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THE AGRIVOLTAIC POTENTIAL OF TÜRKİYE

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ABSTRACT

Agrivoltaic systems, also known as agrivoltaics, represent an innovative approach that combines agricultural activities with solar energy production on the same land. This concept emerged as a solution to the increasing demand for land for food production and the increasing demand for land for energy production. It is also a fact that greenhouse gas emissions will decrease with the increase in agrivoltaic systems and therefore with the increase in clean energy production. This study measures the agricultural potential of Türkiye by region using 1% of Türkiye's farmland, according to TUIK data. In two different PV systems modeled, single-array systems and single-axis tracking configurations will be used. It will also enable the traditional farming of crops (and potentially increase efficiency). The results of the study determined that 398 GWh of electricity would be produced in the single array system and 445 GWh in the single-axis tracking system. As a result of these results, not only can Türkiye meet all of its electrical energy needs in 2023, but also 20.7% and 34.8% more in single array and single-axis tracking systems, respectively, can be provided by agrivoltaics using only 1% of the existing agricultural lands. These results show that agrivoltaics can make a significant contribution to sustainable electricity production and provide the ability to reduce/purify greenhouse gas emissions associated with the Turkish energy production sector.

Keywords: Agrivoltaic, Türkiye, Photovoltaic, Agriculture, Solar energy, Renewable energy.

1 INTRODUCTION

Agrivoltaic, the practice of co-locating agricultural and solar energy systems, maximizes land use efficiency and sustainability, offering a dual-use approach where both food and energy can be produced simultaneously, leading to mutual benefits for agriculture and the energy industry [1]-[3]. Research has shown that agrivoltaic systems can increase land productivity by up to 60-70% [2]. Agrivoltaics combines solar energy production with agricultural activities, creating a mutually beneficial relationship in which both food and energy production can occur simultaneously [4]. This dual-use approach not only optimizes land but also provides additional benefits, such as stabilizing crop production, reducing land occupation, and reducing greenhouse gas emissions [5]-[7].

Eastern Pyrenean region of France (2.2 MWp), Castelvetro Piacentino region of Italy (1.3 MWp) and Monticellid'Ongina region (3.2 MWp), Babberich of the Netherlands (2.7 MWp), Jodhpur of India in (105 kWp / Ground-mounted), in Austria (22 kWp / bifacial PV), in Aasen of Germany (4.1 MWp / bifacial PV) applications such as are available [5].

In addition, studies have highlighted the potential of agrivoltaics in various regions, including Europe [8], Canada [9], India [10] and the United States [11]. Agrivoltaic systems have been found to increase crop yields, increase economic productivity, and support the mainstream market for solar energy systems [12].

The integration of agrivoltaic systems involves installing solar panels on farmland to generate electricity while also allowing agricultural activities to be carried out under or around the panels [13]. This approach not only helps transition to renewable energy but also helps reduce land competition, irrigation requirements, and increase solar panel efficiency [14]. Agrivoltaics have the potential to increase land productivity and efficiency by offering a strategic way to combine solar energy production with agricultural production [15].

The integration of photovoltaics into agricultural frameworks such as greenhouses has emerged as a research focus to increase food production and renewable energy production [16]. Agrivoltaics not only contribute to meeting global commitments and increasing clean energy production but also offer employment opportunities, economic stability, and conservation of natural resources [10]. Additionally, the development of agrivoltaic standards, regulations, and incentives could accelerate the adoption of this technology over traditional PV systems [17].

As a result, agrivoltaics represents a strategic and innovative approach to sustainable land use that combines the benefits of agriculture and solar energy production. Leveraging the synergy between food and energy production, agrivoltaics has the potential to address the challenges of land competition and contribute to a more sustainable future. There are very few applications in the world regarding agrivoltaics. There is no application yet in our country.

2 MATERIAL AND METHOD

This study was carried out to determine the agrivoltaic potential in Türkiye by using 1% of the existing agricultural lands in Türkiye. It was thought that it should not be used in this area to ensure the protection of meadow and pasture lands. Excluding meadow and pasture lands from Türkiye's agricultural areas, the remaining agricultural lands are given in Table 1, and their distribution by region is shown in Figure 1. Calculations will be made using these fields.

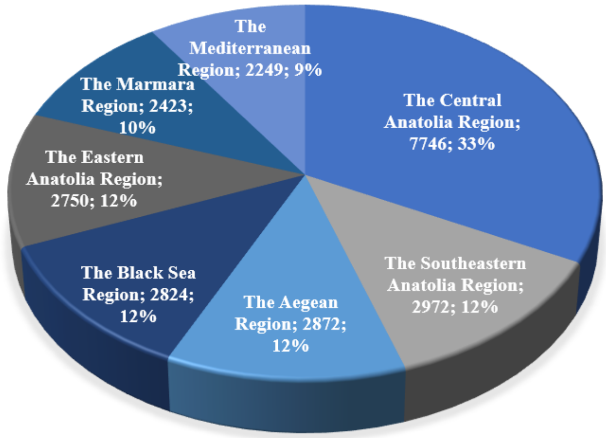

Figure 1. Distribution of Türkiye agricultural lands by regions in 2022 (Thousand Ha) [19].

Table 1. Agricultural areas of Türkiye (Thousand Ha) [18].

Years	Total agricultural area*	Cereals and other plant products area		Vegetable gardens area	Ornamental plants area	Fruits, beverages and spice plants area
		Cultivated area	Fallow			
2018	23180	15421	3513	784	5.2	3457
2019	23099	15398	3387	790	5.2	3519
2020	23145	15628	3173	779	5.4	3559
2021	23473	16062	3059	755	5	3591
2022	23865	16510	2960	718	6	3671

**Meadow and pasture land are excluded in the total agricultural area calculation.*

Türkiye has a significant solar energy potential due to its geographical location. According to the Türkiye Solar Energy Potential Atlas (GEPA) prepared by the Energy Ministry, the average annual total sunshine duration is 2741 hours, and the average annual total radiation value is calculated as 1527.46 kWh/m^2. The general potential view, monthly average global radiation distribution, and sunshine duration values in GEPA are shown in Figure 2. [20], [21].

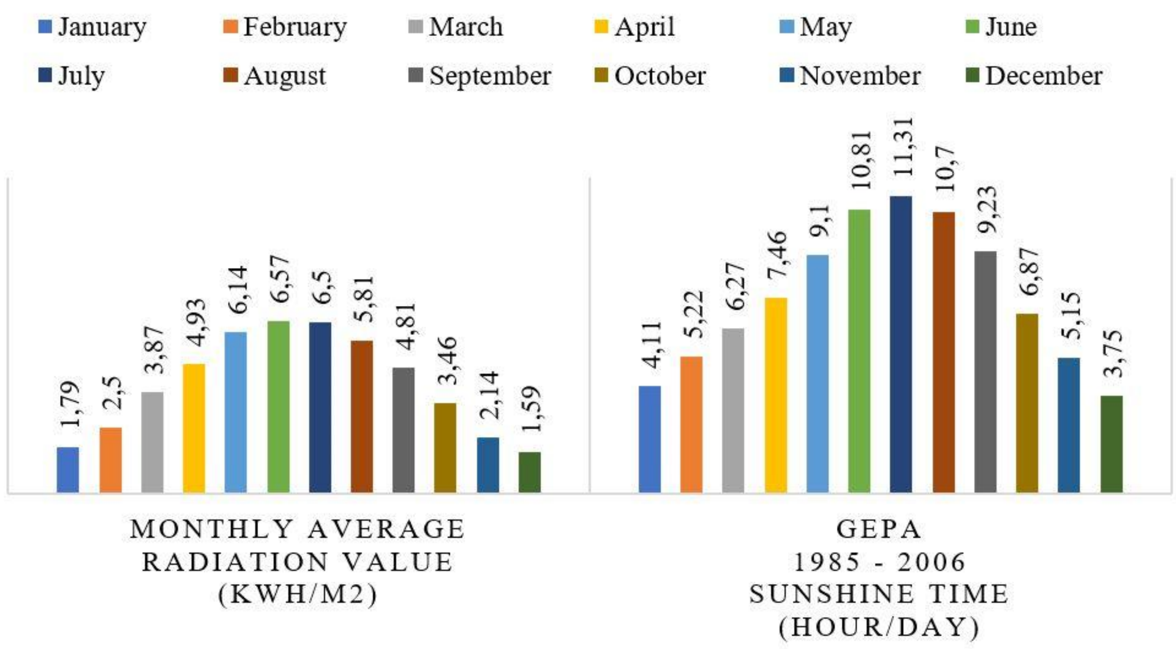

Figure 2. Average solar energy potential per month of Türkiye [21].

The distribution of Türkiye's annual total solar energy potential according to geographical regions is shown in Table 2 [21]. The region that receives the most solar energy in Türkiye is the Southeastern Anatolia Region, followed by the Mediterranean Region.

In the study, the appropriate location was determined for each region, taking into account the distribution of Solar Energy Potential according to regions given in Table 2. These accepted locations are marked on the map in Figure 3. Additionally, details for each region are given in Table 3. The PV section of the Agrivoltaic system to be designed uses Meteonorm 8.1 (2005-2013) climate values of these locations (Table 3).

Table 2. Distribution of Türkiye's annual total solar energy potential by geographical regions.

Area	Sunshine Time (hour/year)	Total Solar Energy (kWh/m^2-year)
The Southeastern Anatolia	2993	1460
The Mediterranean	2956	1390
The Eastern Anatolia	2664	1365
The Central Anatolia	2628	1314
The Aegean	2738	1304
The Marmara	2409	1168
The Black Sea	1971	1120

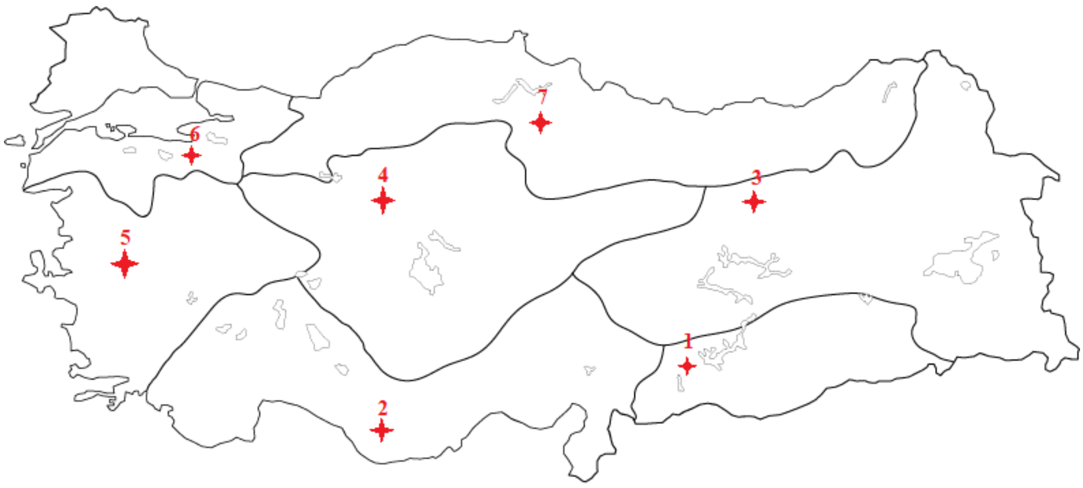

Figure 3. Geographical regions of Türkiye [22].

Table 3. Geographical locations of the Agrivoltaic systems to be designed.

	Geographic Region	Selected Region		Meteonorm Solar Energy (kWh/m^2-year)
		City / District / Location	**Latitude, longitude, altitude**	
1	The Southeastern Anatolia	Gaziantep / Nizip / Çanakçı	37.12ºN, 37.72ºE, 729m	1904.2
2	The Mediterranean	Mersin / Anamur / Kılıç	36.24ºN, 32.77ºE, 769m	1848.9
3	The Eastern Anatolia	Erzincan / Kemah / Kömürköy	39.65ºN, 39.02ºE, 1075m	1819.1
4	The Central Anatolia	Ankara / Sincan / Temelli	39.75ºN, 32.33ºE, 792m	1702.9
5	The Aegean	Manisa / Kula	38.56ºN, 28.66ºE, 860m	1745.3
6	The Marmara	Bursa / Osmangazi / Tuzaklı	40.11ºN, 28.99ºE, 888m	1563.0
7	The Black Sea	Amasya / Merzifon / Aksungur	40.91ºN, 35.51ºE, 885m	1496.2

As the area of interest of this study, 1% of agricultural land was calculated for each region in Türkiye. For the configuration of PV systems on this land, it was designed to be installed on an area of 20m X 500m = 10000 m^2/1 Hectare (1 Ha). The production amount of the agrivoltaic PV system to be installed on an area of 1 Ha was calculated with the PVsyst 7.4 program. The PV production of that region was determined by the proportion of the area corresponding to 1% of the agricultural area calculated for each region. Then, the annual energy production and total agrivoltaic potential for Türkiye was determined. PVsyst 7.4 program and Meteonorm 8.1 climate data, which is a sub-module of this program, were used to determine solar energy electricity production.

The majority of solar power plants installed on land are built permanently. At the same time, efficiency studies aimed at increasing energy production have also come to the fore in recent days. Increasing production efficiency can only be achieved by increasing the radiation intensity falling on the panel. As long as sunlight falls on the modules at a right angle, production is maximized. This is possible with a system that tracks the sun and ensures that the sun's rays are constantly received vertically. In this study, two different agrivoltaic systems, one of which is a single array as a PV system and consists of a single-axis tracking system to increase efficiency, were taken into consideration for analysis. 50 arrays were placed for 500m, with the distance between arrays being 10m. In the PVsyst analysis, it was determined that a 10m distance was sufficient for shading tests. Shading loss tests were carried out separately for each region, and as a result, the shadowing on the panel for a distance of 10m occurred before 9.00 am and after 5.00 pm. This is an expected situation that does not have a negative impact on the efficiency of the PV system. In addition, the distance between single array PV system arrays in System-1 is 10m, which provides easy access to agricultural lands as well as ease of use of agricultural machines. A single-axis tracking (horizontal, 0° inclined, East-West axis tracking) system was designed as System-2. On the electricity side, single-axis tracking systems are used to obtain maximum solar energy per unit area. Having a distance of 10m between the arrays also gave suitable shading results for System-2. System-2 also offers an option for vertical orientation of the panels so that farmers can work on agricultural lands.

The array spacing on the piece of land was determined separately for both systems, ensuring sufficient distance for the mobility of the agricultural equipment and taking into account the distances between the panels shading each other. Once the array spacing was determined, the total number of panels in an area was determined using the number of single array and single-axis tracking arrays. As a result of all these assumptions and designs, for an area of 1 Ha (10000 m^2), in System-1, there are 50 arrays of Panasonic brand AE14-H550-VHC-10B modules with 4x9=36 panels in each array, a total of 1800 pieces. In System-2, there are 36 Panasonic brand AE14-H550-VHC-10B modules in each array. Again, a total of 1800 panels were used in 50 series. As an inverter, 8 units of the SUN2000-100KTL-M1 brand inverter from Huawei Technology were used, calculated according to the system's needs. The panel placement on the land is given in Figure 4, and the technical specifications of the panel and inverter used in the system are given in Table 4.

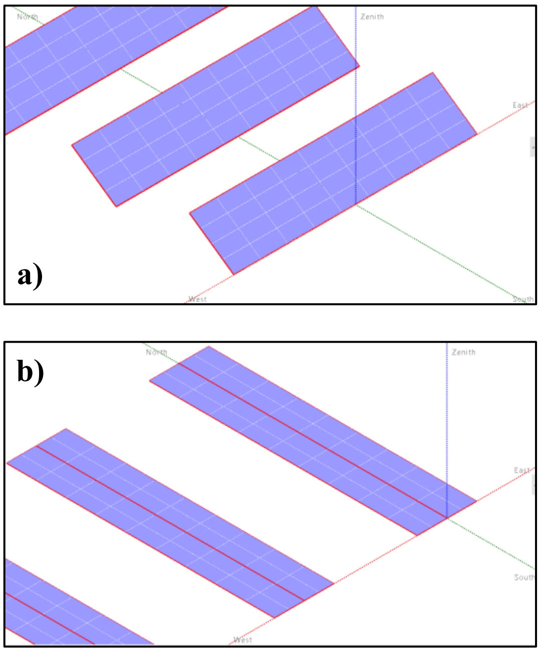

Figure 4. Panel layout (a) System-1, (b) System-2.

Table 4. Features of system components.

PV Modul	**Technical Specifications**
Modul (Panasonic)	AE14-H550-VHC-10B
Prod. Since	2024
Modul power	550 Wp
Modul size (WxL)	1.133 x 2.278 m^2
Open circuit voltage (Voc)	50.3 V
Max. Power voltage (Vmpp)	42.1 V
Short-circuit current (Isc)	13.65 A
Max. power point current (Impp)	13.06 A
İnverter	Technical Specifications
İnverter (Huawei)	SUN2000-100KTL-M1-480 Vac
Prod. Since	2021
Max. Efficiency	98.8%
MPPT Operating Voltage Range	200 V ~ 1000 V
Max. Input Voltage	1100 V
Maximum AC Power (Pmax AC)	110 kWac
Maximum AC current (Imax AC)	134 A

3 RESULTS AND DISCUSSION

3.1 The Southeastern Anatolia Region

The Southeastern Anatolia Region is the region with the greatest potential in terms of solar energy potential and sunshine duration. In this region, in the Nizip District of Gaziantep Province, Çanakcı district, 37.12ºN, 37.72ºE, 729m, was located closest to the region's sunshine potential average. The total agricultural area of the Southeastern Anatolia Region is 2972000 Ha, and the results of the calculations regarding the electrical energy production to be obtained from the agrivoltaic system to be established on an area of 29720 Ha, corresponding to 1% of this area, are given in Table 5.

Table 5. The Southeastern Anatolia Region agrivoltaic potential for 1% of agricultural land.

	Single Array (GWh/year)	**Single-Axis Tracking (GWh/year)**
Unit area ($10000\ m^2 = 1$ Ha)	1.825	2.218
1% agricultural area (29720 Ha)	54239	65919

3.2 The Mediterranean Region

Agrivoltaic system for the Mediterranean region was planned Kılıç location, located at 36.24ºN, 32.77ºE at an altitude of 769m, within the borders of Anamur District of Mersin province. The values obtained are given in Table 6 by the implementation of PVsyst program calculations to 1% of the area's agricultural area size of 2249000 Ha.

Table 6. The Mediterranean Region agrivoltaic potential for 1% of agricultural land.

	Single Array (GWh/year)	**Single-Axis Tracking (GWh/year)**
Unit area ($10000\ m^2 = 1$ Ha)	1.746	1.917
1% agricultural area (22490 Ha)	39268	43114

3.3 The Eastern Anatolia Region

The Eastern Anatolia Region is mountainous and has a higher elevation than other regions. For this region, it is planned to establish an agrivoltaic system at 39.65ºN, 39.02ºE, and 1075m altitude within the borders of the village called Kömürköy in Kemah District of Erzincan province. The Eastern Anatolia Region has an agricultural land of 2750000 Ha. In most of this land are cultivated cereal products such as barley and wheat, which are resistant to cold and arid climate conditions. In addition, legumes, sugar beets, fruits, and vegetables are also grown. The annual electrical energy to be provided by an agrivoltaic system that can be established on 1 Ha land in the region called Kömürköy has been determined for both a single array and solar tracking system power plant. The energy to be provided from 1% of the agricultural lands in the Eastern Anatolia region is given in Table 7 as a result of the calculations.

Table 7. The Eastern Anatolia Region agrivoltaic potential for 1% of agricultural land.

	Single Array (GWh/year)	Single-Axis Tracking (GWh/year)
Unit area (10000 m^2 = 1 Ha)	1.821	2.005
1% agricultural area (27500 Ha)	50077	55137

When Table 2 of the Distribution of Annual Total Solar Energy Potential by Regions is examined, the Eastern Anatolia Region ranks 3rd. However, as a result of the calculations, it produces more than the Mediterranean Region, which ranks 2nd. This situation is thought to be due to the fact that the altitude of the region chosen for agrivoltaic system planned to be established in the region is 1075m. As the ambient temperature decreases with increasing altitude, panel temperature will also decrease. Thus, panel efficiency will increase.

3.4 The Central Anatolia Region

The Central Anatolia Region is the largest region of Türkiye, both in surface area and the size of agricultural lands. It has an agricultural area of 7746000 Ha. In these areas, a wide variety of agricultural products are grown, primarily wheat and barley. For the agrivoltaic system to be established, this region, a location with an altitude of 39.75ºN, 32.33ºE, 792m Temelli, within the borders of the Sincan district of Ankara province, was chosen. The values of the electricity production to be obtained from 1% of the agricultural land, based on the agrivoltaic system to be established for 1 Ha of land and the production of this system, are given in Table 8.

Table 8. The Central Anatolia Region agrivoltaic potential for 1% of agricultural land.

	Single Array (GWh/year)	Single-Axis Tracking (GWh/year)
Unit area (10000 m2 = 1 Ha)	1.671	1.840
1% agricultural area (77460 Ha)	129435	142526

3.5 The Aegean Region

A location within the borders of Manisa province was determined for the Aegean region, which forms the western coast of Türkiye. The production amounts obtained from the PVsyst program of an agrivoltaic system to be built on a 1 Ha area at 38.56ºN, 28.66ºE, and 860m altitude in Kula district of Manisa province are shown in Table 9.

Table 9. The Aegean Region agrivoltaic potential for 1% of agricultural land.

	Single Array (GWh/year)	**Single-Axis Tracking (GWh/year)**
Unit area (10000 m^2 = 1 Ha)	1.686	1.855
1% agricultural area (28720 Ha)	48422	53276

3.6 The Marmara Region

For the agrivoltaic system planned to be established in the Marmara Region, a location at 40.11ºN, 28.99ºE and 888m altitude in the Tuzaklı village of Osmangazi district of Bursa province was chosen. Electricity production estimates to be obtained from the single array system and single-axis tracking system for the region are given in Table 10.

Table 10. The Marmara Region agrivoltaic potential for 1% of agricultural land.

	Single Array (GWh/year)	**Single-Axis Tracking (GWh/year)**
Unit area (10000 m^2 = 1 Ha)	1.496	1.651
1% agricultural area (24230 Ha)	36248	40004

3.7 The Black Sea Region

The Black Sea Region, which has the lowest data on sunshine potential and sunshine duration, ranks 3rd in terms of agricultural lands. The region with high rainfall has high mountain ranges running parallel to the coastline. The majority of agricultural areas are formed on tea and hazelnuts on the slopes of this mountain range. There are various plains in the western and central parts and traditional agriculture can be done. For the calculations to be made for the Black Sea region, a location of 40.91ºN, 35.51ºE and 885m altitude was determined in Aksungur village of Merzifon district of Amasya province. The results are given in Table 11.

Table 11. The Black Sea Region agrivoltaic potential for 1% of agricultural land.

	Single Array (GWh/year)	**Single-Axis Tracking (GWh/year)**
Unit area (10000 m^2 = 1 Ha)	1.455	1.607
1% agricultural area (28240 Ha)	41089	45382

As a result of calculations separately for each region, the amount of electricity production to be obtained by applying agrivoltaic systems to 1% of Türkiye's agricultural lands is given in Table 12.

Table 12. Agrivoltaic potential of Türkiye for 1% of agricultural land.

Area	**Single Array (GWh/year)**	**Single-Axis Tracking (GWh/year)**
The Southeastern Anatolia	54239	65919
The Mediterranean	39268	43114
The Eastern Anatolia	50077	55137
The Central Anatolia	129435	142526
The Aegean	48422	53276
The Marmara	36248	40004
The Black Sea	41089	45382
Total	398778	445358

The amount of electricity production to be obtained by applying agrivoltaic systems to 1% of Türkiye's agricultural lands was calculated in single array and single axis tracking systems at 398778 GWh and 445358 GWh, respectively. In the data of the Ministry of Energy and Natural Resources of the Republic of Türkiye, Türkiye's electrical energy consumption was reported as 330300 GWh in 2023. With these results, the electrical energy obtained from agrivoltaic systems covers Türkiye's consumption by 120.7% in the single array system and 134.8% in the single-axis tracking system. Contribution to the country's economy can be made by selling excess electrical energy produced from agrivoltaics, which has the potential to meet all of Türkiye's electricity needs in the first years. In addition, it is inevitable that the energy need will increase with the increasing population. The excess energy produced can be used to meet the increasing energy demand in the coming years. Thus, problems arising from energy increase and most importantly, foreign dependency in energy will be prevented in the coming years.

4 CONCLUSION AND SUGGESTIONS

This study estimated the agrivoltaic potential in Türkiye using agricultural areas 1% with single array and single-axis tracking system configurations for PV modules. Only 1% of Türkiye's agricultural lands can meet all of the country's total electricity needs. In fact, it has the potential to generate excess electricity, with 20.7% in the single array system and 34.8% in the single-axis tracking system. Overproduced electricity can be sold or used in other areas within the country. The number of electric vehicles in transportation is expected to increase day by day. Agrivoltaics can supply production for use in electric vehicle charging to decarbonize transportation in Türkiye. Finally, it could help Türkiye eliminate its dependence on fossil fuels.

Türkiye has many varieties of agricultural products that can be grown in full shade and semi-shade environments. Various studies have proven that growing these products under agrivoltaic systems contributes to increased product productivity. It has been reported that production losses due to panel heating decrease and system efficiency increases in solar power plants installed on agricultural lands. Agrivoltaics, which is an agriculture-energy system gains can be achieved in both directions.

It is very difficult to reserve 1% of agricultural lands for agrivoltaics and to implement power plants on a single land. This will lead to the establishment of power plants at various scales depending on land suitability and to increase the number of power plants. Although it may seem like a limitation at first glance, increasing the number of power plants and spreading them to different locations will reduce some problems, especially transmission and distribution losses.

When we evaluate agrivoltaics with all these results, agrivoltaic technology reveals a significant potential for Türkiye's efforts to produce renewable energy and reduce greenhouse gases.

Our country legally restricts the installation of solar power on agricultural lands that do not qualify as marginal agricultural land. It has been determined by various studies that agrivoltaic systems do not harm agricultural lands and increase crop yield when appropriate designs are made. Additionally, energy production is also carried out. Considering all these positive aspects, legal regulations can pave the way for the installation of agrivoltaic systems on agricultural lands. A great contribution will be made to Türkiye reaching its green energy target.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that all the rules required to be followed within the scope of "Higher Education Institutions Scientific Research and Publication Ethics Directive" have been complied with in all processes of the article, that BEU Journal of Science and the editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than BEU Journal of Science.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the author.

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