7

In the study, first, optimal tilt angles were determined for three provinces with different solar characteristics in Turkey for fixed-tilt and manual adjustment scenarios. Then, the performance of the three approaches (fixed-tilt, manually adjustable tilt mechanisms and solar trackers) was compared in terms of electricity production. After that, the systems were compared economically and evaluated over LCoE, DPBP, and IRR. Finally, a detailed sensitivity analysis was made and the impact of changes in initial investment costs and real interest rates was examined. The framework of the study is given in Fig. 2.

2. Methodology

2.1. *Solar energy in Turkey*

Turkey has an estimated solar energy potential of about 1000 TWh, 10% of which is considered suitable for electricity generation. The country has an annual average solar radiation of 1527 kWh/m2-year and a sunshine duration of 2741 h [44]. The solar energy potential atlas (GEPA) of Turkey is demonstrated in Fig. 3. The solar radiation density increases from the north to the south of the country [45]. Three provinces representing different solar radiation regions in Turkey were selected from the northern (Istanbul), central (Izmir) and southern (Antalya) regions of the country to be used in the simulations. These

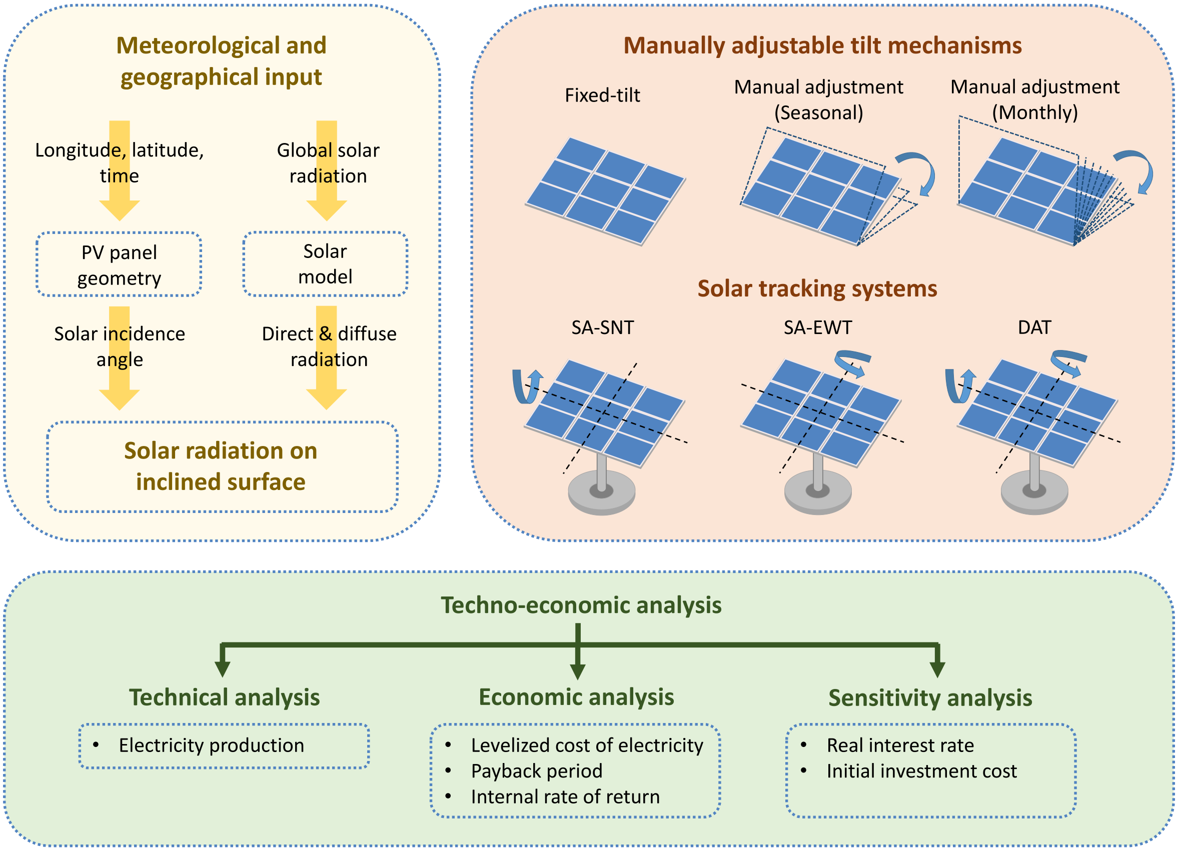

Fig. 2. The framework of the study.

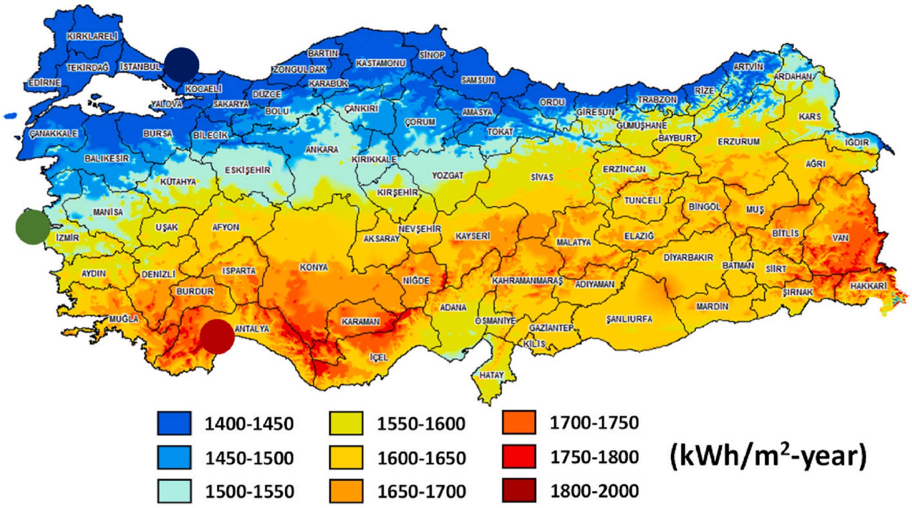

Fig. 3. Solar radiation density map of Turkey and the selected provinces (Istanbul, Izmir, Antalya).

provinces contain approximately 30% of Turkey's population. While Istanbul and Izmir are the main cultural, commercial and industrial centers of the country, Antalya is the top tourism destination. In recent years, there has been a serious increase in the number of solar PV installations in Turkey. The installed PV capacity, which was 40.2 MW in the year 2014, reached 6667 MW in 2020 [46]. The majority of these installations are on the basis of power plants. The rooftop capacity reached 1000 MW including residential, commercial, and industrial applications [47].

2.2. Tilting and tracking mechanisms

To increase the electricity production obtained from PV panels, the amount of solar radiation falling on panel surface should be increased. To achieve this, (1) the panels can be positioned at an annual optimal tilt angle with a fixed system, or (2) the tilt angle can be periodically adjusted at certain periods (such as seasonally or monthly) according to the optimal tilt angle of the relevant period using manually adjustable tilt mechanisms, or (3) the panels can automatically follow the sun using single- or dual-axis solar tracking systems.

In this study, six different alternatives were analyzed from a techno-economic point of view;

- Fixed-tilt system
- Manually adjustable system with seasonal tilt adjustment
- Manually adjustable system with monthly tilt adjustment
- Single-axis east-west tracker (SA-EWT) system
- Single-axis south-north tracker (SA-SNT) system
- Dual-axis tracker (DAT) system

2.3. Solar radiation modeling

Solar radiation reaching outside of the earth's atmosphere from the sun is called extraterrestrial radiation and is defined as in Eq. (1) [48].

$$H_{ext} = H_{sc}\left(1 + 0.033\cos\frac{360N}{365}\right)(\cos(L)\cos(\delta)\sin(h_s) + \sin(L)\sin(\delta)) \tag{1}$$

It is exposed to some atmospheric effects before it reaches the earth's ground. (1) Some of the solar radiation is absorbed, (2) some part is scattered by clouds or other atmospheric aerosols, and (3) a small portion is reflected by landforms and other non-atmospheric effects [49]. Solar radiation measured on the ground is called total (global) radiation and consists of three main components (Eq. (2)). The main component representing the largest quantity of the solar radiation that reaches directly to the ground passing through the atmosphere is called direct (beam) radiation (H_{beam}). The part that is exposed to atmospheric effects is called diffuse radiation (H_{diff}). The remainder, which represents the part outside of atmospheric effects, is called reflected radiation (H_{ref}).

$$H_{Total} = H_{beam} + H_{diff} + H_{ref} \tag{2}$$

The total solar radiation in a location is not always at the same radiation intensity due to the movements of the earth during the day and throughout the year. While the amount of solar radiation and sunshine duration is higher in the northern hemisphere in summer, it is less due to cloudiness in winter. With the fact that the electricity produced from PV panels is directly proportional to the solar radiation falling on the panel, PV panels are either held at a certain angle or solar tracking is done with automatic systems. Several mathematical models are used to estimate the solar radiation falling on the panel, and Liu and Jordan model [50], which is one of the commonly used and easily applied models in the literature, is performed in this study (Eqs. 3–17) [51].

$$H_{Total,t} = H_{beam,t} + H_{diff,t} + H_{ref,t} \tag{3}$$

$$H_{beam,t} = \left(1 - \frac{H_{diff,t}}{H_{Total}}\right)R_b H_{Total} \tag{4}$$

$$H_{diff,t} = 0.5H_{diff}(1 + \cos(\beta)) \tag{5}$$

$$H_{ref,t} = 0.5\rho H_{Total}[1 - \cos(\beta)] \tag{6}$$

$$H_{diff} = H_{Total}(0.9345 - 0.8113K_T - 0.2228(n/DL)) \tag{7}$$

$$K_T = H_{Total}/H_{ext} \tag{8}$$

$$DL = 2h/15 \tag{9}$$

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{10}$$

$$\begin{aligned}\cos(\theta) &= \sin(L)\sin(\delta)\cos(\beta) - \cos(L)\sin(\delta)\sin(\beta)\cos(Z)\\ &\quad + \cos(L)\cos(\delta)\cos(h)\cos(\beta) + \sin(L)\cos(\delta)\cos(h)\sin(\beta)\cos(Z)\\ &\quad + \cos(\delta)\sin(h)\sin(\beta)\sin(Z)\end{aligned} \tag{11}$$

$$\delta = 23,45\sin\left[\frac{360}{365}(284 + N)\right] \tag{12}$$

$$\cos(\theta_z) = \sin(L)\sin(\delta) + \cos(L)\cos(\delta)\cos(h) \tag{13}$$

$$Z_s = sign(h)\left|cos^{-1}\left(\frac{cos(\theta_z)\sin(L) - \sin(\delta)}{\cos(L)\sin(\theta_z)}\right)\right| \tag{14}$$

$$R_b = \frac{a}{b} \tag{15}$$

$$\begin{aligned}a &= (\sin(\delta)\sin(L)\cos(\beta) - \sin(\delta)\cos(L)\sin(\beta)\cos(Z))^*\frac{1}{180}(h_2 - h_1)\pi\\ &\quad + (\cos(\delta)\cos(L)\cos(\beta) + \cos(\delta)\sin(L)\sin(\beta)\cos(Z))^*(\sin(h_2)\\ &\quad - \sin(h_1)) - (\cos(\delta)\sin(L)\sin(Z))^*(\cos(h_2) - \cos(h_1))\end{aligned} \tag{16}$$

$$b = \cos\left(L\right)\cos\left(\delta\right)^*(\sin(h_2) - \sin(h_1)) + \sin\left(L\right)\sin\left(\delta\right)^*\frac{1}{180}(h_2 - h_1)\pi \tag{17}$$

Here, Eqs. 3–12 are general equations of solar radiation calculation on an inclined surface. The diffuse radiation is estimated by using clearness index and sunlight duration in Eq. (7). On the other hand, Eqs. 13–17 are used for tracking systems since the position of the sun changes during the day which causes to change of the angle of the solar rays with the panel. In addition, since the R_b value, which shows the ratio of beam radiation on the inclined surface to that of the horizontal, is infinite at midday, Eqs. 15–17 are used and these equations give the R_b between two adjacent hours.

In addition, the angles of incidence of the sun rays used in the analysis of the tracking systems and the angles made with the ground are given in Table 4.

2.4. Estimation of electricity generation

Ambient temperature is an important parameter that directly affects the amount of electricity produced from the PV panel due to its semiconductor structure. There is an inverse relationship between the temperature and the electrical energy produced. There are some test conditions for that, and any value above 25 °C has a negative effect on the electrical energy produced. Eqs. (18) and (19) represent a simple PV electric power generation calculation in which the temperature effect is considered.

$$T_t^c = T_t^{out} + \frac{H_{Total,t}}{H_t^{NOCT}}\left(T^{c,NOCT} - T^{a,NOCT}\right) \tag{18}$$

$$P_t^{PV,prod} = R^{PV}d^{PV}\left(\frac{H_{Total,t}}{H_t^{STC}}\right)\left[1 + \alpha^P\left(T_t^c - T^{c,STC}\right)\right] \tag{19}$$

For the simulations, a 250W PV module was selected and the technical specifications of the module are given in Table 5 and the derating factor (d^{PV}) is taken as 0.8 [52].

2.5. Economic parameters

In the economic analyzes, three different economic parameters which are levelized cost of electricity (LCoE), discounted payback period (DPBP) and internal rate of return (IRR) were used to compare the PV mechanisms. Firstly, LCoE which shows the unit cost of electricity produced and is a widely-used indicator for comparison of systems is examined in Eq. (20). Basically, initial investment cost, annual operation and maintenance (O&M) cost and fuel cost (which is zero for PV applications) are considered during the system life and then it is divided by the total electricity produced during the system life [54].

Table 4
Solar equations for tracker systems [51].

	Incidence angle (θ)	Tilt angle	Surface azimuth angle
DAT	0	θ_z	Z_s
SA-EWT	$\cos^{-1}(\cos(\theta_z)\cos(\beta) + \sin(\theta_z)\sin(\beta))$	β_{opt}	Z_s
SA-SNT	$cos^{-1}\left(\sqrt{1 - \cos^2(\delta)\sin^2(h)}\right)$	$\tan^{-1}(\tan(\theta)\lvert\cos(Z_s)\rvert)$	90° if $Z_s > 0$ −90° if $Z_s \leq 0$

Table 5
Technical specifications of XP-250 PV module [53].

Specs.	Value
Nominal maximum power (P_m)	250 W
Efficiency	15.4%
Temperature power coefficient (α^P)	$-0.42\%/\ ^\circ C$
Nominal operating cell temperature ($T^{c,NOCT}$)	$44.1\ ^\circ C$
Ambient temperature under NOCT ($T^{a,NOCT}$)	$20\ ^\circ C$
Irradiance under STC (H_t^{STC})	1000 W/ m^2

$$LCoE = \frac{\sum_{t=0}^{T} \frac{IC + O\&M_t}{(1+i)^t}}{\sum_{t=0}^{T} \frac{E_t}{(1+i)^t}} \tag{20}$$

where IC is the initial investment cost, $O\&M_t$ is the annual operation and maintenance cost of the system. E_t stands for the total annual electricity produced from the system and i represents the real interest rate. The real interest rate is used to reflect the real cost of savings after removing the effects of inflation. The real interest rate can be calculated as [55];

$$i = \frac{i_n - f}{1 + f} \tag{21}$$

where i_n represents the nominal interest rate and f stands for the inflation rate.

DPBP calculates the time to return the initial investment cost of the system, taking into account the temporal value of money (Eq. (22)). Thus, the sooner the initial investment cost returns, the lower the investment risks [56].

$$\sum_{t=1}^{DPBP} \frac{cash_t}{(1+i)^t} = IC \tag{22}$$

where $cash_t$ represents the cash flow generated by the system in time t (year).

While DPBP informs us about the payback of the system, it does not give information about the profitability or revenue of the system. That is why, the IRR parameter is evaluated. IRR is considered the value that makes NPV which determines the project value taking into account the discounted cash flows zero (Eq. (23)) and IRR values higher than the interest rate show that the project can generate value [57].

$$\sum_{t=1}^{T} \frac{cash_t}{(1+IRR)^t} - IC = 0 \tag{23}$$

All steps taken from technical to economic analysis (Section 2.3-2.5) are summarized in Fig. 4 with related equations. Similar analyzes can be made for different countries by following the same steps. Although the steps are the same, the results will differ according to different solar radiation and economic parameters of countries.

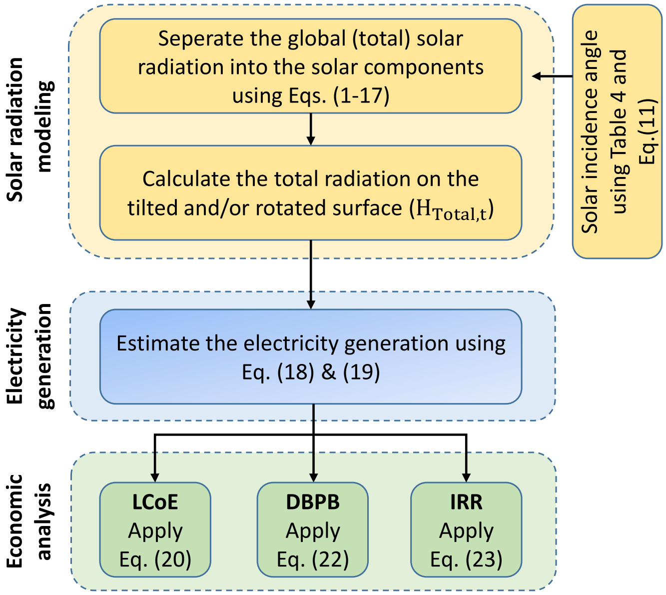

Fig. 4. The flowchart of the steps taken from technical and economic analysis.

3. Simulation results

The simulations are carried out under certain assumptions. It is assumed that the simulated PV system is a small-scale behind-the-meter application. The generated electricity is 100% self-consumed. The investment cost of manual tilt adjustment equipment (such as perforated mounting structures or scissor jacks) is neglected since they are negligibly low compared to the initial investment cost of the PV system. For instance, low-cost simple jacks, which can lift a weight of about 1.5–2 tons, can easily lift 20 or more PV modules of about 20 kg each (for 5 kW and above installations). These equipment costs less than 0.5% of an initial cost of a 5 kW system. In addition, it is assumed that manual tilt adjustment does not impose an additional labor cost on base O&M cost of the PV system since the adjustment can be handled easily and in minutes by a single person [8]. Here, it should be noted that the cost of O&M may increase in utility-scale applications due to the fee to be paid to the personnel responsible for adjustment, yet, utility-scale projects are out of the scope of this study. The manual tilt adjustment period is assumed to be monthly or seasonal (Winter, Spring, Summer, Autumn). The calculations are made assuming the adjustment occurs at equal time intervals and on the first days of January, March, June and September for seasonal adjustment. Here, different and unequal time intervals can be selected for seasonal adjustment to increase the system performance. However, it is assumed that someone who prefers seasonal adjustment will intuitively determine the start date of each season. The person who prefers monthly adjustment, on the other hand, will seek to maximize production.

3.1. Determination of optimal tilt angles

The position of the sun during the day (sunset time or solar incidence angle) changes continuously for a point throughout the year. Accordingly, the amount of solar radiation falling on panel varies due to the angle of incidence. By analyzing this amount, the optimal tilt angle is determined and PV panel is fixed at this angle. If the tilt angle is adjusted periodically (eg. monthly or seasonally) this amount can be further increased in the relevant time interval. To do this, optimal tilt angles for these periods should be determined. Therefore, here, the optimal tilt angles are determined for three provinces with different solar characteristic in Turkey according to monthly and seasonal tilt adjusting scenarios (Table 6). All analyses were conducted with 10-min solar radiation and temperature data provided by the Agricultural Monitoring and Information System (TARBIL).

The optimal tilt angle for Turkey is found to be 30° ranging between 29° (south) and 31° (north). The optimal angle values increase in autumn and winter months and approach the horizontal ground surface in spring and summer months. From June to December, there is a remarkable change in optimal tilt angle above 60°.

3.2. *Electricity production of the PV mechanisms*

Most PV systems in use today are fixed at certain angles. Yet, the amount of energy produced from these systems can be increased further by automatic solar tracking or manual tilt adjusting. Fig. 5 shows the monthly electricity production of these alternatives in three different provinces. It is seen that DAT and SA-EWT systems provide significant increase in each region compared to other alternatives. While the energy production in Istanbul is higher in summer compared to other provinces, it is lower in winter due to the number of cloudy days in this province. On the other hand, there is an increase in manually adjustable scenarios and other tracking system (SA-SNT) compared to the fixed slope system, especially in summer and winter months. The reason why there are no significant increases in other months is that the difference with the annual optimal tilt angle is little.

The results of the change in monthly electricity production compared to the fixed-tilt system are presented in Fig. 6. The monthly increase provided by the DAT system ranges from about 10% to 55%. The production advantage provided by DAT and SA-EWT systems is even higher in the months when the solar radiation is more intense and the cloudy days are less. Significant decreases are experienced especially in January and February. In addition, production increases of 5%–40% are possible for SA-EWT system compared to fixed-tilt system. SA-SNT system cannot provide significant increases. This is because it cannot follow the sun in the east-west direction and it does not take the solar irradiance perpendicular to panel surface. On the other hand, manually adjustable tilt systems have production advantages close to SA-SNT, and in some months, monthly tilt adjustment even contributes more than SA-SNT.

In seasonal tilt adjustment, it is seen that there is lower production in March and September months compared to the fixed-tilt system. This is because the optimal tilt angle for March is 38–39°, whereas the seasonal optimal angle of Spring is 20–22°. Similarly, the optimal tilt angle for September is 32–34°, whereas the seasonal optimal angle of Autumn is 45–46°. The difference is greater than the variation between the annual (29–30°) and monthly optimal tilt angle. In other words, it is further away from the optimal.

Table 6
Optimal tilt angles for fixed, seasonal and monthly scenarios for Turkey.

		Optimal tilt angles (°)		
		Istanbul	Izmir	Antalya
Fixed	31	29		29
Seasonal	Winter	58	57	56
	Spring	22	21	20
	Summer	7	5	4
	Autumn	46	46	45
Monthly	January	60	59	59
	February	52	49	49
	March	39	38	38
	April	22	21	20
	May	10	7	5
	June	0	0	0
	July	3	1	0
	August	18	16	14
	September	34	33	32
	October	49	50	49
	November	59	59	58
	December	62	61	61

The annual electricity production of the systems and the change in production with respect to the fixed-tilt case is given in Table 7. DAT systems have the highest production with annual increase of 30.4–34.6%. This difference is in the range of 22.5–23.9% for SA-EWT systems. Other alternatives (SA-SNT, monthly and seasonal tilt adjustment) contribute between 2.5 and 5.0%. The increase provided by monthly tilt adjustment and SA-SNT are almost the same. This directly shows that SA-SNT systems are not a suitable solution since they require motors for continuous angle adjustment which significantly increases the initial investment and maintenance costs. The obtained results for manually adjustable tilt systems and solar trackers are consistent with other studies at geographically similar or close latitudes (China [19], Saudi Arabia [20], Romania [32], Egypt [38], Kazakhstan [40], Saudi Arabia [41], Japan [42]).

3.3. *Economic analysis*

In calculating the initial investment cost of the systems, the cost of PV panel, inverter, installation equipment and services are taken into account (Table 8). The prices are collected through local market research. It is assumed that the inverter is replaced once in the entire system life (12.5 years on average). Soft costs are set as 15% of the initial investment cost.

For PV systems with solar trackers, there is a wide range of costs for the electro-mechanical mechanism of the systems [9]. In Table 9, the system costs of utility and small-scale system installations are given and were obtained by the authors from the solar system suppliers in Turkey [58,59]. Within the scope of this study, an extra cost of 600 USD/kW for DAT, 350 USD/kW for SA-EWT and 135 USD/kW for SA-SNT is assumed and these costs also comply with the assumptions made in [9]. It is assumed that manually adjustable tilt mechanisms do not have extra costs as the tilt angle can be easily adjusted with simple mechanical equipment.

Another parameter taken into account in the economic analysis is the O&M cost of the system. For fixed and manually adjustable systems, O&M costs are taken as 1%/year of the system cost [60,61]. The O&M costs of tracking systems are higher due to the fact that they are electro-mechanical systems, and it is considered as 5%/year of tracking equipment cost [62,63]. In addition, the real interest rate for the main scenario is determined as 3.88% in the simulation studies by using Eq. (21) [64,65].

The electrical load consumes all of the electricity produced with a self-consumption rate of 100%. The savings from the PV system constitutes the cash inflows. As of the time of the research, residential electricity prices in Turkey are 9.63 cents/kWh for flat-rate tariff [66].

3.3.1. *LCoE*

The results for LCoE are given in Fig. 7 and as can be seen from the figure, there is an increase in LCoE towards northern provinces for all systems. The highest LCoE values for locations with different solar characteristics were obtained with DAT systems. Other tracking systems (SA-EWT and SA-SNT) also have higher LCoE than fixed and manually adjustable systems. Although DAT and SA-EWT systems provide more than 20% production increase compared to fixed systems, the extra energy produced from the tracking systems cannot compansate their additional initial investment costs. On the other hand, due to Antalya's high solar potential, the SA-EWT system in Antalya gives an LCoE value close to the fixed-tilt system in Istanbul. This shows that SA-EWT systems can be an adequate option when it is required to produce energy as much as possible within a limited area for reasons such as high land costs or suitable land unavailability.

On the other hand, since manually adjustable systems do not require an additional investment cost, all the extra electricity production they provide is the factor reducing LCoE and therefore they are the systems with the lowest LCoE. The monthly tilt adjustment scenario is also the

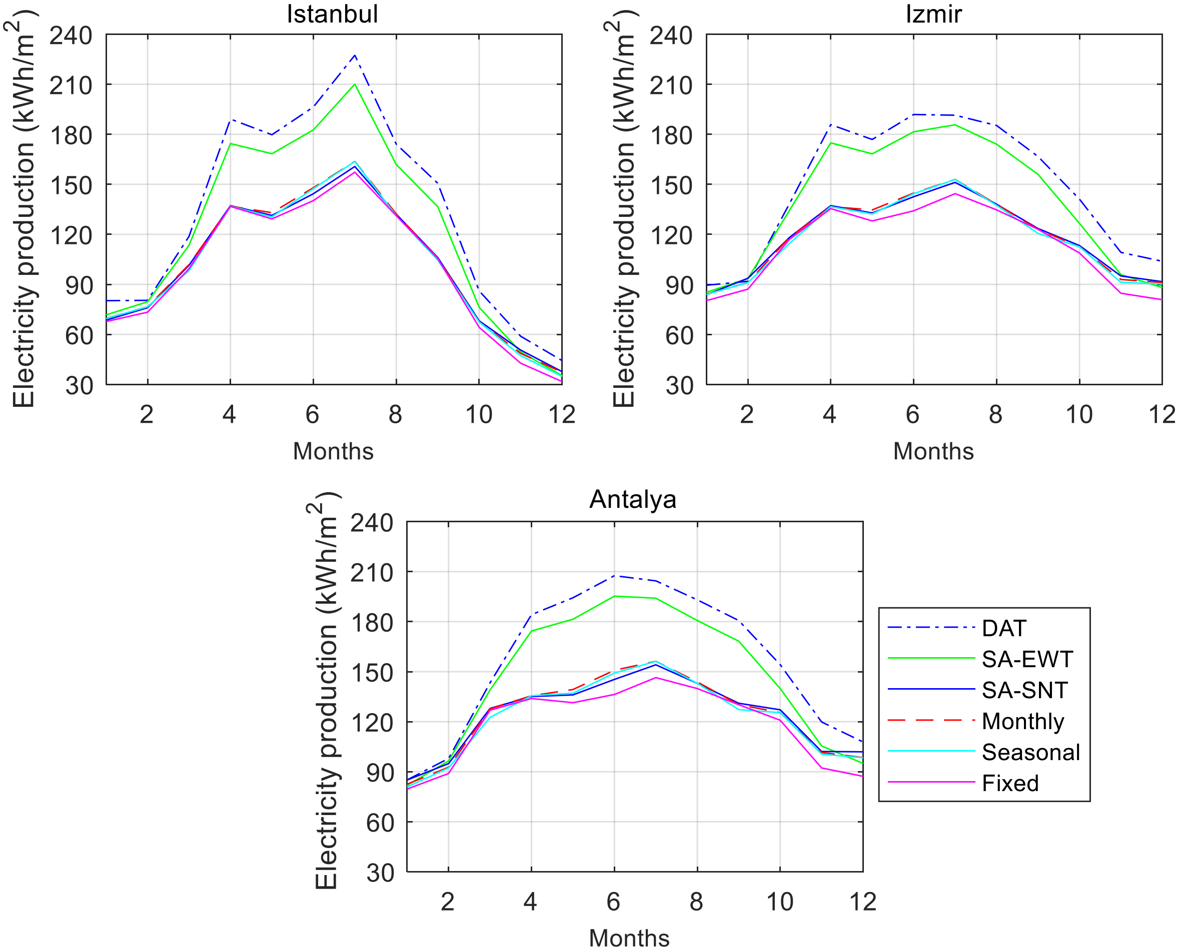

Fig. 5. Monthly electricity production of the systems in the provinces.

most advantageous in terms of LCoE, as it provides more generation than the seasonal tilt adjustment scenario.

3.3.2. *Payback periods*

Another parameter to be considered in the economic evaluation is the payback period. Shorter payback periods are more attractive for investors since the faster an investment pays off, the lower the risk of that investment. The payback periods of solar trackers and manually adjustable systems are given in Fig. 8. It is seen that the payback period of solar tracking systems is quite high. For Istanbul in the north, the approximate payback of DAT systems is 24 years, which is very close to the system lifetime of 25 years. In the south, where the solar radiation is higher, it becomes 16.7 years for Antalya. SA-EWT and SA-SNT systems also have high payback periods, although not as high as those of DAT's. On the other hand, payback periods decrease to 10.3–13.3 years for fixed-tilt and 9.6–12.6 years for monthly adjustable tilt systems. It is likely that these periods will decrease even more in power plant-based projects.

3.3.3. *IRR*

IRR values giving information about the profitability of the projects are shown in Fig. 9. In all three provinces, IRR values of DAT systems indicate that the systems cannot produce value as they are below the interest rate. SA-EWT systems, on the other hand, are at an investment grade and value generating level in Antalya. In addition, all tracker systems for Istanbul are infeasible. Manual adjustable systems, on the other hand, provide an IRR of over 7% for Antalya, 6% for İzmir and 4% for Istanbul, which are all above the interest rate.

3.4. *Sensitivity analysis*

In the sensitivity analysis, the change in the initial investment cost and real interest rate, which directly affect the profitability of the systems, were taken into account. Real interest rates are evaluated with ±2% deviation to represent positive and negative economic indicators. A reduction of 10% and 20% in the initial investment cost is taken into account to consider continuous decrease of PV costs in the market and to consider incentives that can be offered by the government (eg purchase subsidies, value added tax (VAT) exemptions).

Table 10 shows the LCoE values obtained for all scenarios as a heatmap. As it can be understood at first glance, the provinces with red/reddish tones are the values belonging to the tracking systems. Investing in these systems increases the risk considerably or it is not feasible at all. In addition, high real interest rate also seems to reduce the green tones considerably for all scenarios and constitutes a serious obstacle for investment. It is seen that there may be an improvement for investment in low real interest rates for SA-EWT systems. They can be used where land/space constraints exist, as they provide a production increase of over 22%. The monthly and seasonal manual change scenarios also offer considerably lower LCoE values as costs decrease.

The payback periods of the tracking systems decrease significantly with decreased initial investment costs or low real interest rates (Table 11). In such a situation, the most affected provinces are the regions with low solar potential. For example, the payback period of the DAT system in Istanbul, which is 24 years, decreases by 5.8 years in case of low real interest rate, and decreases by 9 years in case of 20% initial investment cost reduction. In similar conditions, the changes in Antalya

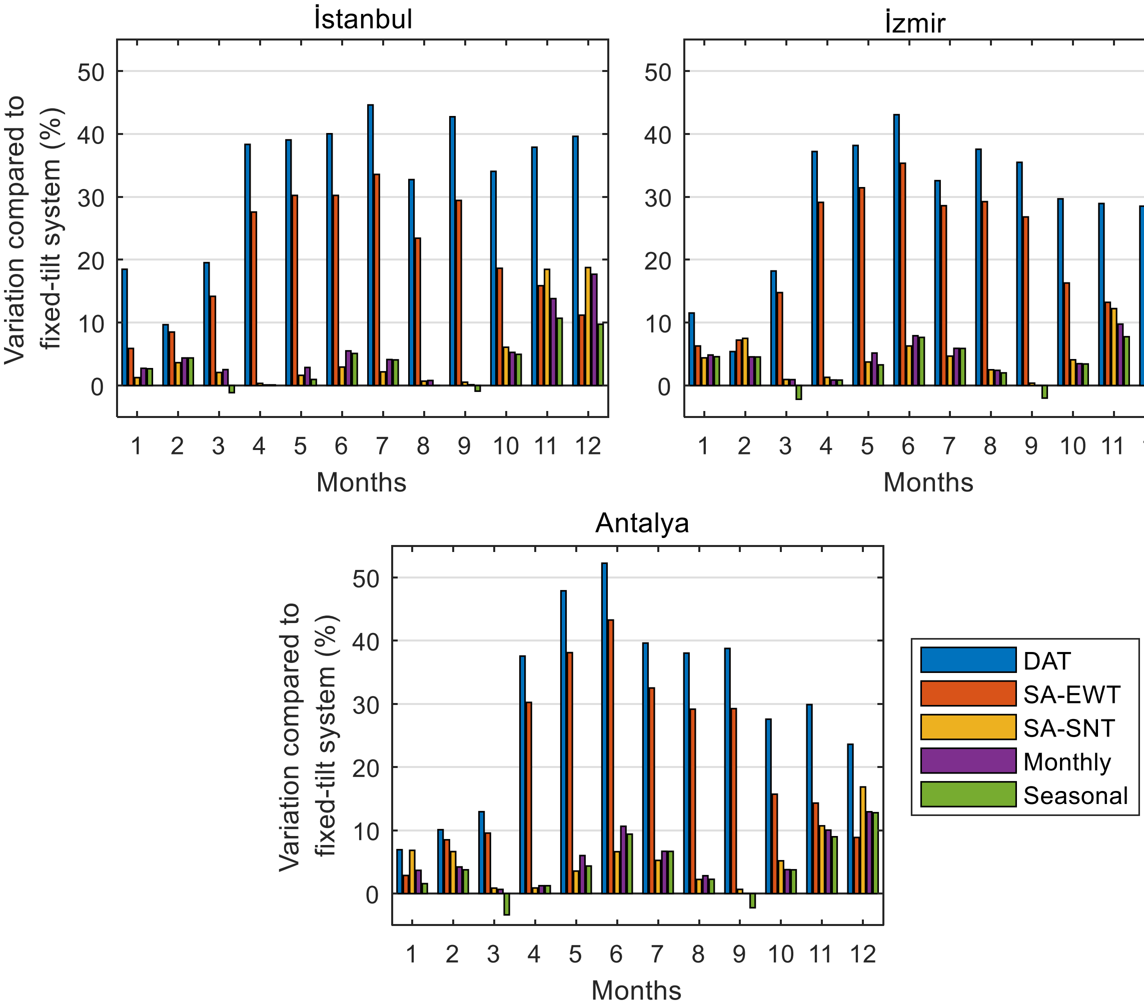

Fig. 6. Change in electricity production compared to fixed-tilt case.

Table 7
Annual electricity production and the change with respect to fixed case.

PV mechanisms	Istanbul		Izmir		Antalya	
	Production (kWh/m^2-year)	Energy gain (%)	Production (kWh/m^2-year)	Energy gain (%)	Production (kWh/m^2-year)	Energy gain (%)
DAT	1586	34.6	1772	30.4	1872	32.4
SA-EWT	1460	23.8	1664	22.5	1752	23.9
SA-SNT	1214	3.0	1421	4.6	1484	4.9
Monthly	1221	3.6	1420	4.5	1484	5.0
Seasonal	1208	2.5	1407	3.6	1468	3.9
Fixed	1179	–	1358	–	1414	–

Table 8
System component price.

System installation equipment	Price (USD/kW)
Photovoltaic panel	410
Inverter	256
PV mounting, cabling, connectors	206
Soft costs	154
Total	1026

Table 9
Prices of fixed-tilt and tracker systems (USD/kW).

	Utility-scale	Small-scale
Fixed-tilt	800–850	1000–1150
SA-EWT[a]	90–160	200–350
DAT	150–250	400–700

[a] Solar suppliers indicate that SA-EWT systems are used instead of SA-SNT in practice.

with high solar potential are 2.9 and 5.3 years, respectively. On the other hand, when the effect of low and high real interest rates is analyzed, it is seen that the range in payback periods is larger for low potential areas in a similar way. For example, while the difference between the payback periods of SA-EWT systems under low and high real interest rates in Istanbul is around 10 years (14.6–24.9 years), it is 4.7 years (11.2–15.9 years) in Antalya.

The change in initial investment cost has a similar effect. The payback period of 18 years in Istanbul (north) with current initial investment costs decreases by 5.8 years to 12.2 years with 20% reduced

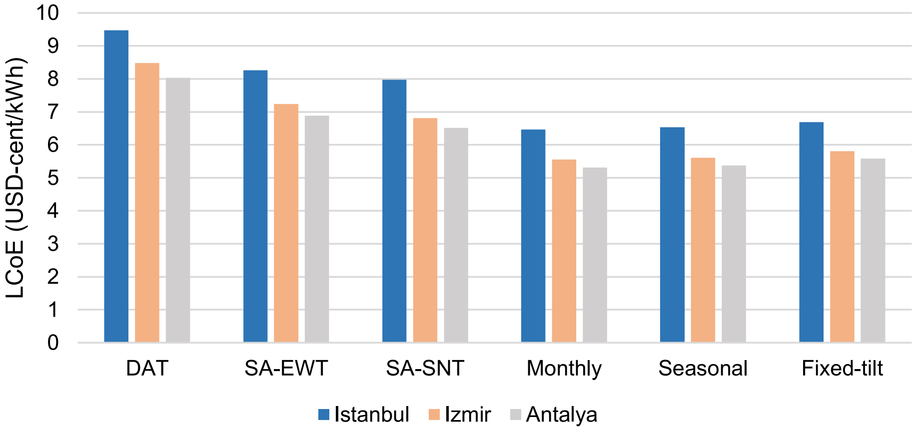

Fig. 7. LCoE of the systems for the provinces.

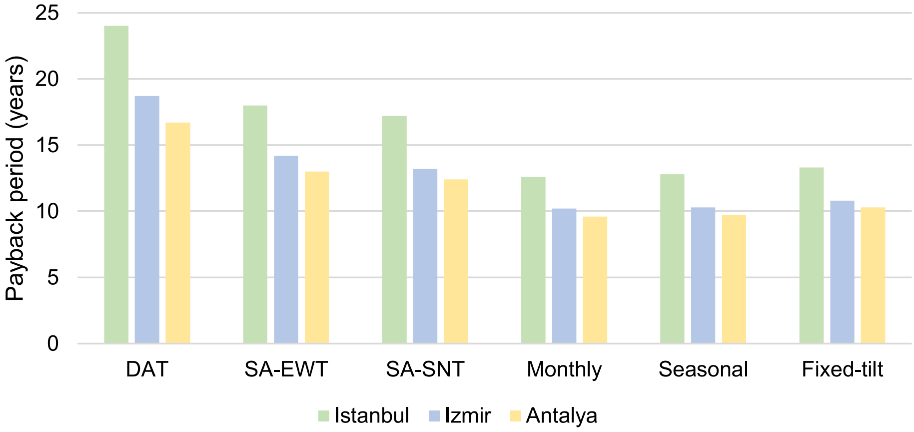

Fig. 8. Payback periods (year) for the PV systems.

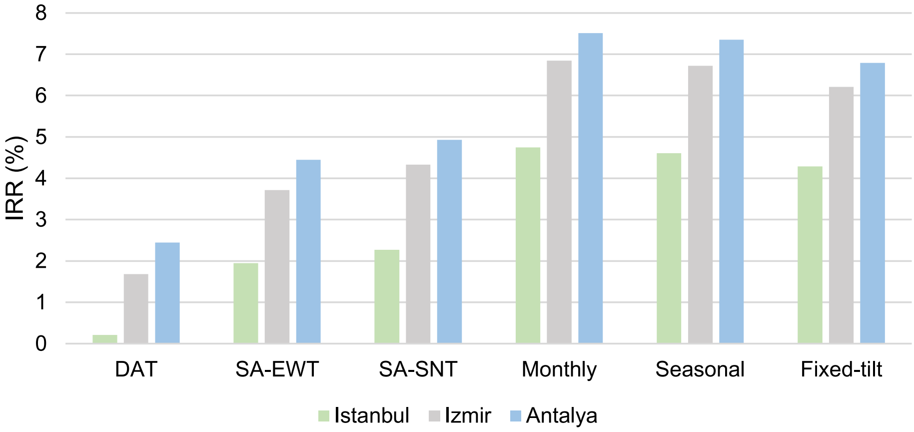

Fig. 9. IRR values of the PV systems.

initial investment cost for SA-EWT systems. Whereas the reduction is lower in Antalya (south) by 3.7 years from 13 to 9.3 years.

IRR analyzes are presented in Fig. 10 and the investments above the related IRR scenario (dashed line) indicate that the system generates a value. High interest rates for all systems hinder the possible investments. Only reductions in initial investment costs make manually adjustable systems and fixed slope systems investable. In addition, the investments of tracker systems in the main scenario are not economically feasible and at high interest rates, the IRR values become negative. However, investments are possible in situations with low interest rates and high solar potential. In the main interest and low interest scenarios, manually adjustable systems and fixed slope systems have high IRR values and are suitable for investment.

4. Discussions

After performing the technical and economical simulations, the following results can be obtained and discussed:

Table 10
Heatmap of LCoE for all scenarios.

		DAT			SA-EWT			SA-SNT			Monthly			Seasonal			Fixed		
		i_{low}	i_{main}	i_{high}	i_{low}	i_{main}	i_{high}	i_{low}	i_{main}	i_{high}	i_{low}	i_{main}	i_{high}	i_{low}	i_{main}	i_{high}	i_{low}	i_{main}	i_{high}
Istanbul	IC_{main}	8.15	9.47	10.9	7.04	8.26	9.61	6.71	7.97	9.36	5.37	6.46	7.67	5.42	6.53	7.76	5.56	6.69	7.95
	$IC_{-10\%}$	7.33	8.53	9.85	6.33	7.43	8.65	6.04	7.17	8.43	4.83	5.82	6.91	4.88	5.88	6.98	5	6.02	7.15
	$IC_{-20\%}$	6.52	7.58	8.76	5.63	6.61	7.69	5.37	6.37	7.49	4.29	5.17	6.14	4.34	5.23	6.21	4.45	5.35	6.36
Izmir	IC_{main}	7.29	8.48	9.8	6.17	7.24	8.43	5.73	6.81	8	4.62	5.56	6.6	4.66	5.61	6.66	4.82	5.81	6.9
	$IC_{-10\%}$	6.56	7.63	8.82	5.55	6.52	7.59	5.16	6.13	7.2	4.15	5	5.94	4.19	5.05	5.99	4.34	5.23	6.21
	$IC_{-20\%}$	5.83	6.79	7.84	4.94	5.8	6.75	4.59	5.45	6.4	3.69	4.45	5.28	3.73	4.48	5.33	3.86	4.65	5.52
Antalya	IC_{main}	6.9	8.03	9.27	5.86	6.88	8.01	5.49	6.52	7.66	4.41	5.31	6.31	4.46	5.37	6.38	4.63	5.58	6.63
	$IC_{-10\%}$	6.21	7.22	8.35	5.27	6.19	7.21	4.94	5.87	6.9	3.97	4.78	5.68	4.02	4.84	5.74	4.17	5.02	5.96
	$IC_{-20\%}$	5.52	6.42	7.42	4.69	5.5	6.41	4.39	5.22	6.13	3.53	4.25	5.05	3.57	4.3	5.11	3.71	4.46	5.3

Table 11
Payback periods of PV system under all scenarios.

		DAT			SA-EWT			SA-SNT			Monthly			Seasonal			Fixed		
		i_{low}	i_{main}	i_{high}	i_{low}	i_{main}	i_{high}	i_{low}	i_{main}	i_{high}	i_{low}	i_{main}	i_{high}	i_{low}	i_{main}	i_{high}	i_{low}	i_{main}	i_{high}
Istanbul	IC_{main}	18.2	24.0	-	14.6	18.0	24.9	14.1	17.2	23.1	10.9	12.6	15.2	11.1	12.8	15.5	11.4	13.3	16.2
	$IC_{-10\%}$	15.2	18.9	-	12.5	14.8	18.8	12.2	14.4	18.0	9.6	10.9	12.7	9.7	11.0	12.9	10.0	11.4	13.5
	$IC_{-20\%}$	12.7	15.0	19.1	10.6	12.2	14.6	10.4	11.9	14.2	8.3	9.3	10.5	8.4	9.4	10.7	8.7	9.7	11.1
Izmir	IC_{main}	15.1	18.7	-	12.1	14.2	17.7	11.4	13.2	16.1	9.1	10.2	11.8	9.2	10.3	11.9	9.6	10.8	12.7
	$IC_{-10\%}$	12.8	15.2	19.5	10.4	12.0	14.2	9.9	11.3	13.2	8.0	8.9	10.0	8.1	9.0	10.1	8.4	9.4	10.7
	$IC_{-20\%}$	10.8	12.4	14.9	8.9	10.0	11.5	8.6	9.5	10.9	7.0	7.6	8.4	7.0	7.7	8.5	7.4	8.1	9.0
Antalya	IC_{main}	13.8	16.7	22.3	11.2	13.0	15.9	10.7	12.4	14.8	8.6	9.6	10.9	8.7	9.7	11.1	9.1	10.3	11.8
	$IC_{-10\%}$	11.8	13.8	17.1	9.7	11.0	12.9	9.4	10.6	12.3	7.6	8.4	9.4	7.7	8.5	9.5	8.1	8.9	10.1
	$IC_{-20\%}$	10.0	11.4	13.3	8.4	9.3	10.6	8.1	9.0	10.1	6.6	7.2	7.9	6.7	7.3	8.0	7.0	7.7	8.5

- DAT systems provide 30–35% higher energy yield than fixed-tilt systems. However, their high initial investment and O&M costs result in high unit electricity cost and long payback period. The LCoE values are determined as 9.47 (Istanbul), 8.48 (Izmir) and 8.03 (Antalya) USD-cents/kWh. The payback periods are 24 years for Istanbul, 18.7 years for Izmir and 16.7 years for Antalya. Given the project lifetime is 25 years, these long periods make investing risky. Similarly, the IRR values are below the real interest rate, indicating that the systems cannot generate value. When the impact of varying real interest rates and initial investment costs are analyzed in the sensitivity analysis, it is seen that even a 10% or 20% reduction in initial investment costs dramatically reduces the payback period. With a 20% initial cost reduction, the payback period decreases from 24 to 15 years in Istanbul, and from 16.7 to 11.4 years in Antalya. Regarding the IRR results, with a 20% reduced initial cost and 2% decreased real interest rate, DAT systems approach to being investable in Antalya in the south, where solar radiation is high. Yet, it is not viable to invest in them in the central and northern parts of Turkey. Here, it can be seen that the biggest obstacle for DAT systems is their high initial investment costs. Still, these systems may gain importance for personal use by providing more electrical energy production per unit area in cases where the investor does not have enough suitable space for installation. In such cases, the advantages and disadvantages should be evaluated in more detail.
- SA-EWT systems have an energy production capacity close to DAT systems. They can provide 22.5–24% more production compared to fixed systems. The fact that they provide movement in a single-axis and accordingly use one motor instead of two makes these systems more advantageous than DAT systems in terms of both O&M and initial investment costs. When SA-EWT is preferred instead of DAT, the payback period decreases from 24 to 18 years in Istanbul and from 16.7 to 13 years in Antalya. This reduction in payback period, together with the fact that there is not much difference in energy yield between DAT and SA-EWT, makes SA-EWT an important alternative. Any reduction in initial investment costs allows these systems to have shorter payback periods. According to the IRR results, if the interest rates remain constant (main scenario) and the initial investment costs decrease (−20%), the systems reach an economically viable level for Antalya and Izmir. If the low real interest rate case is included, the systems generate value in all regions.
- SA-SNT systems offer 3–5% more energy yield compared to fixed systems. Their electricity production capacity is lower than SA-EWT systems but also their initial investment cost. SA-SNT systems have a slightly lower economic feasibility than SA-EWT systems. When they are compared with manually adjustable tilt mechanisms, the electromechanical structure of the former which requires higher O&M costs makes manually adjustable systems a more viable option.

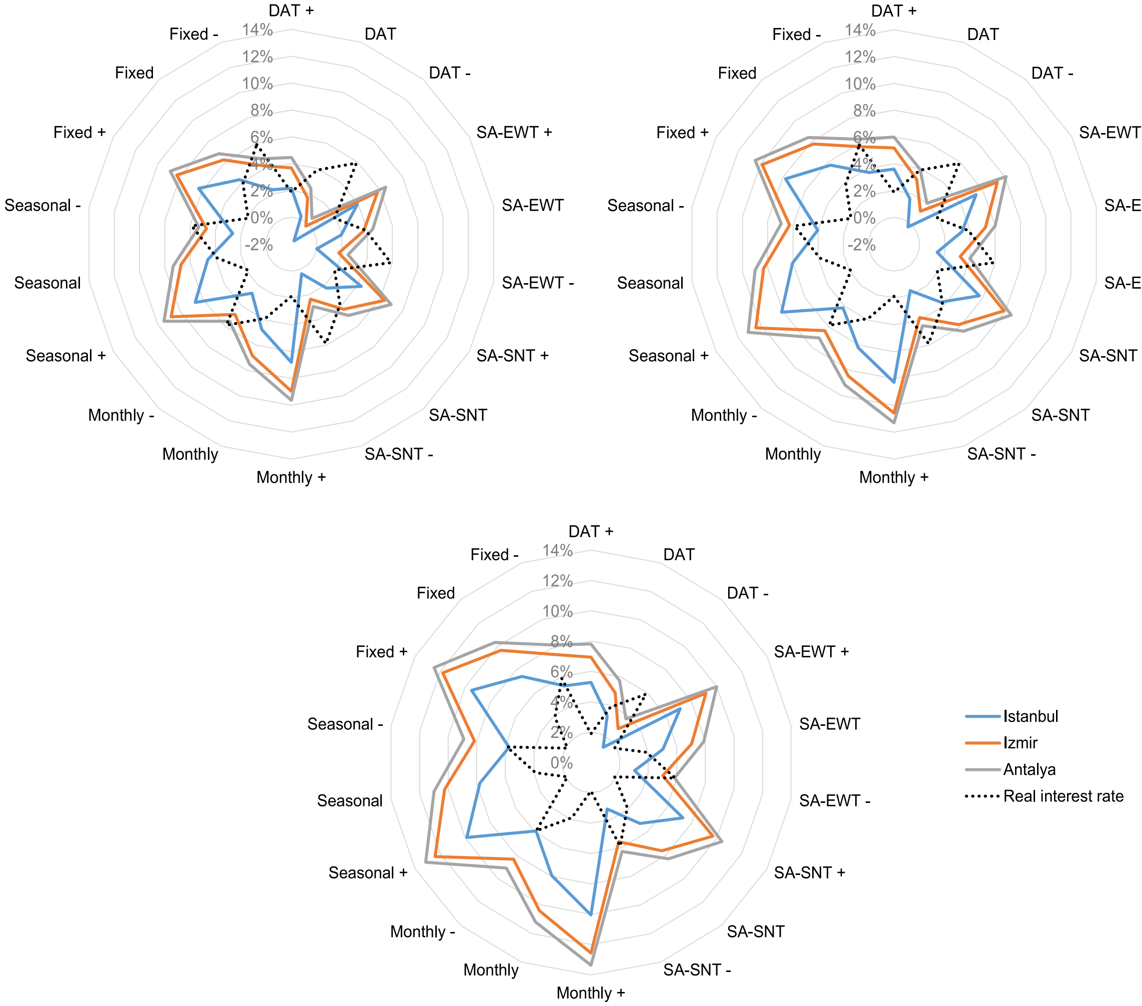

Fig. 10. IRR values under all scenarios; Top-left: Main IC, Top-right: 10% reduction in IC, Bottom: 20% reduction in IC (+ or – signs indicate the high and low interest rates, respectively).

- Manually adjustable tilt mechanisms provide almost the same electricity production as SA-SNT systems. Their main advantage is that they require no additional investment costs or negligibly low ones. In addition, they do not require high O&M costs as electro-mechanical solar trackers do. For these reasons, the payback periods of these systems are shorter than automatic trackers and fixed-tilt systems. It is seen that the minimum achievable payback period of 12–13 years with trackers (SA-EWT) is below 10 years for manually adjustable tilt mechanisms. Therefore, the use of manually adjustable tilt mechanisms is more feasible than solar trackers and fixed-tilt systems which is the main finding of this study. The frequency of adjustment of the tilt angle is a matter that should be evaluated by project owners. However, whether the tilt angle change is adjusted monthly or seasonally, these systems produce up to 10% more than fixed-tilt systems, especially in summer and winter. This is because the difference between the annual optimal tilt angle and monthly optimal angle is higher.
- Fixed-tilt systems are the most used structural installations today. The payback period of fixed-tilt systems is found to be varying between 10.2 and 13.3 years in three different provinces of Turkey. In the cases of decreased initial investment cost or decreased real interest rate, the payback period of the systems can be further reduced. According to the IRR results, fixed-tilt systems offer higher profitability than tracking systems. At low interest rates, IRR values rise above 10%.

It is noteworthy to state that this study was evaluated under the current market conditions in Turkey. The fact that the tracking systems are imported products, their prices constitute a higher portion in the initial investment and the unit electricity prices in Turkey are low (below the average of EU countries and the USA), might change the results for other countries. For example, automatic tracking and manual tilt adjustment may not have much impact in countries where the payback period of PV systems is very low, while it may be more important to consider them in countries where the payback period is high. Or, in countries where electricity prices are high, costly tracking systems may be profitable, as the savings to be provided by PV systems will be high and can meet the investment made. On the other hand, in countries with low electricity prices such as Turkey, low-investment fixed-tilt systems are more profitable, as the savings will be low due to low electricity prices.

5. Conclusions

In this study, a techno-economic comparison of manually adjustable tilt mechanisms and solar tracking systems was made for small-scale behind-the-meter PV systems. DAT systems provided 30–35%, SA-EWT systems 22.5–24%, SA-SNT systems and manually adjustable tilt mechanisms 2.5–5% higher electricity generation compared to fixed-tilt systems. Yet, tracker systems were found to be economically not viable due to their high initial investment and maintenance costs. Among all automatic solar tracking and manual tilt adjustment alternatives, monthly manual tilt adjustment was found to be the most feasible solution with the lowest payback period. The study was carried out in the climatic and economic conditions of Turkey. The research steps followed in this study can be applied for other countries with different solar radiation level, electricity price, initial investment cost, labor cost and real interest rate, and different results can be obtained. In addition, this techno-economic comparison for small-scale PV systems can also be applied to utility-scale plants.

CRediT author statement

Ömer Gönül: Conceptualization, Methodology, Simulation, Visualization, Writing – original draft. **Fatih Yazar:** Conceptualization, Investigation, Methodology, Simulation. **A. Can Duman:** Visualization, Writing – original draft, Writing – review & editing. **Önder Güler:** Conceptualization, Supervision, Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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