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Solar collector tilt angle optimization for agrivoltaic systems

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ABSTRACT

The growing global population increases the need for energy and food. As agricultural land is invaded by renewable energy projects, the area of land that can be cultivated is decreasing day by day. Agrivoltaics offers an alternative solution to this situation by combining agriculture and photovoltaics on the same land. This study investigates the feasibility of a possible 175 m^2 Agrivoltaic system in Ankara Turkey (39.57° N-32.53° E). The study consists of three phases. In the first stage, the annual, monthly and seasonal optimum tilt angle for 39.57° N latitude was determined. In the second stage, eight different models were created for different tilt angles for PV panels of three different efficiencies in the agrivoltaic system to be installed. AC electrical energy and net profit ($) that can be produced with these models were calculated. In the third and final stage, the potential land equivalent ratio amount of seven agricultural cropscombined with eight different models was calculated. In the scenario created for the region, the highest yield increase is 11.2 % with M1 model (β = 31.33°)-Thinfilm, while the lowest yield loss is 33.2 % with M4 (β = 90.00°) Thinfilm. The highest generated electricity and net profit are AC-15674 (kW h) and 1286 ($) respectively. For the agricultural land determined to be grown in the system, the highest yielding agricultural product was kiwifruit with a value of 2.07 and the lowest yielding product was bokchoy with 0.25. This study can serve as a basic technical guidance for the establishment of Agrivoltaic plants with the highest efficiency in the Mediterranean climate and mid-latitude regions.

1. Introduction

Although the production of solar energy, which is one of the renewable energy sources, is increasing rapidly, fossil fuels continue to account for the majority of total global final energy consumption. For this reason, measures are being taken to increase energy efficiency and reduce energy costs in order to make alternative energy sources widespread [1,2]. Adopted in 2019, the European Green Deal represents the EU's biggest action to achieve climate neutrality. According to the realisation target of this memorandum of understanding, photovoltaic panels (PV) systems play a key role in the renewable energy sector. So much so that by 2030, 21–22 GW of PV per year is needed in the EU to reduce emissions by 55 % and The Renewable Energy Directive (RED II) targets a 32 % share of renewable energy and at least 40 % reduction in greenhouse gas (GHG) emissions [3]. In addition, for sustainability, in 2015, the

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United Nations (UN) defined 17 development indices addressing the most pressing global challenges [4]. This index uses many different criteria to determine the level of realisation of sustainable development goals of countries and these criteria include improvements in social, economic and environmental areas. The scope of this study includes Goal 2 (End hunger, achieve food security and good nutrition, and promote sustainable agriculture), Goal 7 (Ensure access to affordable, reliable, sustainable and modern energy for all), and Goal 13 (Take urgent action to combat climate change and its impacts). Possible contributions to the determined targets are as follows, Target 2: The implementation of APV systems are increase in land productivity, and these systems can be effectively utilized to enhance food production., Target 7: As solar-photovoltaic developments progress, the APV systems produce energy that is clean and at an attainable cost., Goal 13: The application of APV systems has been found to be beneficial in not only mitigating climate change through the reduction of GHG emissions, but also in enhancing the carbon sequestration potential of a site through the implementation of on-site habitat restoration practices [5]. These targets frame the urgent challenges in the agriculture and energy sectors that need to be addressed over the next quarter century. To this end, the transition to renewable energy-based generation forms an integral part of the development goals set by EU and national governments. Within the context of these goals, solar energy, as a renewable resource, has the potential to substitute the extensively employed fossil fuels in the near future due to its widespread, sustainable nature. This category of energy has demonstrated its efficacy, owning a share of nearly 31 % among other kinds of renewable energy technologies. In 2022, PV energy secured the second position after hydroelectric technology with an installed capacity of 1.053 GW. It is anticipated that the installed power capacity will reach 5400 GW by 2030 and 18200 GW by 2050, allowing for a global energy output of 25 % [6]. The primary reasons for this situation are heightened efficiency, reduced production and installation expenses, and no emissions of GHG into the atmosphere. PV systems have the potential to mitigate 0.53 kg of carbon dioxide (CO_2) emissions per kilowatt-hour of electricity generated. It is estimated that by 2030, implementation of PV systems can lead to the reduction of 69–100 million tonnes of CO_2, 126,000–184,000 tonnes of sulphur dioxide (SO_2) and 68,000–99,000 tonnes of nitrogen oxides (NOx) [7]. The main common requirement of photovoltaic systems and agricultural crops is radiation from the sun to the earth's surface. In the past, either crop production or a PV panel plant was installed on an agricultural land. However, today, the new generation solution for this dilemma is Agrivoltaic (APV) systems. The idea of farming between PV panel and soil was first proposed by Goetzberger and Zastrow in 1982 [8]. In this alternative hybrid system of the next century, electricity is generated by PV panels mounted on the field, while agricultural production such as cereals, vegetables and fruit is possible in the areas underneath. This allows dual utilisation of the available land area. Advanced PV (photovoltaic) panel systems in APV systems are designed to increase efficiency, produce more energy and collect solar energy without adversely affecting agricultural activities. Examples include Biafacial PV Panels that collect solar energy from both the top and bottom sides, Low Profile Transparent Panels that filter the sunlight passing over them, leaving more light to the plants, and PV panels with solar tracking systems. Global warming exposes agricultural crops to radiative, thermal and rainfall-intensive negative effects in the 21st century. Agrivoltaic application has many advantages such as reduction of carbon emissions, clean energy production, increase in economic benefits, protection against hail and high-low temperatures, and contribution to water efficiency with shading. This will be an important application in the measures to be taken to combat the climate crisis in the long term. In agro-voltaic designs, the sustainability of agricultural production is at the forefront by considering local climatic conditions and the needs of crops for radiation and irrigation [9,10].

The most basic parameters affecting the power efficiency in APV systems are irradiation amount, panel and azimuth angle variation, outdoor temperature, dusting and construction design. The parameters affecting the power generation of APV systems are analysed. The product efficiencies for solar radiation are 30 % for multicrystalline silicon (mc-Si), 30 % for amorphous silicon (a-Si) and 35 % for cadmium telluride (CdTe) [11]. The crop yield of bifacial solar panels was modelled with different land cover and meteorological parameters [12]. For PV panel inclination angle; techno-economic analysis in APV model simulation created for grape production showed that the income can be 15 times more than the initial situation [13]. The effect of photosynthetically active radiation (PAR) on crop production was analysed at different angle positions. Thus, maximum gain can be obtained with shading below 50 % [14]. By determining the tilt angles of PV panels, agriculture and panel efficiencies can reach the highest levels [15]. PV panels reduce the radiation levels by partially shading the crops. This causes the temperature on the crops and land to decrease and protects the crops from excessive heat, and the amount of energy produced from PV panels increases [16]. Optimum panel inclination angle and yield increase were examined with modelling and analyses were also made according to the initial situation [17,18]. It has been calculated that land use efficiency can increase by 60–70 % in APV applications, and shade-tolerant crop production with solar-generated electricity can be 30 % more efficient compared to conventional agriculture [19]. Once installed, regularly maintained APV systems can operate for many years. This shows that energy production can continue throughout the year with seasonal agricultural activities. Food production continues despite the adverse effects of environmental conditions [20]. Therefore, APV systems are more efficient than conventional agriculture not only in terms of crop yield but also in terms of assurance of clean energy production [21]. In addition, to measure the land use efficiency of intercropping systems, Mead and Willey [22] introduced the concept of Land equivalent ratio (LER) in agroforestry. Dupraz et al. [23] proved that yields from the agrivoltaic farm experiment are higher than monosystem equivalents related to the use of LER methodology. In previous studies on LER applications, this methodology has also been used to determine the possibility of integrating agricultural production with a solar farm. LER is a method used to quantify land useefficiency for the simultaneous production of crops and electricity [24–26].

The study's originality lies in the design of an APV system as an alternative solution to the rising energy-related food costs. The aim is to reduce the impact of operational costs on agricultural activities and promote sustainability, particularly in rural areas. The study analysed the design and performance of the APV system to be installed in mid-latitude regions of the northern hemisphere and in regions with Warm-summer Mediterranean climate (Csb) characteristics. The findings represent a step towards increasing productivity for academic and agricultural users. The aim of this study is to investigate the feasibility of a 175 m^2 APV system to be installed in the Ankara region. In the first stage, the annual optimum tilt angle for 39.57° N latitude was determined. In the second stage, annual AC electrical energy (kW.h) and financial gain ($) data were calculated for different angle values and 3 different module types. In the fourth stage, the potential amount of LER was calculated and the overall efficiency was analysed. The fourth and final step was an economic analysis of the current and future predictions for the APV facility.

2. Material and method

The province of Ankara (Turkey), which is analysed in this study, is located at the coordinates 39.57° N and 32.53° E. The average annual temperature of the province is 12 °C, the highest temperature is 30.5 °C, and the average sunshine duration is 6.7 h per year. According to the international climate classification Koppen, Ankara region is characterised as "Csb" climate type (degraded Mediterranean climate) with mild winter, mild summer and arid climate type [27]. Table 1 shows the average meteorological data in Ankara province for many years.

The sunpath diagram and radiation intensity values for Ankara for 12:30 h are shown in Fig. 1. The average day length of the city is 15 h (05:20/20:20) on 21 June and 09 h and 20 min (07:07/16:27) on 21 December. The azimuth angle and solar elevation values

Table 1
Average meteorological values for Ankara province (1927–2021) [28].

ANKARA	January	February	Mart	April	May	June	July	August	September	October	November	December
Temperature (°C)	0.2	1.7	5.7	11.2	16.0	20.0	23.4	23.4	18.9	13.2	7.2	2.5
Highest Temperature (°C)	4.2	6.5	11.5	17.4	22.4	26.7	30.3	30.4	26.1	20.0	13.0	6.5
Lowest Temperature (°C)	−3.3	−2.3	0.7	5.3	9.7	12.9	15.8	16.0	11.8	7.2	2.5	−0.8
Sunshine duration (hours)	2.6	3.8	5.1	6.6	8.4	10.1	11.3	10.8	9.2	6.7	4.6	2.6
Horizontal Radiation Intensity (W/m^2-day)	1610	2610	3320	4320	5460	6540	7110	6400	5170	3090	1840	1210
Number of Rainy Days	14.7	13.2	14.3	14.5	16.1	11.4	5.6	4.5	5.6	9.0	10.6	14.5
Monthly Total Rainfall (mm)	40.1	35.4	39.2	42.4	52.0	35.3	14.2	12.5	18.1	27.9	31.5	44.6

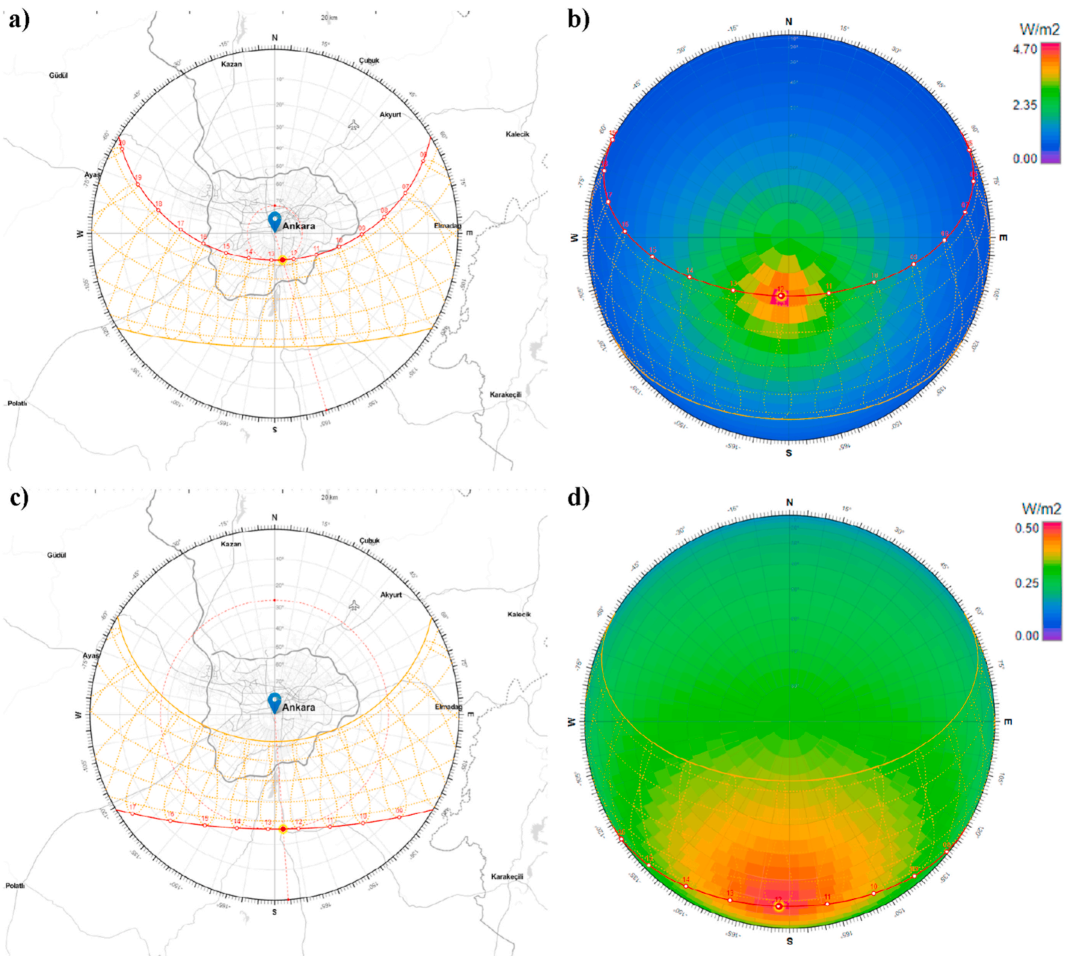

Fig. 1. Ankara province; sun path diagram a) 21 December c) 21 June, radiation intensity b) 21 December d) 21 June.

are 172.45°/73.41° and 176.59°/26.61° for 21 June and 21 December, respectively. Thus, the Central Anatolia region is in a specific position with the number of clear days and high irradiance values, which are the basic requirements of ideal APV systems.

2.1. Optimized tilt angle

The solar radiation values falling on the PV panels vary according to the angle value of the panel with the horizontal. In practice, analyses are often made with the data taken on the horizontal plane ($\beta = 0°$) at a fixed position, while the solar radiation components exposure on an inclined surface are not measured. Maximum efficiency from solar panels is possible by positioning them at optimum monthly, annual or even seasonal solar panels tilt angles. This optimum value varies according to the latitude, surrounding land conditions, solar geometry, the movement of the earth on its axis and the sun's orbit, and the clarity index [29]. In this study, the optimum tilt angle of the APV system located in the middle belt latitude was determined and the electrical energy and financial gain level that can be produced through different scenarios were analysed. Fig. 2 shows the location of the studied region, the design of the APV system and the radiation components falling on the inclined panel. In the design of the APV system, a 12.0 kW h DC power capacity was installed with 40 unit with 300 Watt PV panels. A 3 m gap is left between each PV array and shading is considered to be ineffective. The height of the panels from the ground is assumed to be 3.6 m and an APV design was made in accordance with international standards, with a width of 10.5 m and a length of 16.5 m, totalling 175 m^2 [30].

Various mathematical models have been used to predict the solar radiation incident on the PV-Panel. There are two types of accepted approaches to estimate the diffuse radiation component on an inclined surface: isotropic and anisotropic models. In a comparative analysis of these models for the Northern Hemisphere, the isotropic model was preferred in this study because it was maximally effective [31]. This model is the Liu and Jordan model [32], which is widely used in the literature and easily applied.

In this study, radiation amount on the inclined plane was calculated by accepting azimuth angle as ($\gamma = 0°$) in the northern hemisphere. The monthly average daily global irradiance (H_{Total}) exposure on the inclined plane is given in Equation (1). This equation consists of the sum of direct solar radiation (H_{Beam}), reflected radiation ($H_{Reflected}$) and scattered radiation ($H_{Scatter}$) values [33].

$$H_{\mathbf{Total}} = H_{\mathbf{Beam}} + H_{\mathbf{Reflected}} + H_{\mathbf{Scatter}} \tag{1}$$

The amount of solar radiation upon the solar collector is incessantly altering because of the sun's shifting position in relation to Earth. For this purpose, calculations are made depending on Julian day and latitude. Equations (2)–(12) used to calculate various terms involved in determing H_{Total} [34]. In the equations in the calculation; It is defined as Latitude (Ø), Declination angle (δ), solar panel tilt angle (β), average sunrise angle (ω_s) and also sunrise angle on the inclined plane (ω'_s).

$$H_B = \left(H - H_d\right) R_b \tag{2}$$

$$R_b = \frac{\cos(Ø - \beta)\cos(\delta)\sin\left(\omega'_s\right) + \omega'_s\left(\frac{\pi}{180}\right)\sin(Ø - \beta)\sin(\delta)}{\cos(Ø)\cos(\delta)\sin\left(\omega_S\right) + \omega_S\left(\frac{\pi}{180}\right)\sin(Ø)\sin(\delta)} \tag{3}$$

$$H_R = \left(\frac{H\ (\rho)(1 - \cos\ \beta)}{2}\right) \tag{4}$$

$$H_S = H_d\ R_d \tag{5}$$

$$H_d = H\left(1 - 1.13\frac{H}{H_0}\right) \tag{6}$$

$$H_o = \left(\frac{24}{\pi}\right) G_{sc}\ k \left[\cos Ø \cos\ \delta\ \sin\ \omega_s + \left(\frac{\pi}{180}\right)\sin Ø \sin\ \delta\omega_s\right] \tag{7}$$

$$k = 1 + 0.033\ \cos\left(360\frac{n}{360}\right) \tag{8}$$

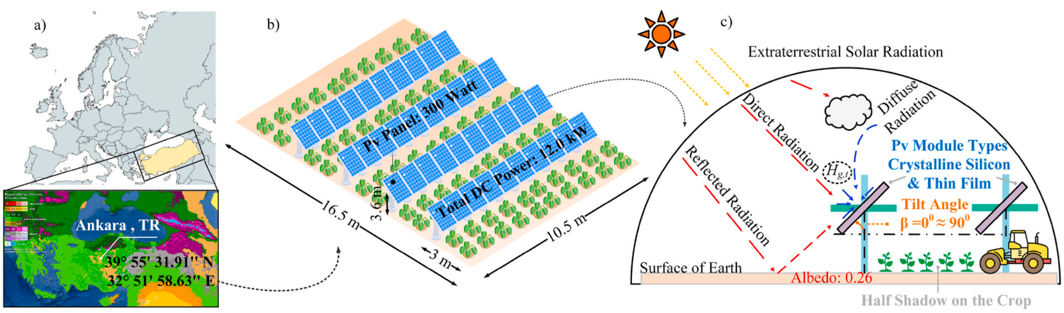

Fig. 2. APV system a) Position b) Design c) Optimum angle.

$$\delta = 23.45^\circ \sin\left(360\frac{n+284}{365}\right) \quad (9)$$

$$\omega_s = \cos^{-1}\left(-\tan\emptyset.\tan\ \delta\right) \quad (10)$$

$$\omega_s' = \min\left[\frac{\omega = \cos^{-1}\ (-\tan\ \emptyset\ \tan\ \delta)}{\cos^{-1}(-\tan(\emptyset-\beta)\tan\ \delta}\right] \quad (11)$$

$$R_d = \left(1 + \frac{\cos\ (\beta)}{2}\right) \quad (12)$$

The general solar angle and calculation equations used in the calculation of solar radiation on the inclined surface are shown. The diffuse radiation calculation used in Equation. 2 and Equation (5) is the diffuse radiation in the horizontal plane in Equation (6). In this equation, the amount of radiation emitted from the firmament is assumed to be uniform and is an isotropic model [33,35,36]. The albedo value in Equation (4) is taken as 0.26 (plantation) [37].

2.2. Estimation of electricity generation

The amount of electricity generation from PV panels varies depending on many parameters. These can be characterised as the amount of solar radiation and outdoor temperature. Above 25 °C, there is an inverse relationship between increasing outdoor temperature and the amount of electricity generated [34,38]. Equations (13) and (14) show the PV electricity generation considering the average monthly outdoor temperature of Ankara province.

$$T_t^c = T_t^{out} + \left(\frac{H_{Total,t}}{H_t^{NOCT}}\right)\left(T^{c,NOCT} - T^{a,NOCT}\right) \quad (13)$$

$$P_t^{PV,prod} = R^{PV} d^{PV}\left(\frac{H_{Total,t}}{H_t^{STC}}\right)\left[1 + \propto^P\left(T_t^c - T^{c,STC}\right)\right] \quad (14)$$

The technical specifications of the PV modules used in the simulation are shown in Table 2 and d^{PV} (derating factor) is taken as 0.8 [39,40]. In the calculations, the back of the PV panels is open and the wind speed is assumed as 1 m/s.

The DC system size of the Agrivoltaic system in this study is taken as 12 kW This value predicts the installation of 40 panels of approximately 300 W. Panels categorised in 3 different cases according to their characteristics in the PV-Market were used. Table 2 shows the modules with different production technologies. The efficiency of these modules varies between approximately 18 % and 21 %. The type selected as standard is poly-or mono-crystalline silicon modules and its efficiency varies between ~18 and 20 %. The difference of the module selected as premium from other modules is high efficiency (~20–22 %), anti-reflective coating and lower temperature coefficients. Thin film modules have lower efficiency (~18 %) than others, but are popular in PV market due to cheapness and low index temperature [41].

The DC to AC size ratio is the ratio of the DC nominal size of the array to the AC nominal size of the inverter. For the default value, it is 1.2. A typical range is 1.10–1.25, but some large-scale systems have ratios as high as 1.50. The optimum value varies according to the location of the PV panels, array orientation and module and inverter costs. Other parameters in the AVP installed system are; inverter efficiency 96 %, Ground Cover Ratio (albedo) 0.26 and azimuth angle (south facing) 180°. The total losses that may occur in the installation of a medium-sized system are calculated by formula 15 and shown in Table 3. The sum of 10 types of loss data is calculated as 14.08 % [42,43].

$$L_{total}(\%) = 100\left[1 - \prod_i 1 - \frac{L_i}{100}\right] \quad (15)$$

2.3. The agrivoltaic land equivalent ratio (LER)

Ankara province where the study was conducted is located in Central Anatolia region. Sample agricultural products that can be grown in this region are shown in Fig. 3. Fig. 3 is shown in basic categories. Crops in the plus (+) "blue" category have better crop

Table 2
Different Module types and their characteristics.

Module type	Cell material	Efficiency	Cover type	Temperature coefficient of Power (α^P)	Nominal operating cell temperature ($T^{c,NOCT}$)	Irradiance under STC (H_t^{STC})
Standard	Crystalline silicon	~19 %	Glass	−0.37 %/°C	48 °C	1000 W/m^2
Premium	Crystalline silicon	~21 %	Anti-reflective	−0.35 %/°C	48 °C	1000 W/m^2
Thin film	Thin film	~18 %	Glass	−0.32 %/°C	48 °C	1000 W/m^2

Table 3
Default values for the system loss categories.

Category	Default value (%)
Soiling	2
Shading	3
Snow	0
Mismatch	2
Wiring	2
Connections	0.5
Light-induced degradation	1.5
Nameplate Rating	1
Age	0
Availability	3
Total	**14.08 %**

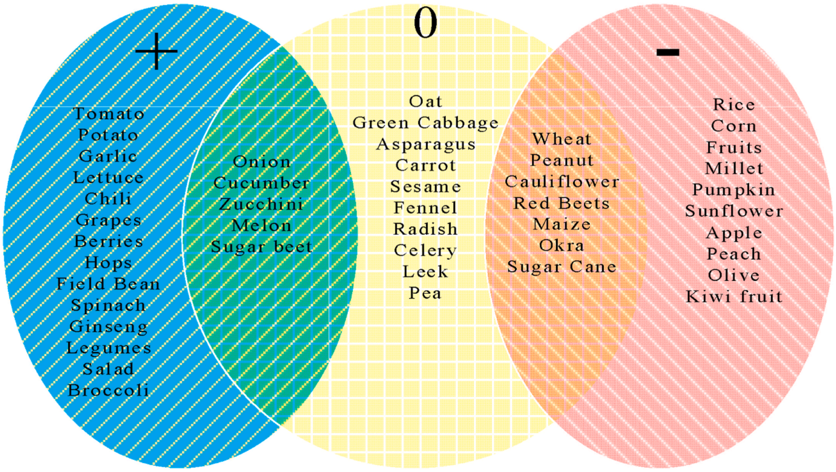

Fig. 3. Shade requirements of crops.

yields with shading. On the other hand, crops that are stimulated against shading are shown with minus (−) in the "red" category and need more sunlight. Crops in the zero (0) category are characterised as sun-indifferent according to total crop yield. This theoretical classification may vary in different locations according to soil fertility and meteorological climate characteristics. The products that can be grown in the installation of APV systems should be preferred first from the blue category and then from the green and yellow parts respectively. There are examples in the literature that APV system increases crop yield. These are; broccoli [44], celery [45], corn [46], lettuce [47,48], potatoes-spinach-salad [49], tomatoes-chiltepin peppers [50]. The characteristics of all these mentioned crop yields are shown in Fig. 3.

The land equivalent ratio (LER) is a method used to measure the efficiency of land use for the simultaneous production of crops and electricity and a measure of the efficiency of two different cropping systems compared to a reference cropping system. It is used to determine the possibility of integrating agricultural production with a solar farm. In the case of agrivoltaics, the LER will compare the efficiency of a solar farm combined with agriculture to a stand-alone solar farm or stand-alone agricultural land. The LER can be calculated by dividing the total efficiency of the agrivoltaic system by the sum of the efficiencies of the individual solar farm and agricultural land. This ratio can help determine the potential benefit and efficiency of combining solar energy production and agriculture on the same land. Furthermore, the LER for PV output is obtained by comparing the power output of the agrivoltaic system with that of a standard PV farm and is shown by equation (16).

$$LER = \frac{Y_{crop(AV)}}{Y_{crop(OF)}} + \frac{Y_{electricty(AV)}}{Y_{electricty(PV)}} \tag{16}$$

where Ycrop (AV), crop yield for AV farm, Ycrop (OF) stands for agricultural yield (kg/ha for instance) in a single use of land for farming, Yelectricty (AV) Energy yield for AV farm and Yelectricty (PV), Energy yield for traditional solar PV farm [24]. Among the various factors for crops grown on an AV farm, the influence of radiation intensity is high [51]. Therefore, the model assumes that crop yield is primarily affected by the shade intensity caused by solar panels. Assuming a linear relationship between crop yield and shade intensity, for the behavior of crop yield as a function of solar radiation [52] to Equation (17).

$$\frac{Y_{crop(AV)}}{Y_{crop(OF)}} = m \text{ x } G_{GR} + (1 - m) \tag{17}$$

where the linear slope (m) is kept variable as an indicator for the crop sensitivity to the shade. A smaller m represents that crop yield is more tolerant to shade. If the LER is less than 1, then producing crops and energy together is inefficient. When compared to mono-generation, APV systems with LER > 1 are more productive [21].

2.4. Economic analysis of agrivoltaic plant

Economic analysis methods are needed to assess the financial attractiveness of the project or investment of APV systems, to make comparisons between different projects and to support investment decisions.

NPV is used to calculate the present value of an investment or project. This is the difference between the present value of future cash flows and the present value of the investment cost [53]. The NPV is expressed as equation (18).

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - C_0 \tag{18}$$

where T is the lifetime of the project or investment, t is a specific period, CF_t refers to the net cash flow in period t, r is discount interest rate and C_0 is initial cost of the investment. According to the average values of the last 10 years, Turkey's real interest rate is calculated as 3 % [54].

DPBP, "Discounted payback period" shows how long it takes for a project to recover its initial investment cost through the net cash flows generated from the project. This metric is particularly useful for evaluating short-term projects or low-risk investments. The lower the DPBP, the lower the risk of a project. The DPBP is calculated by Equation (19).

$$DPBP = N_y + \frac{|C_n|}{C_p} \tag{19}$$

where Ny is the number of years in which the last negative value of the cumulative discounted cash flow occurs after the initial capital investment, Cn is the number of years in which the last negative cumulative discounted cash flow occurs, and Cp is the discounted cash flow in the year in which the first positive value of the cumulative discounted cash flow occurs [55].

IRR, "Internal Rate of Return" represents the discount rate that will make the NPV of a project zero. The IRR of a project shows the rate of return on investment. A high IRR indicates that the expected return of the project exceeds the cost, suggesting that the project is acceptable [56]. The IRR is calculated by Equation 20

$$0 = \sum_{t=1}^{T} \frac{CF_t}{(1+IRR)^t} - C_0 \tag{20}$$

The APV system's nominal power to be calculated is 12 kW-DC. The capital expenditure (CAPEX) and operational expenditure (OPEX) values that determine the system cost for the standard PV panel are calculated for today (2023) and future values (2035–2050) [57]. The PV-CAPEX values for 2023, 2035, and 2050 are 1044 US$/kW, 579 US$/kW, and 466 US$/kW, respectively. The PV OPEX values for 2023, 2035 and 2050 are $18.88/kW, $12.63/kW and $10.86/kW respectively. It should also be noted that the APV system is 5 % more expensive than ground-mounted systems [58]. The unit cost of premium PV panels (~21 %) and thin film PV panels (~18 %) varies by approximately +3 % and −4%, respectively, compared to the standard panel [59].

3. Results

3.1. Optimum slope conditions and angles

In this study, the optimum panel angle for both solar energy investments and agricultural production in the Middle Anatolia region of Turkey (upper Sakarya) has been determined for Ankara province. 39.93° N (Ankara) latitude for other calculated parameters are shown in Fig. 4.

These are Declination Angle, Non-atmospheric solar radiation (Ho), Diffuse solar radiation, and Clearness index, which change monthly during the year. Clearness index (Kt = H/Ho) values of the region are around 0.46 on average per year and are advantageous in agricultural terms. When the region is examined in general, the slope angles vary according to the months and the lowest is 0° and the highest is around 56°. The seasonal optimum slope angle values are winter-55°, spring-20°, summer-7°, autumn-45° and the total annual average is around 31.33°. At the optimum monthly panel angle, the yield is the highest in winter months with an average of 40.01 % and the lowest in summer months with an average of 1.01 %. In case of adjusting the annual panel tilt angle, an efficiency increase of around 19.02 % was obtained compared to the first case (horizontal). The annual panel solar radiation change of Ankara province is shown in Fig. 5.

When the optimum panel tilt angle results are analysed, agrivoltaic systems provide maximum benefit due to the monthly changing PV panel (see Fig. 6). However, this process means more cost and labour compared to fixed systems. For this purpose, in cases where monthly angle change is not possible, the fixed angle should be determined by analysing according to the usage status of the

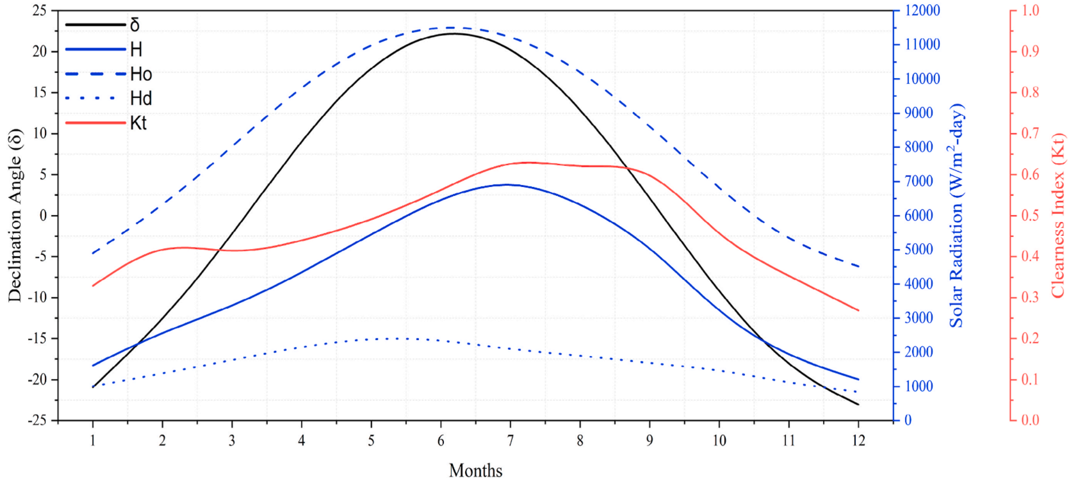

Fig. 4. Calculated and measure solar radiation variation of Ankara province.

agricultural land. If the system is to be installed for a seasonal work that should work with maximum efficiency, adjusting the tilt angle accordingly will provide serious economic contribution efficiency. In this direction, 8 different scenarios that can be encountered in the installation of AV systems are shown in Table 4. Models of PV panels under different scenarios M1: Annual average of different optimum angle values calculated according to months. M2: In this model, it is assumed that the highest efficiency of PV modules is equivalent to the latitude by many researchers [60]. M3: In this scenario, the APV system is created by positioning it above the ground to act as a horizontal roof. M4: By positioning PV panels close to the ground and vertically, it is aimed for agricultural vehicles to operate more functionally. M5: It was created by adapting the optimum angle value covering the months of December-January-February (winter) to the whole year. M6: It is the adaptation of the average optimum angle values of March-April-May (Spring) to the whole year. M7: It is the application of the average optimum angle value of the months June-July-August (Summer) to the whole year. M8: It was created by applying the average angle value of the September-October-November (Autumn) period to the whole year. Thus, the models evaluated under different scenarios were developed to increase the practical applicability of optimum slope angles. AC energy (kW.h), Value ($) and Solar Radiation (Wh/m^2/day) that can be produced for PV modules in different scenarios are simulated for Ankara region.

When the different scenario models are analysed, the highest performance is in the M1 model while the lowest rate is in M4. In the comparison between the panels, the highest value is in thin film for all cases, followed by premium and standard modules respectively. Fig. 7 shows the annual performance of different models and modules. The AC Energy (kWh) amount in this graph is highest in M1-Thin Film with 15674 kWh and lowest in M4-Standard with 9438 kWh. The highest and lowest yield of annual profit ($) are M1-Thin Film 1286 $ and M4-Standard 775 $, respectively. The efficiency comparisons of the models are based on the horizontal case ($\beta = 0°$) where the diffuse irradiance is measured. According to this situation, the highest efficiency gain is about 11.20 % at the optimum angle ($\beta = 31.33°$) and in the M1-Thin Film model, while the lowest efficiency is at the steep angle ($\beta = 90.00°$) and in the M4-standard case-33.00 % loss.

The performance of photovoltaic (PV) panels is impacted by various factors, namely the spectrum and intensity of incoming light, as well as the module temperature [61]. Except for scenario M4, thin-film panels exhibit superior performance in most cases owing to variations in temperature and spectrum levels during the seasons. For instance, in Ankara, the highest temperature at noon reaches approximately 28 °C during the summer season. This situation has a smaller impact on the performance of thin-film panels in comparison with crystalline-silicon [62]. Ankara's climatic characteristics (Csb) in the winter result in a reduction of the blue component of the spectrum (Air Mass 1.5) below the standard reference spectrum. Additionally, as the solar elevation angle decreases, and the distance travelled by radiation in the atmosphere increases, the light spectrum components begin to shift towards red (610–700 nm). This situation results in a greater power output in thin-film panels that are more responsive to the red wavelength in mid-latitude regions like Ankara. Research highlights that the efficacy of Thin-Film solar cells can increase by up to 4 % or decrease by up to 6 % compared to crystalline silicon solar panels, which tend to maintain more stability year-round [63].

3.2. LER capacity factor analysis

In the literature, the LER capacity of different agricultural crops has been investigated at constant annual inclination angles in experimental studies for APV system. These crops are shown in Fig. 8: Turmeric (Curcuma longa) inclination angle $\beta = 45°$ - Jatni (20.16° N, 85.70° E) India [64], Olive (Olea europaea) inclination angle $\beta = 45°$ - Cordoba (37.58° N; 4.18° W) Spain [65], Winter cabbage (*B. oleracea* var. capitata) inclination angle $\beta = 35°$ - Naju (34.58° N, 126.45° E) Korea [66], Kiwi Fruit (Actinidia chinensis) inclination angle $\beta = 28°$ - Chengdu, (30°19 N, 103.25 E) China [67], Corn (Zea mays) inclination angle $\beta = 30°$ - Chiba (35.37 N, 140°13 E) Japan [46], Lettuce (Lactuca sativa) slope angle $\beta = 25°$ - Montpellier (43.65° N, 3.87° E) France [15,48], bok choy (Brassica rapa subsp. Chinensis L.) slope angle $\beta = 36°$ - Chiang Mai (18.80° N, 98.98° E) Thailand [68]. The annual optimum angle values of the specified sample regions were determined by the Third-degree polynomial correlation ($R^2 = 0.9980$) model with only latitude

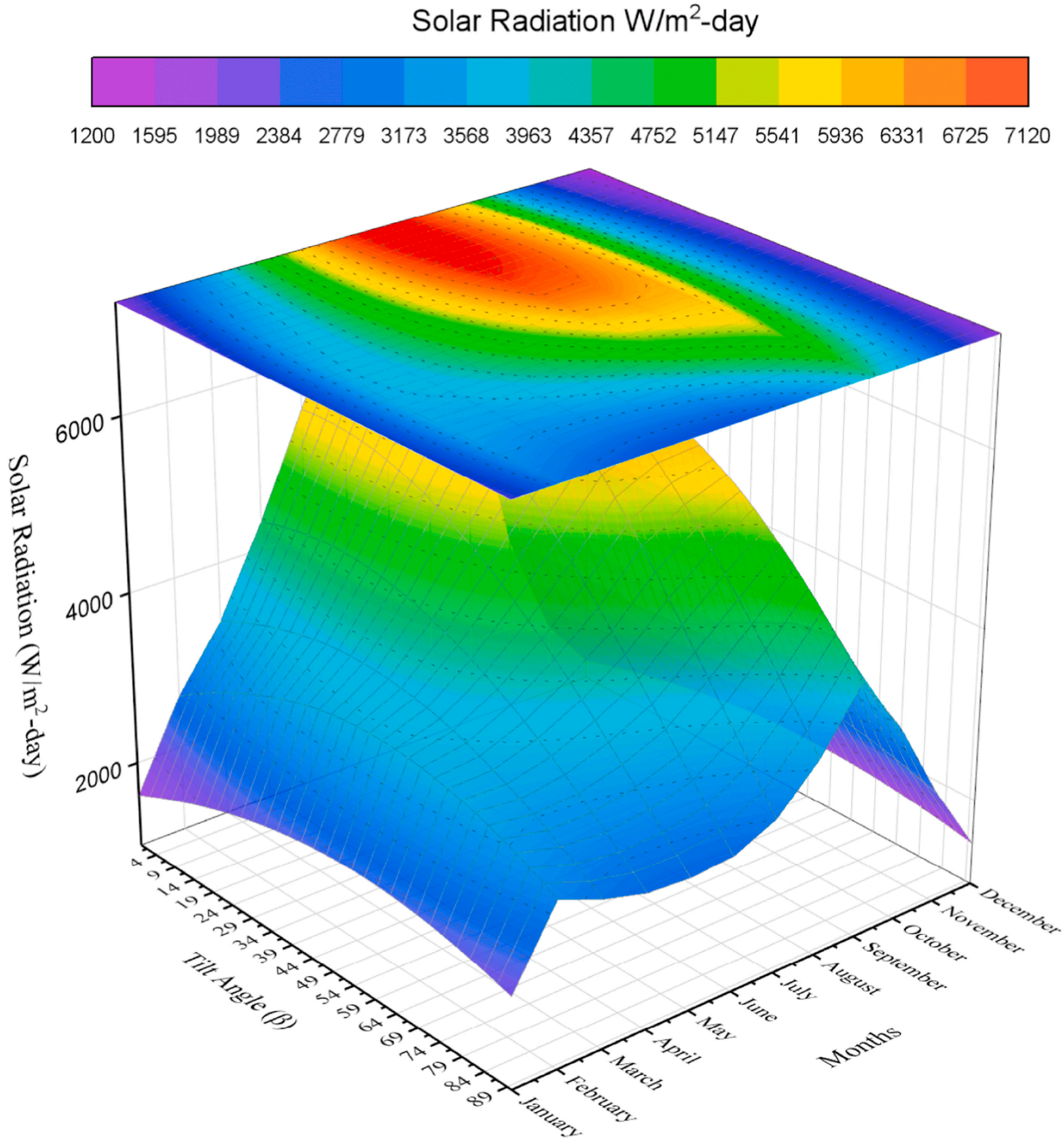

Fig. 5. Optimum panel angle for Ankara province.

values used in Ref. [17] and adapted to the eight different models in this study. Accordingly, the annual optimum angle values of the regions are; Jatni $\beta_{opt} = 22^\circ$, Cordoba $\beta_{opt} = 33^\circ$, Naju $\beta_{opt} = 30^\circ$, Chengdu $\beta_{opt} = 35^\circ$, Chibas $\beta_{opt} = 31^\circ$ Montpellier $\beta_{opt} = 39^\circ$, Chiang Mai $\beta_{opt} = 16^\circ$. In the calculations, the horizontal plane angle of 0° is taken as a reference and the annual fixed panel angle for 175 m^2 area is accepted for PV panel installation in APV system. Results were shown in Table 5.

The calculations were evaluated according to the first case M3 model. In this case, the best yield increase is M1 with 3.44 % for Turmenic, M1 with 6.08 % for Olive, M1 with 4.68 % for Winter cabbage, M1 with 4.54 % for Kiwifruit, M1-M2 with 4.54 % for Kiwifruit, M1 with 4.56 % for Corn, M1 with 5.66 % for Lettuce and M6 with 7.01 % for Bok Choy. For all cases, 90° angle M4 model has the highest yield loss compared to the first case.

3.3. Economic analysis

The power generation data of the APV system at different tilt angles were analysed using a techno-economic feasibility method. The analysis considered Turkey's current economic parameters, with an installed power capacity of “12.0 kW”, an electricity price of “0.082 $“, a project lifetime of “25 years”, and a real interest rate of “0.03”. The calculation of agricultural production in developing countries like Turkey excludes successive crops of various agricultural products grown in different climates throughout the year to avoid inconsistency. The analysis includes present (2023) and future (2035–2050) forecasts for standard PV panels (~19 %) at eight different tilt angles. Fig. 9 displays the NPV values for the selected models.

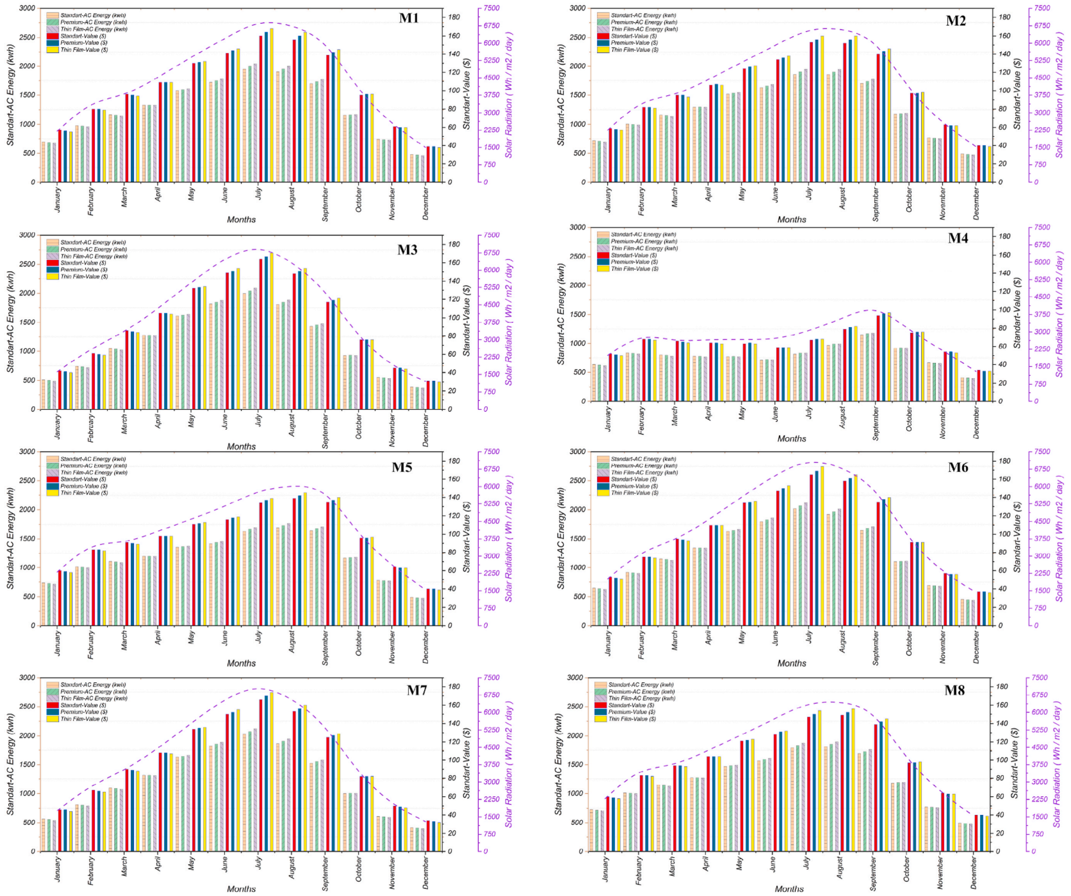

Fig. 6. Models and annual performance of PV panel.

Table 4
Models for different angle values.

Case	Description	Condition	Panel tilt angle (β)
M1	Optimum Slope	Whole Year	31.33
M2	Latitude	Whole Year	39.93
M3	Horizontal Plane	Whole Year	0
M4	Vertical Plane	Whole Year	90
M5	Winter Optimum Slope	Whole Year	55
M6	Spring Optimum Slope	Whole Year	20
M7	Summer Optimum Slope	Whole Year	7
M8	Autumn Optimum Slope	Whole Year	45

The analysis shows that the M1 model consistently yields the highest gain, followed by M6, M2, M8, M7, M5, M3 and M4 respectively. As of 2023, the DPBP value for the M1 model is 15.8 years, while the M4 model fails to meet the investment cost. By 2035, the DPBP value for the M1 model decreases to 7.8 years, while for the M4 model, it becomes 13.6 years. In 2050, the DPBP values are 5.4 years for the M1 model and 10.1 years for the M4 model. APV systems are generally more expensive than flat roof or ground mounted systems, resulting in a longer payback period. However, the long-term benefits such as increased crop yield, rainwater harvesting and crop profit are likely to result in a greater return at the end of the project.

Table 6 shows the calculation of IRR values (%) at the current 3 % real interest rate for sensitivity analysis with respect to varying CAPEX and OPEX values. In all cases, the best scenario is realized at the optimum panel tilt angle with the M1 model. Sensitivity analysis is used as a type of financial analysis to assess the sensitivity of the APV system to critical variables. This analysis is typically used to assess the impact of changes to different variables (interest rates, selling prices, costs, etc.) on the project's return. The worst case scenario is at 90° inclination angle in the M4 model and the IRR value of 2.9 % for 2023 is below the real interest rate, making it unfavorable for investment. This unfavorable situation shifts to a positive one for 2035 and 2050 thanks to decreasing production costs. In 2023, CAPEX and OPEX values decrease by 35 % compared to 2035 and thus IRR values increase by 104 %. The same can be seen from 2035 to 2050 when the cost decreases by 20 % and the IRR value increases by 25 %. Overall, the benefit of

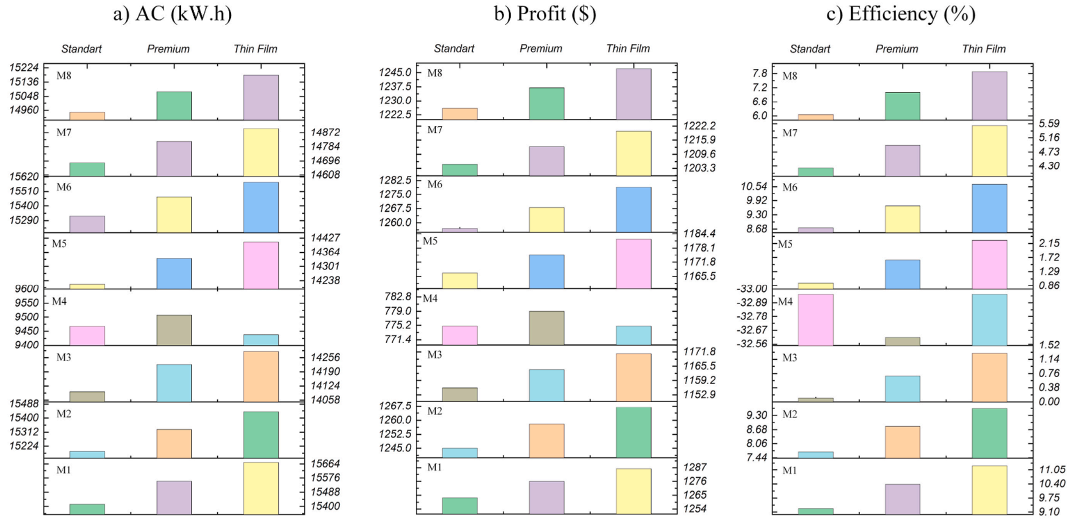

Fig. 7. Annual performance of the models a) AC (kW.h) b) Profit ($) c) Efficiency (%).

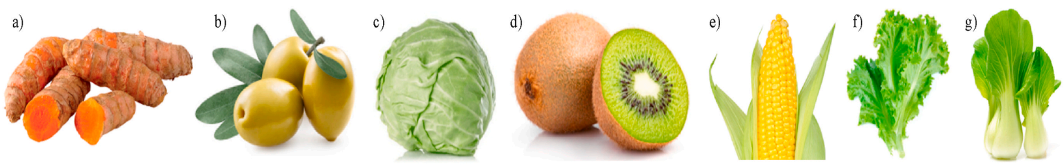

Fig. 8. Products of the LER factor analysed for Ankara; a) Turmenic b) Olive c) Winter cabbage d) Kiwifruit e) Corn f) Lettuce g) Bok Choy.

Table 5
Land equivent ratio values according to the created scenario.

Crop	APV Yield (kg/m^2)	M1	M2	M3	M4	M5	M6	M7	M8
Monosystem	0	1.09	1.08	1.00	0.67	1.01	1.09	1.04	1.06
Turmenic	0.73	1.80	1.75	1.74	0.70	1.55	1.83	1.79	1.69
Olive	0.47	1.57	1.56	1.48	1.20	1.51	1.56	1.52	1.55
Winter cabbage	0.91	2.01	1.99	1.92	1.52	1.92	2.00	1.96	1.97
Kiwifruit	0.97	2.07	2.07	1.98	1.76	2.02	2.06	2.02	2.05
Corn	0.96	2.06	2.05	1.97	1.62	1.98	2.05	2.01	2.03
Lettuce	0.58	1.68	1.68	1.59	1.46	1.65	1.66	1.62	1.67
Bok Choy	0.13	1.11	0.97	1.14	0.25	0.52	1.22	1.21	0.83

the IRR values for panel inclination angles is more apparent in 2023 when the initial investment cost is high. As costs decrease, the NBD earnings return becomes more similar across the models. This situation shows us that APV plants can be concluded as systems that will provide high earnings in the next 30 years and beyond.

4. Conclusion and discussion

Agrivoltaic system offers an alternative approach to the competition of land resources between food and energy production. With this system, it is possible to use limited resources more efficiently. In this study, a possible Agrivoltaic system with a DC load capacity of 12.5 kW h has been analysed in the mid-latitude "Csb" climate zone. The findings obtained from these analyses are as follows:

1. The optimum annual slope angle value for Ankara province is determined as $\beta_{opt} = 31.33^\circ$. In winter, spring, summer and autumn seasons, this angle value is 55°, 20°, 7°, and 45°, respectively. The lowest and highest angle values are 0° in June and 56° in January, respectively.
2. The efficiency increase calculated according to the optimum angle value is 19.2 %. In winter, spring, summer and autumn seasons, the yield increases by 40.1 %, 6.1 %, 1.1 %, and 29.6 %, respectively.
3. The highest performance is M1 model-thinfilm with an annual financial gain of $1286 and AC electricity generated of 15674 kWh. The lowest performance is M4 model-thinfilm, with a financial gain of $775 and AC electricity generated of 9438 kW h.
4. In all scenarios, except for the M4 model, the thinfilm panel has the highest performance, followed by the premium and standard models respectively.

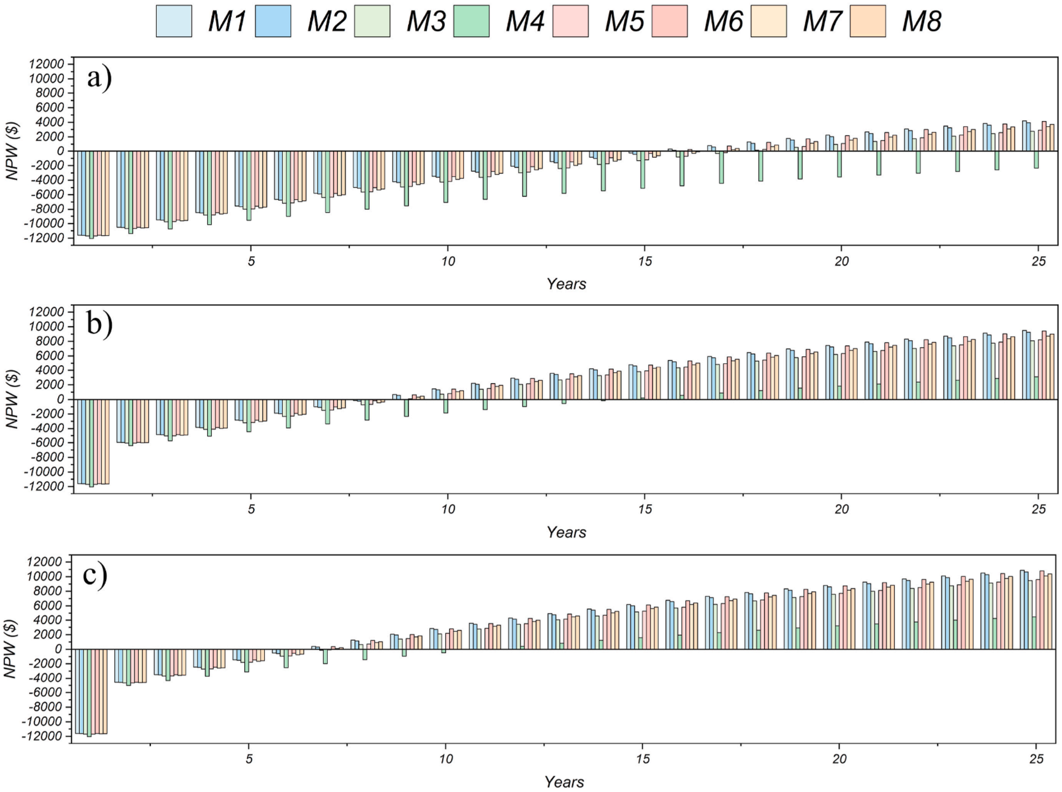

Fig. 9. Variation of NPW values according to scenarios a) 2023, b) 2035, c) 2050.

Table 6
IRR values (%) under different initial investment costs.

Years	M1	M2	M3	M4	M5	M6	M7	M8
2023	8.1	7.9	7.1	2.9	7.2	8	7.5	7.7
2035	16.6	16.3	15	9.3	15.2	16.5	15.7	16
2050	20.8	20.5	19	12.2	19.2	20.7	19.8	20.2

5. When the Land Equivent Ratio values of the agro-voltaic system are analysed, the highest capacity factor is M1 model with "Kiwifruit" and the lowest factor is M4 model with "bokchoy". The LER capacity factor range varies between 2.07 and 0.25.
6. It diversifies regular income streams for farmers, minimising fluctuations in food and energy prices and reducing costs.
7. This study supports indexes 2, 7 and 13 of the United Nations Sustainable Development Goals to 2030.
8. In the best case scenario, the DPBP value for standard, premium, and thin film are 15.8, 15.3, and 14.6 years for 2023. For 2035, these values are 7.7, 7.3, and 6.8, and for 2050, they are 5.4, 5.2, and 5.1, respectively.
9. The IRR values (%) were evaluated using the best model (M1). In the high-cost period (2023), the values were 8.1, 8.3, and 8.8 for standard, premium, and thin film, respectively. In the medium-cost period (2035), the values were 16.2, 16.6, and 17.7, respectively. For the low-cost period (2050), the values were 20.8, 21.3, and 22.1, respectively. The IRR difference between PV panels is within acceptable limits.
10. The analysed values can be used in the central Mediterranean region of similar latitude and climatic conditions (Csb) and in different regions of the world. The main ones are Portland in USA, Braga in Portugal, Valladolid in Spain, Terni in Italy and Žabljak in Montenegro.

More advanced systems can be designed to increase the efficiency of APV systems;

- The tilt angle of the PV modules can be varied using automated systems so that shading is minimised during the germination phase to avoid inhibiting the growth of crops and then the PV modules can tilt back to the optimum tilt angle.
- The partial shading offered by PV arrays can help protect temperature-sensitive crops from excessive heat.
- Cultivated crops can reduce the temperature rise in the PV panels, resulting in higher electrical energy yields.

There is a need for further studies in this area and significant future research with simulations or experimental findings based on crop morphological characteristics such as photosynthetically active radiation (PAR), angle of inclination and row spacing of the panels, soil temperature and moisture, etc. for an optimum balance between PV power output and crop growth worldwide. Overall, the APV system offers a promising solution to the intense competition for land resources between food and energy production.

CRediT authorship contribution statement

Mehmet Ali Kallioğlu: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Ali Serkan Avcı:** Methodology, Writing – review & editing. **Ashutosh Sharma:** Formal analysis, Investigation, Writing – review & editing. **Rohit Khargotra:** Methodology, Writing – review & editing. **Tej Singh:** Conceptualization, Methodology, Writing – 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".

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2024.103998.

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