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Techno-economic analysis of PV systems with manually adjustable tilt mechanisms

Ömer Gönül [a,b], A. Can Duman [a,b], Burak Barutçu [a,*], Önder Güler [a]

[a] Istanbul Technical University, Energy Institute, Ayazaga Campus, 34469 Maslak, Istanbul, Turkey
[b] Turkish-German University, Department of Energy Science and Technology, 34820 Beykoz, Istanbul, Turkey

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ABSTRACT

Solar radiation falling on photovoltaic (PV) panel surface can be maximized via solar tracking systems, however, in return for infeasible investments. On the other hand, manual and periodic tilt adjustment of PVs can increase energy yield significantly and cost-effectively. Therefore, this study presents a techno-economic analysis of 1 MW PV power plants with manually adjustable tilt mechanisms. Firstly, the optimal tilt angles for fixed and periodically adjusted (monthly, seasonal, and semi-annual) PV systems in locations with different solar characteristics in Turkey are estimated, and then an economic analysis is performed, including a sensitivity analysis. The results show that, manual tilt adjustment provides a remarkable net present value (NPV) increase in Turkey between 12.4 and 14.9% compared to fixed-tilt. The discounted payback period (DPBP) ranges between 9.20 and 12.36 years and can be shortened by 8–10 months. The internal rate of return (IRR) of 5.4–8.6% can be increased by 0.7–0.9%.

1. Introduction

1.1. Motivation and background

Sustainability in the context of energy is a challenge that can be surmounted by the harmonization of social, environmental, technical, economic and political factors [1]. Renewable energy is a key element for a sustainable energy transition. Its adoption highly relies on top-down measures that enables promotion of sector and affordability of the technology via policies and incentives [2] and bottom-up developments focusing on social-acceptance through participative and consensual decision-making [3]. Among renewable technologies, solar photovoltaics (PVs) is in high demand recently, not only due to being environmentally friendly, but also to rapid developments occurred in PV module manufacturing technology which significantly reduced the costs.

PV module prices between 2.2 and 3.1 US $/W in 2010 [4] have dropped to around 0.306 US $/W today [5]. The fall in the module prices led to a rapid increase in global installed PV capacity, which increased from 9.19 GW in 2007 to 480.36 GW in 2018 [6]. In addition to falling prices, ever-evolving engineering solutions increased the efficiency of PV systems. A significant part of these studies focused on increasing the amount of radiation falling on panel surface.

PV systems are optimally oriented and tilted to benefit more from solar radiation. Solar tracker systems, continuously following the sun, can increase energy yield more. Dual-axis tracking systems offer 30–45% more energy yield than fixed-mounted systems, and single-axis tracking systems provide an increase of around 15–25% [7–9]. However, due to their high initial and maintenance costs, tracking systems are not widely preferred [10]. A dual-axis system adds an extra cost of 600–1900 US $/kW to the base cost of a PV installation, and a single axis east–west or north–south system adds an extra 135–700 US $/kW (1–200 kW) [7,11]. These prices take a large share in the initial system cost, and since PV module prices are coming down, using a tracking system only increases the payback period of systems.

A cost-effective alternative to tracking systems are adjustable tilt mechanisms. Their working principle is based on increasing the utilization of solar radiation by periodically changing the angle of inclination, such as monthly, seasonal, or semi-annual, by using simple lifting devices. These systems do not require extra mounting costs or need a relatively low, negligible cost compared to the initial investment cost and more advantageous to use in locations where the angle of inclination varies in a wide range than the fixed-angle system. Moreover, tilt adjustment can easily be handled by power plant staff with a little training.

* Corresponding author.
E-mail address: barutcub@itu.edu.tr (B. Barutçu).

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Nomenclature

List of symbols

$C_{t,0}$	The initial investment cost
C_t	The net cash flow in time t
H_0	Extraterrestrial solar radiation (W/m^2)
$H_{B,t}$	Beam radiation on a tilted surface
H_B	Beam radiation on a horizontal surface
$H_{D,t}$	Diffuse radiation on a tilted surface
H_D	Diffuse radiation on a horizontal surface
$H_{R,t}$	Reflected radiation on a tilted surface
H_R	Reflected radiation on a horizontal surface
H_{STC}	Solar radiation under standard test conditions
$H_{T,t}$	The global solar radiation on a tilted surface
H_T	The global solar radiation on a horizontal surface
I_{sc}	Solar constant (W/m^2)
K_T	Clearness index
$P_{PV,out}$	The power output of a PV panel
P_{STC}	The rated capacity of the PV system
R_b	The ratio of beam radiation on the tilted surface to that a horizontal plane
T	System lifetime
$T_{a,NOCT}$	Ambient temperature under NOCT
T_a	Ambient temperature
$T_{c,NOCT}$	Cell temperature under NOCT
$T_{c,STC}$	Cell temperature under STC
T_c	Cell temperature
a_p	Temperature coefficient of power
i'	The nominal discount rate
$\eta_{m,STC}$	The maximum power point efficiency
ω_s	Sunset hour angle (°)
ω_s'	Solar hour angle for an inclined plane
N	Maximum day length
d^{PV}	Derating factor of the panel
f	Inflation rate
i	Real interest rate
n	The day of a year from the first of January
α	Solar absorbance
β	The tilt angle of a panel with a horizontal plane
δ	Solar declination (°)
ρ	The ground reflectance – Albedo constant
τ	Solar transmittance
φ	The latitude of the location

List of abbreviations

DPBP	Discounted payback period
EIE	Electricity Affairs Survey Administration
GEPA	The solar energy potential atlas of Turkey
IRR	Internal rate of return
NOCT	Nominal operating cell temperature
NPV	Net present value
S1	Scenario for fixed-tilt system
S2	Scenario for semi-annual tilt adjustment
S3	Scenario for seasonal tilt adjustment
S4	Scenario for monthly tilt adjustment

1.2. Literature review

There are various studies in the literature dealing with the estimation of the optimal tilt angle of a location. Some of these concentrate on establishing a relationship between the latitude of a region and the PV tilt angle. Benghanem [12] determined that the latitude is almost equal to the optimal tilt angle of Medina, Saudi Arabia. The monthly tilt adjustment provided 8% more solar radiation than fixed-tilt systems in Medina. Kaldellis and Zafirakis [13] investigated the performance of different tilt angles during the summer period in Athens, Greece and the angle of 15 ± 2.5° was found to be optimum according to the experimental results. Elminir et al. [14], determined the optimal tilt angle for a south-facing collector in Helwan, Egypt as 43.33° during the winter period, and as nearly horizontal during the summer period. The authors concluded on that, a general rule of yearly optimal tilt of $\varphi \pm 15°$, (where φ is the latitude of the location, and plus and minus indicate winter and summer) is accurate for this region. The rule of $\varphi \pm 15°$ were expressed by earlier studies by Duffie and Beckman [15], Garg [16] and Lunde [17].

Several studies concentrated on the determination of optimal tilt angles at single or several locations in a country. Bakirci [18] developed regression models to estimate the optimal tilt angle based on the day of a year using data of eight cities for Turkey. Garni et al. [19] studied optimal tilt angles in 18 locations in Saudi Arabia. The authors recommended on sites to invest in large-scale PV systems using a multi criteria suitability analysis. Le Roux [20] used data from nine measuring stations and considered the effect of weather conditions and soiling on the determination of optimal tilt angles for South Africa. Raptis et al. [21] investigated the solar irradiance at the inclined surface on real atmospheric conditions considering the cloud effect to maximize the energy capture with four different pyranometer in Athens, Greece. According to model calculations, the optimum tilt angle was found around 30°. Babatunde et al. [22] investigated the effects of dust, tilt, and orientation angles on the performance of PV plants located on a university campus in Cyprus. Khorasanizadeh et al. [23] developed diffuse solar radiation models for the city of Tabass in Iran, analyzed them using statistical methods, and determined the optimum tilt angles for certain time intervals. Jacobson and Jadhav [24] chose pilot locations from various countries and estimated optimal tilt angles for the entire world using PVWatts software.

Various studies are concentrated on periodic tilt adjustment. Ullah et al. [25] performed optimal tilt angle optimization for Lahore, Pakistan, and obtained 6.6% increase in the annual energy production with four adjustments in a year. Kaddoura et al. [26] investigated the optimal tilt angle variations in Saudi Arabia and indicated that changing the PV tilt angle six times in a year collects 99.5% of the solar radiation that could be gathered with daily adjustment. Jafarkazemi and Saadabadi [27], estimated optimal tilt angles for Abu Dhabi, UAE. Bi-annually, seasonally and monthly tilt adjustment brought, 10.5%, 10.7%, and 11.7% increased annual radiation respectively. Despotovic and Nedic [28] determined and compared optimum PV tilt angles at annual, seasonal, and monthly levels for Belgrade, Serbia. The tilt adjustment by using the three methods increased the energy gain by 5.98%, 13.55%, and 15.42%, respectively. Herrera-Romero et al. [29] estimated optimal tilt angles for Veracruz, Mexico. Apart from the other studies, annual cash flows that can be earned by tilt adjustment were calculated. Although all of these studies have provided valuable contributions to the literature, none of them addressed a detailed life cycle cost analysis of manually adjustable tilt mechanisms.

Some of the studies concentrated on the performance comparison of isotropic or nonisotropic solar radiation models. Danandeh and Mousavi [30] made a general review of the beam and diffuse solar radiation models and applied them to determine the optimal tilt angles for different cities of Iran. David et al. [31] performed a similar study for Reunion Island and Perez model performed better than Hay, Gueymart, and Skartveit & Olseth, whereas the difference was not significant. Bahrami et al. [7] implemented the Perez and Koronakis solar radiation models with different tilt angles to evaluate the solar resource potential in some provinces of Nigeria and the results are verified with the outputs of the System Advisor Model (SAM) software. Li et al. [32] compared isotropic Liu & Jordan and anisotropic Hay, Reindl, Klucher, and Perez models to real measurement data, and Liu & Jordan was reported to be the most accurate for the conditions of Wuhan, China. These sky radiation models were also compared in review studies in detail in [33] and [34].

Solar trackers are in high interest for their higher energy capture. However, the feasibility of tracker systems are reported to be low due to their high installation cost. Hammad et al. [35] made an economic comparison of fixed and double-axis tracking PV systems in Jordan. The annual PV production of the tracking system is found to be 31.29% higher than of the fixed system, however, with a higher payback period. Eke and Senturk [36] compared the performance of fixed and double-axis tracking systems based on measurements in Mugla, Turkey. The double-axis tracking system increased the energy gain by 30.79%. Garni et al. [37], studied economic analysis of a fixed system with no tracking, vertical-axis with continuous adjustment, the horizontal axis with continuous, daily, weekly and monthly adjustment, and two-axis systems. Only the vertical-axis with a continuous adjustment system showed close feasibility to the fixed-tilt system.

There are many commercially available softwares dedicated to the design and simulation of PV systems such as, TRNSYS, PVSyst, PVSOL, PVGIS, HOMER, PVWatts, and RETScreen. They are all reportedly to be accurate tools depending on the solar data availability [38–42]. Although all of them can optimize tilt angle for fixed-tilt systems, they may not provide the optimal angles at monthly, seasonal, or semi-annual levels.

1.3. Content and contributions

The papers reviewed above with many others not referred here have provided valuable contributions to the literature. However, although there exist numerous studies regarding the feasibility of PVs with fixed-tilt or automatic tracking systems [7,35,43–47], no study addresses the feasibility of PVs with manually adjustable tilt mechanisms. Therefore, as its main contribution, this study evaluates the economic benefit brought by manual tilt adjustment. To this end, a techno-economic feasibility analysis of 1 MW PV power plants is conducted to investigate the impact of the tilt adjustment on net present value (NPV), internal rate of return (IRR), and discounted payback period (DPBP) of the systems. In addition, a sensitivity analysis is performed to determine the impact of changing real interest rate and initial investment cost values on the results. The framework of the study is presented in Fig. 1.

The minor contributions of the study are twofold: (1) Generally, tilt adjustment-oriented studies are carried out for a single location [26,27,36]. However, this study is conducted for six provinces from three solar parts of Turkey, both for a countrywide analysis and to examine the impact of solar radiation differences on the performance of tilt adjustment mechanisms. (2) In 2019, Turkey amended its feed-in tariff scheme which was in force since 2010. Until now, no study in the literature has examined the impact of the new prices on the feasibility of PV projects. Therefore, the study is a first in this regard.

1.4. Organization of the paper

This paper is organized as follows; in Section 2 the status of solar energy in Turkey and the selected provinces used in the analysis are presented. In Section 3, manually adjustable tilt mechanisms are presented. In Section 4, the methodology part that consists of solar radiation modeling, electricity production estimation, and economic determinants is presented. In Section 5, the results of the optimal tilt angle variations under different cases, the estimated electricity production of a sample 1 MW PV system and its detailed economic analysis are discussed. Lastly, the conclusion is given in Section 6.

2. Solar energy in Turkey and the selected provinces

The total solar potential in Turkey is assumed to be approximately 1000 TWh and 10% of this potential is thought to be suitable for electricity production concerning annual solar radiation of 1527 kWh/m^2-year and sunshine duration of 2741 h [48]. According to the solar energy potential atlas of Turkey (GEPA) created by the Electricity Affairs Survey Administration (EIE) in 2010, the amount of solar radiation decreases from the south (1800–2000 kWh/m^2-year) to north (1400–1450 kWh/m^2-year) [49]. The majority of the solar PV system installations are located in the southern part of the country. The number of solar PV installations in Turkey has increased dramatically in recent years (Fig. 2) and by the end of 2019, the total installed capacity of PV systems reached 5995.2 MW [50,51]. In 2014, the total installed PV capacity was only 40.2 MW and an approximately 150-fold growth was achieved between 2014 and 2019.

In the selection of the sites, the GEPA is separated into three solar parts, namely, southern, central, and northern. From each solar part, two representative provinces are selected to cover the status of the whole country and to see the differences between the solar parts. The selected provinces are introduced in Table 1. Their monthly average solar radiation and average sunshine durations are shown in Fig. 3. The identified solar parts and the selected sites are demonstrated in Fig. 4.

3. Manually adjustable tilt mechanisms

Manually adjustable tilt mechanisms allow PV power plant staff to adjust the tilt angle of PV arrays by hand to certain degrees easily and within minutes to increase the amount of solar radiation falling on array surface. Unlike solar trackers, manually adjustable tilt mechanisms do not require large investments as they do not contain any electromechanical components. The mechanisms work with integration of simple mechanical lifting devices like scissor jacks or perforated mounting brackets to PV mounting structures. Considering a car weighing more than one ton can be lifted easily with a jack, the angle of inclination of the PV arrays with an average weight of 20–25 kg/module can also be changed with jack-like systems. With a short training, present power plant staff can handle the tilt adjustment. The design of the mechanisms is demonstrated in Fig. 5.

4. Methodology and simulation parameters

4.1. Solar radiation modeling on an inclined plane

Solar radiation experiences some changes due to the atmospheric effects before it reaches the solar energy system [54]. Eq. (1) represents the extraterrestrial radiation that reaches the outside of the earth atmosphere coming from the Sun [55].

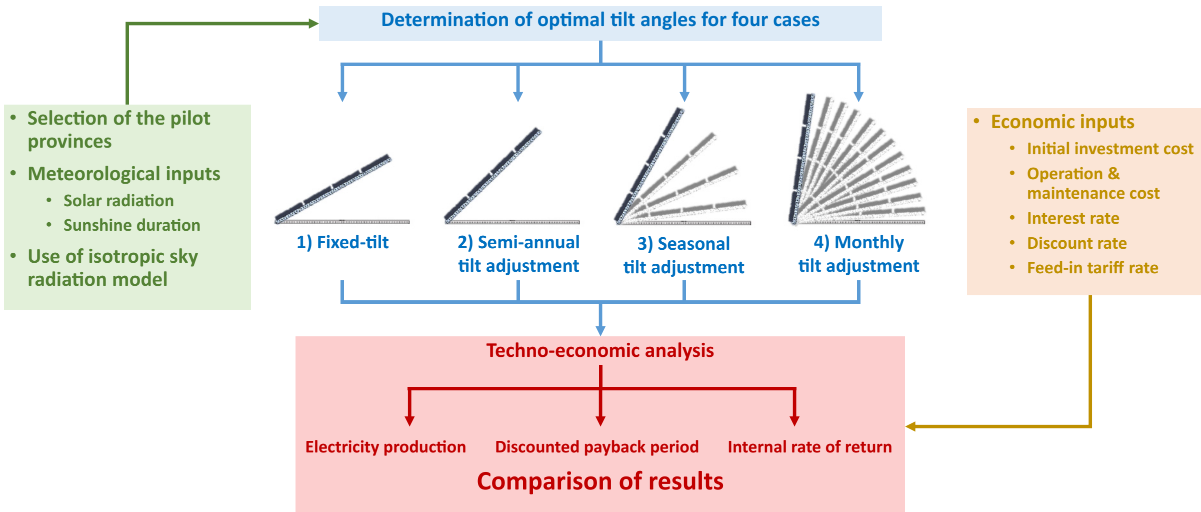

Fig. 1. Framework of the study.

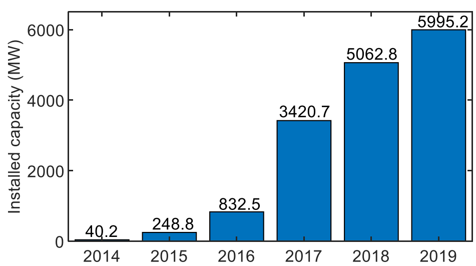

Fig. 2. The cumulative installed capacity of solar PV systems in Turkey.

$$H_0 = I_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right)(\cos\varphi\cos\delta\sin\omega_s + \sin\varphi\sin\delta) \quad (1)$$

where I_{sc} is the solar constant (1367 W/m^2), n is the day of a year from the first of January, φ is the latitude of the location, δ is the solar declination, and ω_s is the sunset hour angle for the horizontal plane [56]. Solar declination and sunset hour angle are calculated as follows:

$$\delta = 23.45\sin\left(\frac{360(n+284)}{365}\right) \quad (2)$$

$$\omega_s = \arccos[-\tan(\delta)\tan(\varphi)] \quad (3)$$

Part of the solar radiation is absorbed, reflected, or scattered after passing through the atmosphere. These differences are caused by factors such as clouds in the atmosphere, air particles, water vapor, dust, and pollutants. The part of the solar radiation passing through the atmosphere that reaches the ground directly without any scattering or reflection is called beam (direct) radiation [25], and the part that is distributed in all directions due to atmospheric effects is called diffuse radiation [57]. Reflected radiation represents the amount of radiation reflected outside of atmospheric effects. All of these three types of radiation constitute the total (global) solar radiation which can be defined as;

$$H_T = H_B + H_D + H_R \quad (4)$$

where H_T represents the total (global) solar radiation and H_B, H_D and H_R symbolize the beam, diffuse, and reflected radiations, respectively.

Global solar radiation is not always at the maximum level on the horizontal plane, and the amount of solar radiation falling on the surface varies with the tilt angle. The tilt angle also varies depending on the geographical location and local climate conditions, that is, it is specific to the location [18]. For solar system applications, the solar radiation data of the location are evaluated and analyzes are made. However, solar radiation data is mostly measured in horizontal planes, and for the analysis of solar radiation data on inclined planes, either a special measurement mechanism should be established or the data should be examined using mathematical models. The use of mathematical models is quite common due to the costs of measuring devices. Therefore, Liu and Jordan model [58], which is widely used in the literature, is implemented to evaluate the solar radiation on inclined planes in this study.

The total radiation on a tilted surface ($H_{T,t}$) which is constituted from beam ($H_{B,t}$), diffuse ($H_{D,t}$) and reflected ($H_{R,t}$) radiation can be defined as in Eqs. (5) to (8).

$$H_{T,t} = H_{B,t} + H_{D,t} + H_{R,t} \quad (5)$$

$$H_{B,t} = (1 - H_{D,t}/H_T)R_b H_T \quad (6)$$

$$H_{D,t} = 0.5H_D(1 + \cos(\beta)) \quad (7)$$

Table 1
Coordinates and annual solar radiation of the selected provinces.

Solar part	Location	Latitude (°)	Longitude (°)	Solar radiation (kWh/m^2-year)
Northern	Tekirdag	40.98	27.52	1340
	Artvin	41.18	41.82	1412
Central	Izmir	38.42	27.13	1501
	Kirsehir	39.14	34.17	1513
Southern	Antalya	36.88	30.71	1650
	Sanliurfa	37.16	38.80	1590

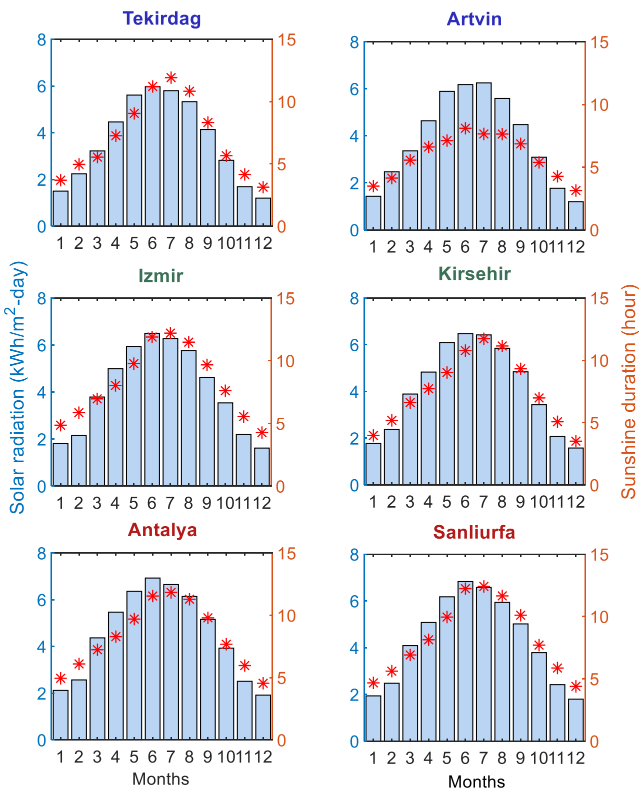

Fig. 3. Monthly average daily solar radiation and sunshine duration of the selected sites.

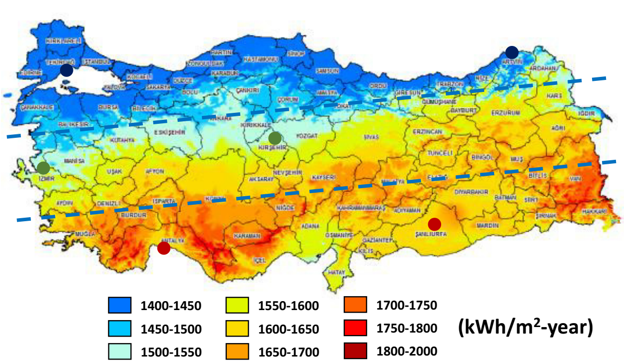

Fig. 4. Solar potential map of Turkey, formed solar parts and the pilot provinces [52].

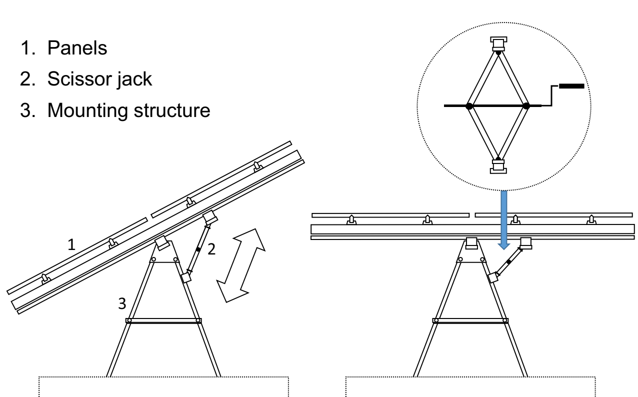

Fig. 5. The design of a manually adjustable tilt mechanism (adopted from [53]).

$$H_{R,t} = 0.5\rho H_T[1 - \cos(\beta)] \tag{8}$$

$$H_D = H_T(0.9345 - 0.8113K_T - 0.2228(n/N)) \tag{9}$$

where β is the tilt angle of the panel with a horizontal plane and ρ is the ground reflectance (taken as 0.2 for this study). The diffuse radiation on the tilted surface is derived by the clearness index, sunshine duration, or maximum day length using the data of clearness index and sunshine duration of all 81 cities in Turkey [49] and the correlations are proposed in the literature for certain locations [60]. The K_T and N in Eq. (9) refer to clearness index and maximum day length, respectively and defined in Eqs. (10) and (11) [61].

$$K_T = H_T/H_0 \tag{10}$$

$$N = 2\omega_s/15 \tag{11}$$

In Eq. (6), R_b represents the ratio of beam radiation on the tilted surface to that on a horizontal plane [62] and it is expressed as follows:

$$R_b = \frac{\cos(\varphi-\beta)\cos(\delta)\sin(\omega_s') + \omega_s'(\pi/180)\sin(\varphi-\beta)\sin(\delta)}{\cos(\varphi)\cos(\delta)\sin(\omega_s) + \omega_s(\pi/180)\sin(\varphi)\sin(\delta)} \tag{12}$$

where ω_s' stands for the solar hour angle for an inclined plane, described as follows:

$$\omega_s' = min\{\omega_s, \arccos[-\tan(\delta)\tan(\varphi-\beta)]\} \tag{13}$$

4.2. Estimation of electricity generation from PV module

The power output a PV panel is primarily dependent on solar radiation and PV module cell temperature and it can be calculated as follows [63]:

$$P_{PV,out} = P_{STC} d^{PV}\left(\frac{H_T}{H_{STC}}\right)[1 + a_p(T_c - T_{c,STC})] \tag{14}$$

where P_{STC} is the rated capacity of the system under standard test conditions (STC). d^{PV} is the derating factor that accounts for wiring losses, shading, soiling, and aging effects. H_T is the solar radiation on the PV system and H_{STC} is the radiation at STC which is 1 kW/m^2. a_p stands for the temperature coefficient of power, and T_c and $T_{c,STC}$ are the cell temperature under the current conditions and under STC, respectively.

The PV cell temperature represents the temperature of the surface of the PV panel. Under environmental conditions, the cell temperature also changes. When the cell temperature exceeds the $T_{c,STC}$, the efficiency of the PV panel reduces. Therefore, the cell temperature T_c should be estimated properly to calculate the PV output. T_c is expressed as follows, which is derived from the balance of absorbed energy by the PV panel, and electrical output and the heat transfer to the environment [64]:

$$T_c = \frac{T_a + (T_{c,NOCT} - T_{a,NOCT})\left(\frac{H_T}{H_{STC}}\right)\left[1 - \frac{\eta_{m,STC}(1-a_pT_{c,STC})}{\tau\alpha}\right]}{1 + (T_{c,NOCT} - T_{a,NOCT})\left(\frac{H_T}{H_{STC}}\right)\left(\frac{a_p\eta_{m,STC}}{\tau\alpha}\right)} \tag{15}$$

where T_a is the ambient temperature, and $T_{c,NOCT}$ and $T_{a,NOCT}$ are the cell and ambient temperature under nominal operating cell temperature, respectively. $\eta_{m,STC}$ is the maximum power point efficiency under STC, τ and α are the solar transmittance and absorbance of the PV panel respectively and $\tau\alpha$ is assumed as 0.9 [64].

There are various PV modules in the solar market with different power, efficiency, current–voltage, or semiconductor technology. The analyzes are performed based on the Canadian Solar CS6P-250 PV module of which technical specifications are given in

Table 2
CS6P-250 PV module specifications used in the analysis [65].

Specification	Value
Nominal maximum power (P_m)	250 W
Module efficiency ($\eta_{m,STC}$)	15.54 %
Temperature coefficient of power (a_p)	−0.43 %/°C
Nominal operating cell temperature ($T_{c,NOCT}$)	45 °C
Ambient temperature under NOCT ($T_{a,NOCT}$)	20 °C
Irradiance under standard test conditions (H_{STC})	1000 W/m^2

Table 2 [65]. The derating factor of the system is taken as 0.80 [66,67].

4.3. Economic determinants

According to the International Renewable Energy Agency (IRENA), PV module prices reached 0.306 US $/W by the end of 2018 [68]. The additional costs of PV systems, including inverters (assuming two times replacement in power plant lifetime [69,70]), transformers, distribution center, AC-DC cables, protection and security equipments, construction, transportation, mounting, excavation, official institution expenses, financing cost, SCADA and other unexpected expenses are investigated in [71] and found as 386,000 US $/MW for Turkey. Thus, in this study, the initial investment of a 1 MW solar PV plant is estimated as 692,000 US $ without value-added tax (VAT) of 18%, and the total cost of the plant including VAT is taken as 816,560 US $. It is assumed that these costs do not distinguish between different provinces in Turkey.

Tilt angle can be adjusted manually by using perforated mounting brackets or simple scissor lift jacks [53]. Assuming there are 15–20 panels (20–25 kg each) in a typical PV array, it can be lifted easily with three scissor jacks (one at each of two ends and one in the middle). In a 1 MW power plant, there exist 200–250 series like this, which roughly makes 600–750 scissor jacks. Since the marginal cost of these equipment is less than 1% of the initial investment cost, the construction cost of the tilt adjustment mechanism is neglected. Also, as noted in [71] unexpected and extra expenses are already accounted in a project as approximately 2% of the system's initial investment cost, creating an extra margin. Additional labor cost for the manual adjustment is neglected as well since with a short training, the present power plant staff can handle the tilt adjustment easily. The tilt angle of the arrays can be adjusted less than a minute (around 30 s) and the whole process can be completed within a day. Therefore, the annual O&M cost of the power plant is considered the same for the fixed and periodically adjusted cases (2% of the total investment) [72,73]. Another motivating reason for neglecting the labor cost is that the adjustment can be handled during the dust removal process, especially in regions close to the desert or in areas exposed to dust, and this prevents an extra cost. Moreover, tilt adjustment mechanism has additional monetary benefits due to snow sliding. Tilt adjustment is already an applied method for snow removal which justifies the neglected costs [74].

Cash flows of PV systems are dependent on feed-in tariff rates. The previous feed-in tariff scheme for renewable production in Turkey, which was valid between 2011 and 2020, was 0.133 US $/kWh for solar PV [75]. The law has been amended by the new Regulation of Unlicensed Electricity Production in Electricity Market and the Presidential Decree No. 1044, dated 10 May 2019 [76], and the new amount is determined as the retail energy price (without distribution fee, and VAT) which is 0.481 TL/kWh on average and corresponds to 0.081 US $/kWh, depending on the currency rate. This rate applies to unlicensed renewable plants with installed capacity up to 5 MW.

In the study, 1 MW PV systems with manually adjustable tilt mechanisms are evaluated through three economic determinants, namely NPV, IRR and DPBP, due to their different advantages and disadvantages.

NPV determines the end-of-life value of a project considering discounted cash flows. It is a useful determinant when comparing projects with similar lifetime and initial investment cost [77]. Positive NPV indicates that a project generates value. Yet, NPV does not give an idea about the profitability of a project. Also, NPV can fail in comparing projects with different sizes. NPV is suitable for use in this study since equal systems are compared [52]. NPV is calculated as follows [78]:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+i)^t} - C_{t,0} \tag{16}$$

where C_t is the net cash flow in time t, i is the real interest rate and $C_{t,0}$ is the initial investment cost of the PV project. The real interest rate is calculated as follows [79]:

$$i = \frac{i' - f}{1 + f} \tag{17}$$

where i' is the nominal discount rate and f is the expected inflation rate. The real interest rate of Turkey is calculated as 3% based on the average values of the past 10 years. The real interest rate of 3% is used in the base case scenario for economic calculations.

DPBP is a practical and an easy to understand economic determinant. DPBP indicates how many years it takes for a system to return the initial investment cost considering the time value of money within the project lifetime (25 years). The lower the DPBP, the lower the risk of a project [80]. Yet, DPBP does not cover future cash flows beyond the cut-off date and does not give an idea about the total revenue. DPBP is found as follows [81,82]:

$$DPBP \rightarrow \sum_{t=1}^{DPBP} \frac{C_t}{(1+i)^t} \equiv C_{t,0} \tag{18}$$

IRR is the discount rate that makes the NPV zero. Unlike NPV, IRR does not give information about total revenue, but gives an idea about the profitability by giving the rate of return earned by a project [52,83]. An IRR greater than the interest rate means that a project generates value. IRR is suitable for comparing projects with the same project lifetime (which complies with the current study), but can fail when the lifetime is different [84]. The projects with higher IRR have higher profitability and therefore are more attractive. IRR is calculated as follows [85,86]:

$$\sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_{t,0} = 0 \tag{19}$$

5. Results and discussions

5.1. Optimal tilt angles

To determine the optimal tilt angles under different tilt adjustment scenarios, fixed, semi-annual, seasonal, and monthly tilted south-facing (solar azimuth angle = 0°) PV systems are analyzed for the cities which are located in different solar potential parts of Turkey, based on the Liu-Jordan solar model given in Section 4. The optimal values are presented in Table 3.

According to the obtained results, the optimal tilt angles in different parts of Turkey are in the range of 28 – 29° for the fixed-tilt case (S1) and these results are coherent with the results obtained from other studies conducted in Turkey. For instance, in [87] the optimal tilt angle for the province of Izmir is found as 30°, and in

Table 3
Optimal tilt angles (°) of the selected provinces under fixed (annual), semi-annual, seasonal, and monthly tilt adjustment scenarios.

		Northern		Central		Southern	
Scenario		Tekirdag	Artvin	Izmir	Kirsehir	Antalya	Sanliurfa
S1	Fixed	29	29	29	29	29	28
S2	W-A	50	50	50	50	49	49
	S-S	14	14	12	13	12	11
S3	Win	57	57	57	57	56	56
	Spr	21	22	21	21	20	20
	Sum	7	7	5	6	4	4
	Aut	45	46	46	46	45	45
S4	Jan	60	60	59	60	59	58
	Feb	52	53	49	50	49	48
	Mar	38	39	38	39	38	37
	Apr	22	22	21	21	20	20
	May	8	8	6	6	5	5
	Jun	0	0	0	0	0	0
	Jul	3	3	0	2	0	0
	Aug	18	17	16	16	14	15
	Sep	34	34	33	34	32	32
	Oct	49	50	50	50	49	49
	Nov	59	59	59	59	58	58
	Dec	61	62	61	62	61	61

[18] the optimal tilt angles are determined between 31 and 32° for different cities in Turkey. The minor differences between the tilt angles are caused from the data used in the studies, yet, 1-2° difference does not cause a considerable change in the energy production. Therefore, as a rule of thumb, optimal fixed-tilt angle in solar applications in Turkey can be adjusted as φ-9°, where φ is the latitude of a location.

If the angle of inclination is aimed to be adjusted semi-annually (S2), then the optimal tilt angle becomes 49–50° in the winter-autumn (W-A) period, and 11–14° in the summer-spring (S-S) period in Turkey. In [88], the optimal tilt angles for W-A and S-S periods are found as 57° and 16° for the city of Sakarya which is close to Tekirdag.

If the tilt angles are adjusted seasonally (S3), the optimal angle values vary in the range of 56–57° in winter, 45–46° in autumn, 4–7° in summer and 20–22° in spring. In [87], the seasonal tilt angles for Izmir are found as 55.7°, 43°, 4.3° and 18.3° and in [18], the average optimal tilt angles for Turkey are found as 57°, 46°, 5° and 21° for winter, autumn, summer and spring respectively.

If the tilt angles are adjusted monthly (S4), the optimal angle values vary between 0 and 62° in Turkey. The inclination angle becomes smaller in summer months and larger in winter months to benefit more from the solar radiation. Also, in the literature, the monthly optimal tilt angle ranges are determined as 0-61° for Izmir [87], 0-65° for Erzurum which is close to Artvin [89], 0-65° for different locations in Turkey [18].

As can be seen from the results, optimal tilt angle values vary in a wide range throughout the year depending on a tilt adjustment scenario. When a PV system is placed at a fixed angle, the amount of radiation falling on a panel surface decreases in almost all months.

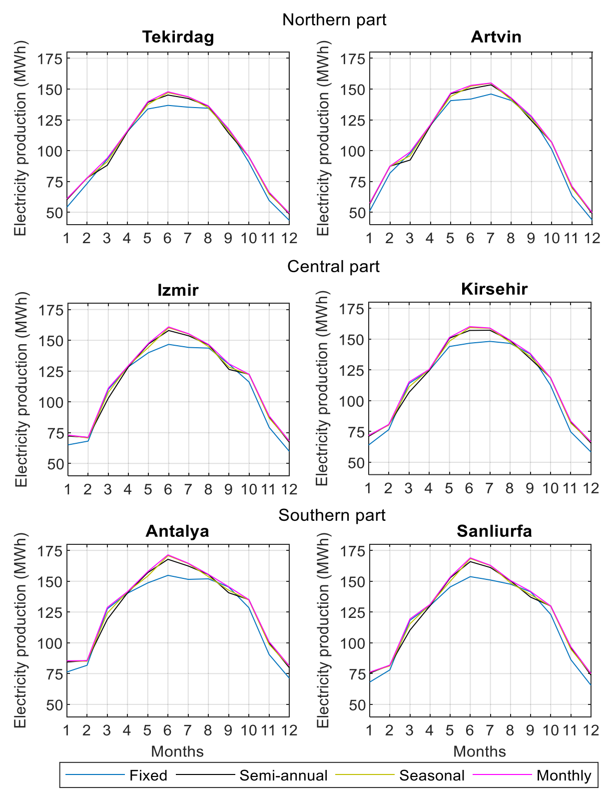

Fig. 6. Monthly electricity production of the selected cities in each solar part.

5.2. Electricity yields from the PV system

Tilt adjustment brings increased energy yield as expected. Thus, in this section, electricity production of PV plants with fixed-tilt and adjustable tilt systems are given and compared. In Fig. 6, electricity production of 1 MW plants in six provinces of Turkey are shown, and the energy yield in cases of fixed-tilt, semi-annual, seasonal, and monthly adjustments are compared.

It is seen in Fig. 6 that the most obvious changes in the electricity production occur during the summer and winter months in all provinces. For instance, in Tekirdag, the electricity production of 121.1 MWh in June in fixed-tilt scenario, increases by 7.1% to 129.7 MWh in monthly tilt adjustment scenario. Similarly, the electricity production of 45.6 MWh in December in fixed-tilt scenario, increases by 12.9% and reaches 51.5 MWh in monthly tilt adjustment scenario. The increase in energy yield from switching from fixed-tilt to monthly tilt adjustment in Izmir and Antalya is 8.43% and 9.31%, respectively in June, and 13.31%, and 13.29%, in December.

In Table 4, the annual energy productions for all locations are given and the annual increase in energy production provided by tilt

Table 4
Annual energy production for all cases and relative increase rate of tilting scenarios compared to S1.

		Northern part		Central part		Southern part	
	Scenario	Tekirdag	Artvin	Izmir	Kirsehir	Antalya	Sanliurfa
Annual energy production (kWh/kW)	S1	1,114	1,177	1,221	1,266	1,284	1,361
	S2	1,150	1,215	1,264	1,310	1,331	1,412
	S3	1,154	1,220	1,270	1,316	1,337	1,419
	S4	1,164	1,231	1,283	1,328	1,350	1,433
Increase rate (%) compared to S1	S2	3.21	3.23	3.53	3.45	3.71	3.64
	S3	3.64	3.67	4.02	3.95	4.26	4.15
	S4	4.53	4.57	5.02	4.94	5.30	5.16

adjustment (scenarios of S2–S4) is compared to the fixed-tilt system (scenario of S1). According to the results, the ratio of energy gain by tilt adjustment increases from north to south. In S2 (semi-annual tilt adjustment) annual energy production increase is between 3.21 and 3.71% from north to south, whereas, in S3 (seasonal tilt adjustment), the increase is between 3.64 and 4.26%. The highest energy gain is obtained in S4 (monthly tilt adjustment) as expected, with an annual energy increase between 4.53 and 5.30% in Turkey.

In Fig. 7, the comparison of monthly electricity production changes under different tilt adjustment scenarios relative to fixed-tilt are presented. It can be seen that, in the winter period, electricity production increase is more than 10% compared to the fixed-tilt. The highest increase is noticed in December (13.29%). On the other hand, not in S4 (monthly tilt adjustment) but in S2 (semi-annual tilt adjustment) and S3 (seasonal tilt adjustment), electricity production decreases in March and September, however, with a lower portion when compared to the gain obtained during the whole winter and summer months.

5.3. Economic analysis

Until here, the optimal tilt angles and the electricity production of 1 MW PV plants in six provinces of Turkey with periodic tilt adjustment scenarios are given. Here, a techno-economic feasibility analysis of 1 MW PV plants for the selected provinces is made. In the analysis, the current economic parameters and the amended feed-in tariff scheme of Turkey are considered and the results are evaluated through NPV, DPBP and IRR. The NPV and IRR results are given in Table 5 for the selected provinces. The DPBPs in the selected provinces are shown in Fig. 8.

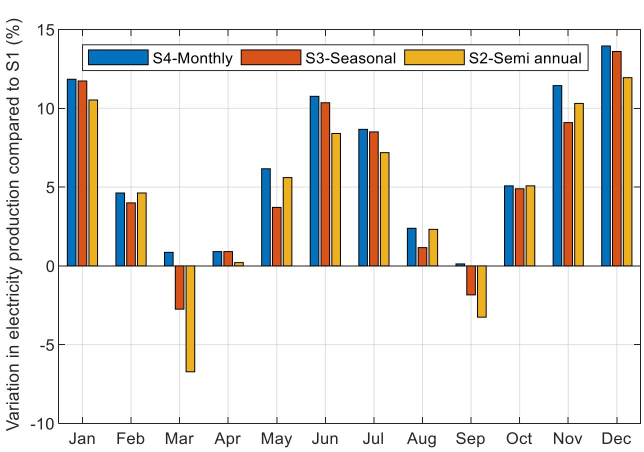

Fig. 7. Monthly variations of electricity production under different scenarios relative to S1.

According to the results, in Turkey, the DPBP of 1 MW fixed-tilt PV systems are between 9.20 and 12.36 years and the NPV of the systems are between 474,052 and 823,746 US $. In [82], the DPBP is found as 7.03 years for Izmir, whereas it is 10.51 years in this study. Likewise, in [71], the DPBP is 10.5 years for Elazig, a close province to Kirsehir, for the real interest rate of 5%. The reason for the higher DPBP values in this study is the new feed-in-tariff scheme of Turkey which reduced the feed-in tariff rate from 0.133 to 0.081 US $/kWh. The decrease of DPBP of the systems by tilt adjustment is around 6–7 months in scenario 2, 7–8 months in scenario 3, and 8–10 months in scenario 4, compared to the fixed-tilt system.

The increase in NPV of the systems varies between 70,000 and 100,000 US $/MW which is considerably high. Such that, the NPV increases by around 14.9%, 13.7%, and 12.4% from the north to the south, respectively, by monthly tilt adjustment. The increase in cash flows in the northern part is important due to the lower NPV and DPBP of the northern provinces.

IRR gives an idea of the profitability of a project and allows us to compare it to others. In all cases, the IRRs are found to be higher than the interest rate, meaning that the projects generate value in all six provinces. The IRR values in the southern-part are higher than in the central and northern part as expected due to higher solar potential. Among the tilt adjustment scenarios, the mechanisms provide IRR increase in the range of 0.7–0.9% relative to fixed-tilt case (S1).

5.4. Sensitivity analysis

Economies of the developing countries, such as Turkey, are relatively unstable and these countries are likely to be dramatically affected by currency and interest rate fluctuations. Therefore, in addition to the current real interest rate of 3%, different interest rates in case of positive or negative economic situations are taken into account in the sensitivity analysis, as 1% and 5%, respectively.

Moreover, the cost of PV systems is continuing to fall. Thus, 10% and 20% decrease in the initial investment costs were also considered in the sensitivity analysis as future scenarios. These two scenarios also correspond to the past tax practices of the central government in Turkey, such as reduction of the VAT by 10% or complete removal of it to revive the PV sector.

The NPV of the systems in case of a change in real interest rates are given in Table 6 and the DPBPs are shown in Fig. 8. When the real interest rate is taken as 1% to represent the positive progress in the economy, the DPBP of the systems reduce almost 7 months, and the NPV increases by approximately 50% compared to the base scenario shown in Table 5.

On the contrary, when the real interest rate is taken as 5% to represent a worsening economy, the DPBP of the systems in the northern provinces increases more than 2 years and the NPV reduces remarkably which makes it to question to invest in PV plants.

Table 5
The NPV (thousand $) and IRR (%) of the selected provinces (Real interest rate: 0.03).

	Scenario	Northern		Central		Southern	
		Tekirdag	Artvin	Izmir	Kirsehir	Sanliurfa	Antalya
NPV	S1	474	563	626	689	715	824
	S2	525	617	687	751	781	895
	S3	532	624	696	760	790	906
	S4	545	639	713	778	809	926
IRR	S1	5.4	6.2	7.1	7.2	7.9	8.6
	S2	5.9	6.7	7.6	7.8	8.5	9.2
	S3	5.9	6.8	7.7	7.9	8.6	9.3
	S4	6.1	6.9	7.9	8.0	8.8	9.5

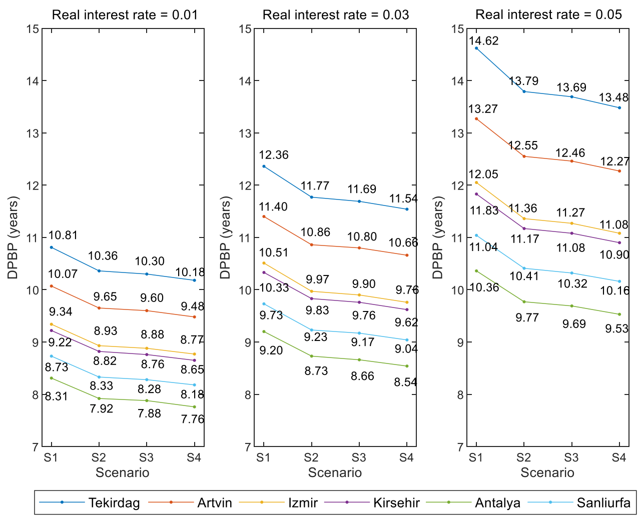

Fig. 8. The DPBP of the cities under different real interest rates.

Therefore, the effect of tilt adjustment becomes more apparent under higher real interest rates. Under 5% real interest rate, switching from S1 (fixed-tilt) to S4 (monthly tilt adjustment) provides a remarkable NPV increase between 16% (southern part) and 25% (northern part). Therefore, it can be concluded that tilt adjustment should be seriously considered in countries with high real interest rates, especially if they are located in northern latitudes.

Under 1% real interest rate, switching from S1 (fixed-tilt) to S4 (monthly tilt adjustment) provides an NPV increase between 10% (southern part) and 11% (northern part). Although the NPV increase is not as high as in cases of 3% and 5%, it is still significantly high. As seen, under low real interest rates, solar radiation differences between different regions do not make much difference in terms of the NPV gain when tilt adjustment is applied.

The effect of a possible decrease in initial investment cost on NPV is given in Table 7 (10% reduction) and Table 8 (20% reduction), and the effect on DPBP is shown in Figs. 9 and 10. Under 10% reduction, the DPBP of the investments in 3 of 6 provinces stay above 10 years, whereas in the rest drop below 10 years. In case of 10% reduced initial cost along with reduced real interest rate from 3% to 1%, the DPBP of the systems drop below 10 years in all solar parts of Turkey except Tekirdag and if the real interest rate increases to 5%, then the DPBP of the systems exceeds 10 years in 5 of 6 provinces.

Moreover, the NPV of a sample system for each location increases due to a 10% reduction in the initial investment cost compared to base initial investment case. In the case of 5% real interest rate, the NPV of a system reduces remarkably compared to other real interest rate cases. By adjusting the tilt scenarios monthly, the NPV of the system rises more than 11% for all parts compared to the fixed-tilt case.

In the case of a 20% reduction in initial investment cost, almost all investments have a payback period (in Fig. 10) less than 10 years (with an exception in Tekirdag and Artvin in case of 5% real interest rate). For the base scenario (3% real interest rate), the investments produce 10% more value in terms of NPV. When both the real interest rate and initial investment cost is reduced, then the DPBP of the systems drop below 8 years in 4 of 6 provinces with very high profitability.

It should be noted that, for the tilt scenarios, adjusting tilt angle has a slight advantage when both interest rates and initial investment costs are low. However, in case of increased interest rate, tilt adjustment affects payback periods considerably. The advantage provided in northern latitudes becomes around 7–8 months.

The results of the sensitivity analysis for the IRR are given in Fig. 11. For the sake of simplicity, the results are demonstrated over three provinces, one of each representing each solar part. When the IRRs of the all locations are examined under different initial investment cost and interest rate scenarios, it is seen that the investments in the southern regions are more advantageous economically.

In the base real interest rate scenario (3%), IRR values increase where the initial investment cost decreases. Approximately for every 10% initial investment cost reduction, IRR increases by 1.5–

Table 6
The NPV (thousand $) under different real interest rates.

Real interest rate	Scenario	Northern		Central		Southern	
		Tekirdag	Artvin	Izmir	Kirsehir	Sanliurfa	Antalya
0.01	S1	816	929	1,008	1,088	1,121	1,258
	S2	880	997	1,085	1,166	1,204	1,348
	S3	888	1,006	1,096	1,177	1,216	1,362
	S4	906	1,025	1,118	1,200	1,239	1,387
0.05	S1	228	300	351	402	423	511
	S2	269	344	401	452	477	569
	S3	275	350	407	456	484	577
	S4	286	362	421	474	499	594

Table 7
The NPV (thousand $) with 10% reduced initial cost and with different real interest rates.

Real interest rate	Scenario	Northern		Central		Southern	
		Tekirdag	Artvin	Izmir	Kirsehir	Sanliurfa	Antalya
0.01	S1	933	1,046	1,126	1,206	1,238	1,376
	S2	997	1,114	1,203	1,284	1,322	1,466
	S3	1,006	1,124	1,214	1,295	1,333	1,479
	S4	1,024	1,142	1,235	1,317	1,357	1,505
0.03	S1	584	673	736	799	825	934
	S2	635	727	797	861	891	1,005
	S3	642	735	806	870	901	1,016
	S4	656	749	823	888	919	1,036
0.05	S1	333	405	456	507	528	616
	S2	374	449	505	557	581	674
	S3	379	454	512	564	589	682
	S4	390	466	526	576	604	698

Table 8
The NPV (thousand $) with 20% reduced initial cost and with different real interest rates.

Real interest rate	Scenario	Northern		Central		Southern	
		Tekirdag	Artvin	Izmir	Kirsehir	Sanliurfa	Antalya
0.01	S1	1,051	1,164	1,243	1,323	1,356	1,493
	S2	1,115	1,232	1,321	1,402	1,439	1,584
	S3	1,124	1,241	1,331	1,413	1,451	1,597
	S4	1,141	1,260	1,353	1,435	1,474	1,622
0.03	S1	694	783	846	909	935	1,044
	S2	745	837	907	971	1,001	1,115
	S3	752	845	916	980	1,011	1,126
	S4	767	859	933	998	1,029	1,146
0.05	S1	437	510	561	612	632	720
	S2	478	553	610	662	686	778
	S3	484	559	617	669	693	787
	S4	495	571	631	683	708	803

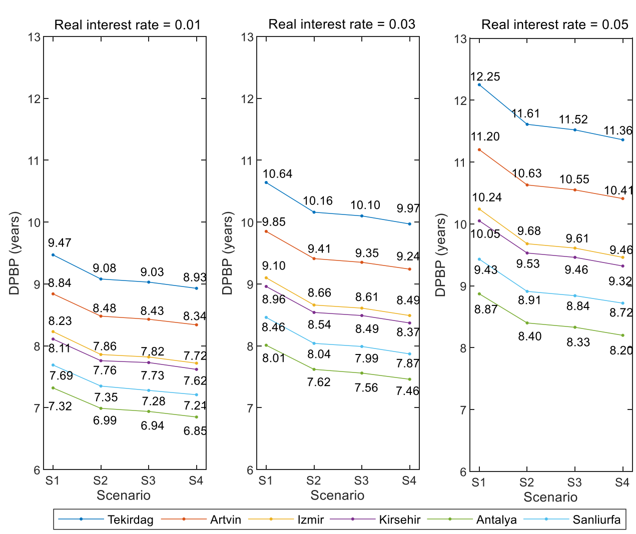

Fig. 9. The DPBP with 10% reduction in initial investment cost.

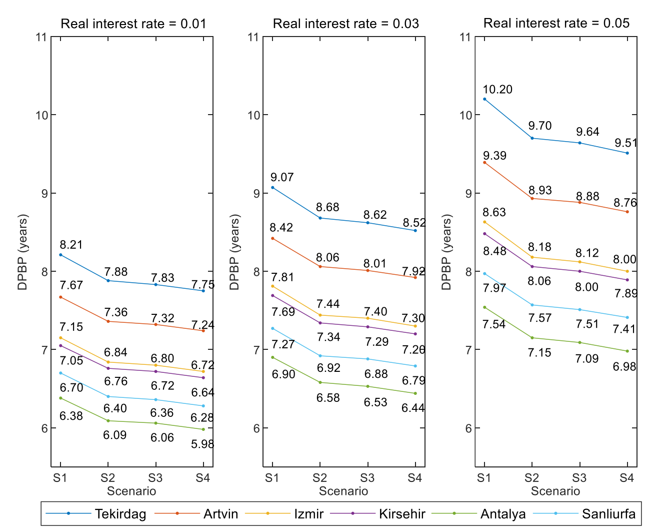

Fig. 10. The DPBP with 20% reduction in initial investment cost.

2.1%. In addition, as the initial investment costs decreases, the profitability of tilt adjustment increases, albeit slightly. For instance, the IRR rise of 0.9% in Antalya due to monthly tilt adjustment (from 8.6% to 9.5%), becomes 1.1% (from 12.5% to 13.6%) in the case of 20% decreased initial investment cost.

In the decreased real interest rate scenario (1%), the IRR values for each location increase by more than 2% and the investments provide very high profitability. With the decrease in the initial investment cost, 3–4% increase in IRR values occurs. As such, this situation can be considered as the most favorable conditions for investment.

In the increased real interest rate scenario (5%), investment conditions become unfavorable in some provinces. Especially in the northern part, IRR values of 3.4% for Tekirdag and 4% for Artvin stay below the real interest rate. Yet, they can become investable if the initial investment cost decreases. As for tilt adjustment scenarios, the increase in IRR is higher in the southern part with high solar

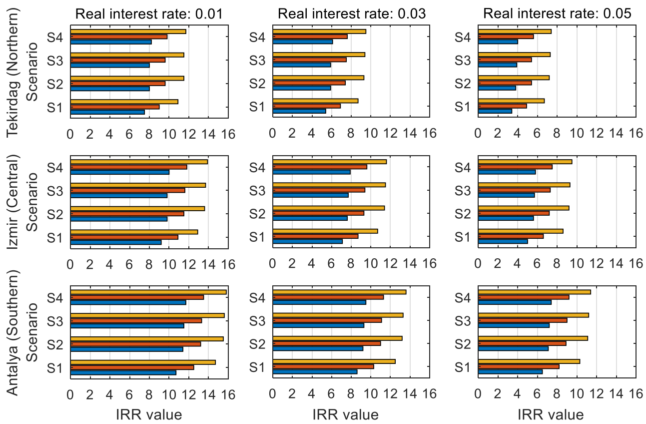

Fig. 11. IRR values (%) under different interest rate and initial investment costs (current initial cost (blue), 10% reduced initial cost (orange), 20% reduced initial cost (yellow)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

potential. While the increase is approximately 0.7% in the northern part, it is about 1% in the southern part.

6. Conclusions

The integration of solar PVs into the grid network, as well as the number of stand-alone PV applications, have increased considerably in the last decade. However, the benefit from PV systems can be maximized only to an extent, limited by their structural efficiency and sunshine duration. To generate more electricity from solar PV, the solar radiation falling on a panel surface can be increased. Tracking systems can enable higher energy capture in return for extra installation costs, however, resulting in infeasible investments. On the other hand, periodic tilt adjustment mechanisms can remarkably increase the energy production with negligible structural costs.

The electricity production of a sample system is evaluated and analyzed. According to the obtained results;

- semi-annual tilt adjustment (S2) provides 3.21–3.71%,
- seasonal tilt adjustment (S3) provides 3.64–4.26%
- monthly tilt adjustment (S4) provides 4.53–5.30%

more electricity production compared to the fixed-tilt (S1).

Afterward, a sample 1 MW PV system is evaluated to examine the economic contribution of periodic tilt angle adjustments. When fixed-tilt systems are used, the DPBP of the systems varies between 9.20 and 12.36 years in Turkey. In the case of monthly tilt adjustment, this period is shortened by around 8–10 months and the DPBP of the PV systems becomes between 8.54 and 11.54 years. Similarly, monthly tilt adjustment provides a remarkable NPV increase between 14.9 (Tekirdag) and 12.4% (Antalya) in Turkey relative to the fixed-tilt case. The IRR of the systems, which is in the range of 5.4–8.6%, increases by 0.7–0.9% and becomes 6.1–9.5%.

Furthermore, as a sensitivity analysis, the impact of change in real interest rate and initial investment cost on the feasibility of the systems is examined. If the economic indicators turn negative and real interest rates increase, then monthly tilt adjustment can provide a payback advantage up to 1.14 years.

Consequently, manually adjustable tilt mechanisms add a remarkable value to PV systems, especially in particular months in terms of electricity production, and they provide shorter payback periods with increased NPV. Considering that these mechanisms require negligibly low additional structural costs and PV plant staff can handle the periodic adjustment easily with a little training, manually adjustable tilt mechanisms can be preferred instead of fixed-tilt structures.

Although this study is carried out for Turkey, the same methodology can be applied in other countries which have different solar conditions and economic parameters, and the impact of manually adjustable tilt mechanisms on feasibility of PV systems can be further examined.

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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