Journal of Applied Mathematics and Physics, 2024, 12, 4274-4290
https://www.scirp.org/journal/jamp
ISSN Online: 2327-4379
ISSN Print: 2327-4352

Heliostat Design and Calculations with an Algorithm Developed on Heliostat in Adana

Mahpeyker Kocakoç Toprakoğlu

Department of Computer Technologies, Çukurova University, Adana, Türkiye
Email: mkocakoc@cu.edu.tr

How to cite this paper: Kocakoç Toprakoğlu, M. (2024) Heliostat Design and Calculations with an Algorithm Developed on Heliostat in Adana. *Journal of Applied Mathematics and Physics*, **12**, 4274-4290.
https://doi.org/10.4236/jamp.2024.1212262

Received: October 30, 2024
Accepted: December 28, 2024
Published: December 31, 2024

Abstract

Solar energy is also a major renewable energy source that is clean and can be sustained at a minimum cost. CSP systems are another highly developed solar energy system that is environmentally friendly and can be installed with simple technology and rational cost. PV solar panels generate electric power when sunlight exists. Similarly, CSP system also generates electric power for immediate consumption when there is sunlight, but it also stores some of the solar energy as heat to be able to continue generating electric power when the weather is cloudy or during the night. In this study, an algorithm and software for effective heliostat were developed. Six districts were selected in Adana province to design and calculate solar power received by heliostat mirrors and delivered to the heat exchanger on top of the tower. Because a solar tracking mechanism is necessary for correct and instant orientation of mirrors, the developed software can calculate the orientation angles of each mirror at any moment of a day of the year. The algorithm also calculates the power received by PV solar panels with fixed orientation and with the same surface area as those of mirrors to compare the energy yields.

Keywords

Concentrating Solar Power, CSP, Heliostat, Photovoltaic

1. Introduction

Today, fossil fuels are the most used energy source. However, in addition to the very serious damage that they cause to the environment at the end of long-term use, these resources cannot be found everywhere and impose a lot of financial burden on energy-importing countries such as Türkiye. For these and many other reasons, the need for new energy sources is increasing. At this point, renewable energy sources come to the fore with their environmentally friendly and sustainable features. As renewable energy sources, primarily solar, wind, hydroelectric, biomass, geothermal, and hydrogen can be shown.

Concentrated solar power (CSP) systems, which generate electricity from solar energy and whose technology is developing day by day, stand out as an alternative technology. CSP systems are electricity generation facilities that do not require high technology and can be developed and produced by using known technologies. A CSP system mainly consists of heliostat, which consists of mirrors that collect the solar radiation at one point, heat exchangers, insulated molten hot material tanks, and turbine-generator pairs.

CSP systems can be applied in any sunny area. The lands on which the CSP system will be installed should be ecologically insignificant, barren, decertified, or non-farming lands with a tendency to desertification. In addition to instantaneous electricity generation performed when there is sunlight, CPS systems can use the stored heat energy to generate electricity when there is no sunlight. Thus, it can be considered an uninterrupted energy production facility. Although the initial facility costs of these systems may be high, their operating cost is low. CSP systems are safe and environmentally friendly, and if regularly maintained, they have a long life. They do not require any additional fossil fuels, do not leave any harmful waste to the environment, and do not emit harmful or greenhouse gases into the air.

Although their operational structures and the magnitudes of the energy they produce are different, CSP systems are used in many countries such as the USA, Spain, Morocco, China, and India. Especially after the 2000s, CSP systems that produce very high power have been developed and continue to be developed. Türkiye's first CSP system with a power of 5 MW was installed in Mersin in 2013. However, although the southern regions of Türkiye are very suitable for the installation and operation of these systems, and although there is a need for them, the number of these facilities is low in Türkiye and especially in the southern regions of the country.

Scientific studies and publications on the CSP systems began to intensify in the 1980s [1]. The first commercial solar power collector systems were trough-type collectors with parabolic sections. [2] investigated the conversion of solar energy into electrical energy via a thermal system with a 50 MW parabolic trough collector. In the following periods, the CSP systems have become widespread, and many studies have been conducted on them [3]-[18].

In this context, it can be said that Türkiye has been quite late in using the CSP system, which is an alternative system for utilizing solar energy, although there are quite suitable geographical regions for the installation of CSP systems in the country and although it has the capacity and technology to produce these systems with purely domestic facilities.

In this study, with an algorithm created and software developed, heliostat designs were made for the lands determined in Yumurtalık, Tufanbeyli, Karaisalı, Karataş, Aladağ, and Pozantı districts and towns of Adana province, which is located in the south of Türkiye and receives plenty of sunlight. With this software, inputs such as the latitude-longitude coordinates of the selected land, dimensions, tower height, slope of the land, the positions of the mirrors in the field, their numbers, the orientation of the mirrors for every day of the year and every hour of the day, and the collected power values can be calculated.

2. Material and Method

2.1. Concentrated Solar Energy (CSP) Systems

CSP systems stand for concentrated solar energy. It is defined as an energy production method used to reach high temperatures and high energy conversion efficiencies by increasing the flux density of sunlight and thus obtaining thermal energy [19].

According to the estimate of the International Energy Agency (IEA), the global installed capacity of CSP will reach 261 GW [20] by 2030, while the global installed capacity of PV will reach 1721 GW [20].

The CSP system consists of a heliostat and tower, heat exchangers, insulated molten hot material tanks used for heat storage, a turbine, and generator pair. The heliostat, which is the subject of this study, consists of a tower and many mirrors that instantly monitor the Sun around the tower and collect its radiation in the heat exchanger located at the top of the tower. The placement and orientation of the mirrors are based on the Fresnel lens theory; that is, it is the mirror system formed by moving a large paraboloidal concave mirror to the plane by using the Fresnel method [9] [21]-[23] **Figure 1** shows two different heliostat structures in a field. Solar radiation focused on the heat exchanger at the top of the tower increases the temperature of the heat storage material and the emerging heat is sent to the insulated heat storage tanks. After that, electricity is generated in the steam turbine and generator by evaporating the water in a second heat exchanger. **Figure 2** illustrates the structure and operation of a CSP system as an example.

Tower at the southern boundary of the heliostat. Each of the mirrors that constitute the heliostat should be directed in such a way that they can focus the Sunlight momentarily on the heat exchanger at the top of the tower; that is, the

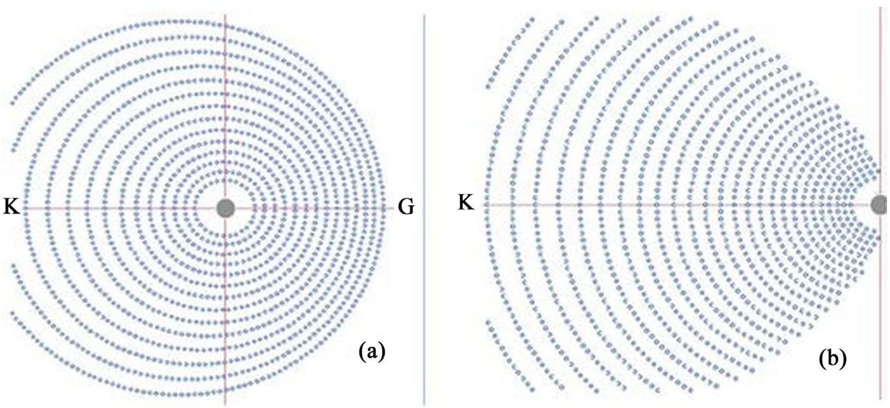

Figure 1. Two different heliostat designs: (a) Tower at the center of the heliostat and (b).

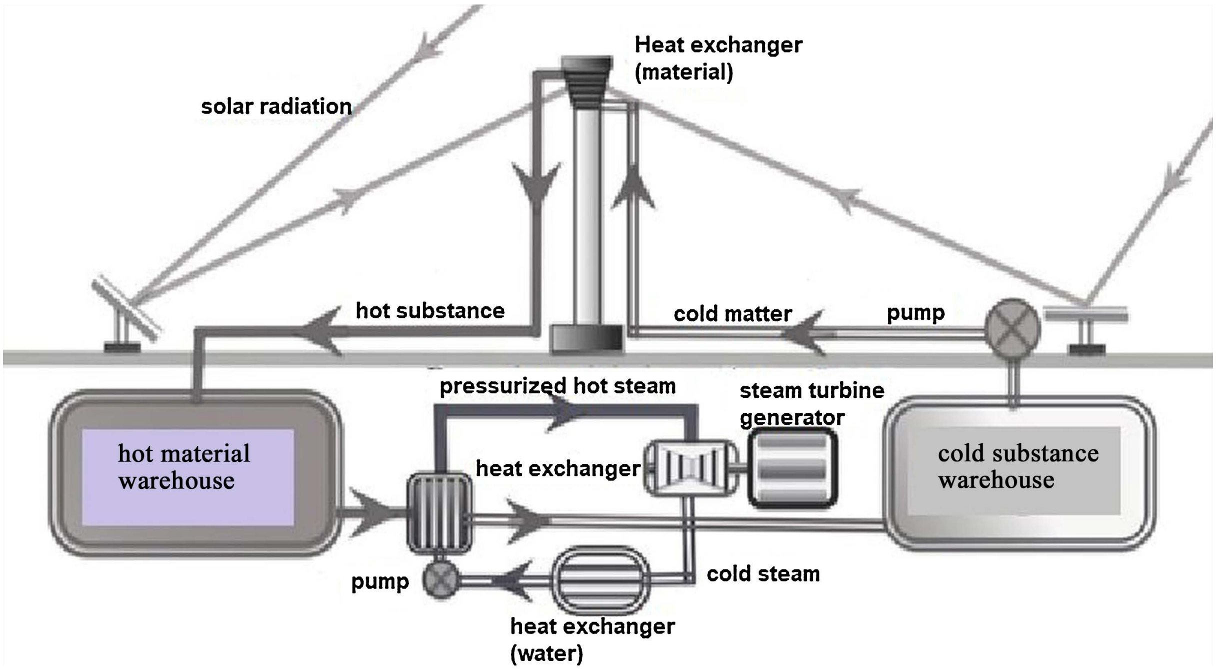

Figure 2. For example, the structure and operation of a CSP system consisting of a tower, solar radiation, heat storage tanks, steam turbine and generator.

mirrors should have at least a biaxial sun tracking mechanism. The sun tracking mechanism can work depending on an independent optical sensor in each mirror, or it can work based on a software calculating the orientations of the mirrors and transmitting them to the mirrors for every day of the year and every moment of the day. This algorithm was developed in this study.

2.2. Heliostat Design

Many considerations must be taken into account when designing a heliostat and creating the computational algorithm. Foremost among these considerations are the geographical location of the land where the heliostat and thus the CSP will be built, the latitude and longitude coordinates, the size of the land, its slope, and the annual sunshine duration. After the location of the tower on the land is chosen, it should be preferred to be as high as the current technique allows. However, the dimensions of each mirror and the dimensions of the heat exchanger at the top of the tower must be compatible with each other. Therefore, the maximum number of mirrors can be placed on the selected land. In this case, a well-insulated liquid pipe should be used for the path length of the heat transfer agent. Because the positions of the mirrors will be fixed, the most appropriate day of the year must necessarily be determined when calculating the mirror positions. For example, June 21, the longest day of the year, can be taken for calculation at noon. However, the algorithm should be able to calculate on different days of the year so that the day and time of the year when maximum efficiency can be obtained can be determined. One of the other factors is that the land is flat or sloping. If the slope of the land is towards the south, this will be reflected in the system as a plus advantage.

In addition to these, the algorithm and the software based on this algorithm should be able to allow some interventions of the user during the calculation. For example, the mirror positions optimized in the calculation, the spacing of the heliostat rings, and the spacing between the adjacent mirrors in a ring should be able to be changed arbitrarily within certain limits. Preferably, for comparison purposes, the same algorithm and software should be able to calculate the power and energy of the fixed orientation of the PV panel, whose surface area is the same as the area of the heliostat mirrors.

At the end of the calculation performed with the given inputs, the placements of the mirrors in the land and the orientations of each of the mirrors for any given moment of any given day should give the solar power that the mirrors focus on the heat exchanger at the top of the tower. The power calculated here is not the power generated by the CSP system, but only the theoretical power focused by the heliostat. For the calculation of the output power of the CSP system, the efficiency of the entire system should be considered.

Creating the Heliostat Design Algorithm

The day of the year, which is one of the necessary input information and parameters for a heliostat design, is the expression that gives the number of days of the year starting from January 1. The hour angle is the expression that gives the Earth's rotation angle corresponding to the time in one-day expressions that give the altitude and horizon (azimuth) angles of the sunlight coming to the geographical location determined throughout the year by taking into account its slope (declination) taken from astronomy sources [3].

By taking into account the angles of incidence of sunlight, altitude α, and horizon (azimuth), the representation of the mirror normals for the mirrors in a heliostat to focus the light on the tower is given in **Figure 3**. The altitude angle of solar radiation is relative to the horizon plane or is defined by $\alpha = 90 - \theta$ with an angle (θ) relative to the zenith.

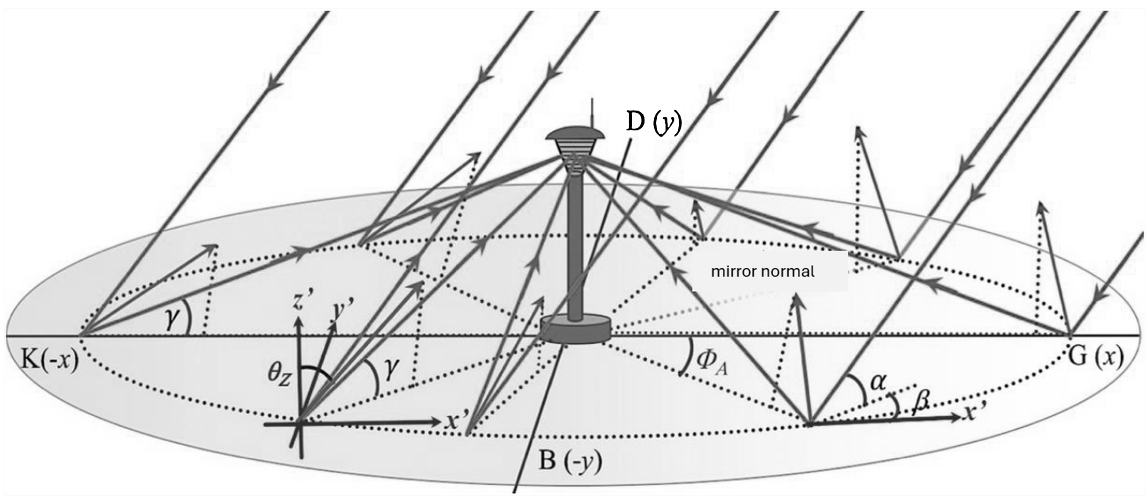

Figure 3. Representation of the normals of the mirrors in a heliostat, in which the mirrors in different positions with respect to the tower focus the solar radiation on the tower [25].

In the context of the study, the expressions giving the azimuth angle (Φ_N) and zenith angle (θ_N) of the mirror normals of the heliostat were determined on the model. The expressions of α, β and Φ_A are defined above. Ω_0, Ω_1,, and Δ are temporal intermediates, and γ is the angle of the tower top with respect to the terrain plane when viewed through the mirror. This angle is found by taking into account $\tan\gamma = h_T/r_i$, the tower height h_T, and the distance r_i of each mirror from the tower (Figure 4).

$$\Phi_N = 270 + \frac{\Phi_A + \beta}{2}; \quad \Phi_A = \begin{cases} < \beta & \text{ise} \quad \Phi_N = 180^\circ + \Phi_N \quad \text{al} \\ = \beta & \text{ise} \quad \Phi_N = 180^\circ + \beta \quad \text{al} \\ \geq 360^\circ + \beta & \text{ise} \quad \Phi_N = 180^\circ + \Phi_N \quad \text{al} \\ = 360^\circ \text{ ve } \beta = 0 & \text{ise} \quad \Phi_N = 180^\circ \quad \text{al} \end{cases} \tag{1}$$

$$\begin{aligned} &\Phi_N \geq 360^\circ \Rightarrow \Phi_N \to \Phi_N - 360 \ \text{al} \\ &\Omega_0 = \alpha + \frac{180^\circ - \alpha - \gamma}{2} \\ &\Omega_1 = \alpha + \frac{90^\circ - \alpha - \gamma}{2} \\ &\Delta = \left| \Omega_0 - \Omega_1 \sin\left(\frac{\Phi_A - \beta}{2}\right) \right| \\ &\Delta > 90^\circ \Rightarrow \Delta \to 180^\circ - \Delta \ \text{al} \\ &\theta_N = 90 - \Delta \ \text{al.} \end{aligned} \tag{2}$$

2.3. Placement of Mirrors Based on Fresnel Mirror Theory

After defining the geometry of the orientation of the heliostat mirrors, the computational algorithm of the orientation of each mirror and the mirror normal

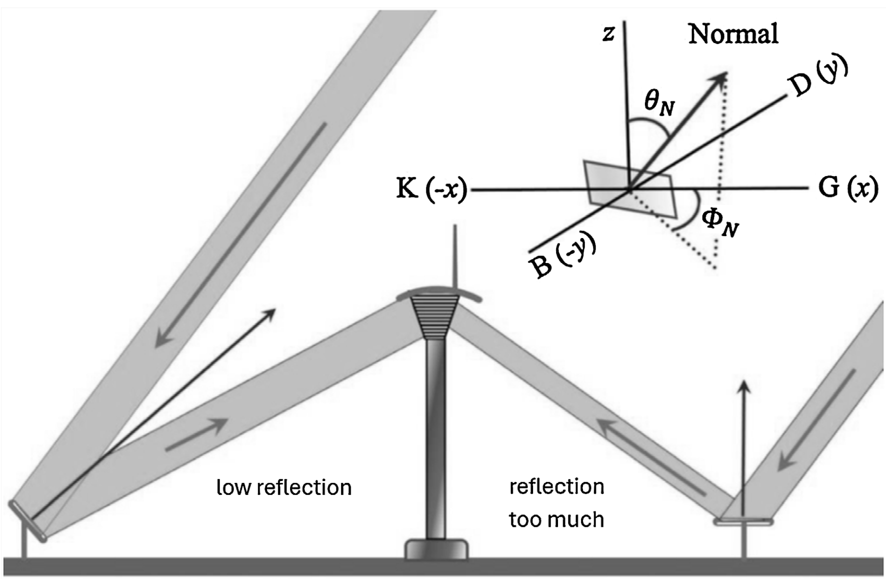

Figure 4. Representation of mirrors and variables in a heliostat [25]. The detailed structure of Figure 3 is available here.

can be created. After the angle of incidence of sunlight is calculated instantly depending on the seasons and days, the position and orientation expressions of each mirror can be created. In the Heliostat design, the alignment of the mirrors can be done manually one by one, but this will cause a loss of efficiency since it is done randomly. Arranging the mirrors in the form of regular shapes by an algorithm based on the geometry of the land and the system should be considered in terms of appearance, efficiency, and operation. This method will enable calculations on the heliostat. By using this method, the heliostat mirrors can be arranged in non-concentric rings. Arranging the heliostat mirrors in this way in existing CSP systems will also provide maximum efficiency [21] [23] [24].

Adaptation of the Fresnel lens theory for mirrors is a suitable method in terms of a regular arrangement of the heliostat. According to this theory, to be able to focus solar radiation on the tower, a front mirror should not shadow or minimally block the mirror behind it.

Calculation of the instantaneous orientation of the positions and normals of the heliostat mirrors was made based on the illustration given in **Figure 3** and **Figure 4**. The variables and parameters shown in these figures are given below (**Table 1**).

Table 1. The variables and parameters shown in **Figure 3** and **Figure 4**.

h_T	tower height	β	Projection azimuth angle of the sun on the ground plane
h_m	mirror height	χ	Tower angle of the heliostat ring
w_m	Mirror width	Φ_A	azimuth angle of land
r_i	*Radius of the* i^{th} *heliostat ring*	Φ_N	Azimuth angle of mirror normal
α	altitude angle of solar radiation	θ_N	Zenith angle of mirror normal

As shown in the figure, because a front mirror should not cut off the radiation going to the tower, the distance between two consecutive mirrors or the distance between the mirror bases will be $d_i + \delta_i$. The important thing here is to determine this distance. The same is true for radiation coming from the Sun (it should not be confused with the angle difference δ_i and the Earth's declination). In order for the heat collector part of the tower to receive maximum radiation, the distance between the mirrors can be determined from the right triangle between the dashed line drawn to the mirrors from the lower border and the distance δ_i Since the angle χ_i of the right triangle and the tower angle γ defined above are quite close to each other, $\chi_i \approx \gamma$ can be taken with a good approximation. Thus, expressions that give the positions of the mirrors are found and based on this, the radius of the heliostat is shown in the following Equation (3).

$$\tan \chi_i \approx \frac{h_T}{r_i} \approx \frac{h_i}{d_i} \text{ ve } h_i = h_m \sin \theta_i, (i = 1, 2, 3, \cdots, M)$$

$$d_i \approx \frac{h_i}{\tan \gamma_i} \approx \frac{h_m \sin \theta_i}{\tan \gamma_i} = \frac{h_m r_i \sin \theta_i}{h_T} \text{ ve } \delta_i = \frac{h_m}{2} \cos \theta_i \approx \delta_{i+1}, (i = 1, 2, 3, \cdots, M) \quad (3)$$

$$r_{i+1} = r_i + \frac{h_m \sin\theta_i}{\tan\gamma_i} + h_m \cos\theta_i \tag{4}$$

In the equations, M is taken as $\xi_i = 90 - \theta_i$ and it is the number of heliostat rings, and θ_i is the zenith angle of the normal of each mirror. The θ_i angle is the angle that the mirror normal makes with respect to the zenith.

The orientation of the heliostat mirrors (*i.e.*, their normal angle) will vary depending on the angle of incidence of solar radiation and the position of the mirrors relative to the tower. Because of this, the rings in which the mirrors are arranged will not be concentric. As can be seen in **Figure 4**, if the mirror is on the south side of the tower, the normals of the mirrors will be closer to the zenith (*i.e.*, their normal angles will be small), and if the mirror is on the north side, their normal angles will be larger. The reason for this is that since the mirrors on the south side of the tower will not shade each other, they will be closer to each other; however, since the mirrors on the north side of the tower will shade each other more, the distances between them will be greater. As a result, the centers of the heliostat rings will shift southward. Similarly, there may be a shift in the East-West axis, but this shift has been considered unsuitable in order to make maximum use of sunlight. Equations of each heliostat ring and in polar coordinates are given in Equations (5) and (6), respectively:

$$(x_i - a_i)^2 + (y_i - b_i)^2 = r_i^2 \tag{5}$$

$$x_i = a_i + r_i \cos\theta_i, \quad y_i = b_i + r_i \sin\theta_i, \ (i = 1, 2, 3, \cdots, N) \tag{6}$$

In this study, assuming that there is no spring in the east-west direction, $b_i = 0$ is taken.

Using the last equation in Equation (4), the initial slip ai of the rings is found. The initial slip amount of the rings should be taken as $a_0 = 0$ (Equation (7)),

$$a_{i+1} = r_{i+1} - \left(\frac{r_i}{h_T} + \cos\theta_i\right) h_m \tag{7}$$

2.4. Distances between Side-By-Side Mirrors in the Heliostat Ring

The spacing of the adjacent rings in a heliostat ring is as important as the distance between the rings in the heliostat. Side-by-side mirrors in a ring should not shade or minimally shade solar radiation incoming from different angles. In reality, considering the variation of solar radiation by the days of the year, the distances between the mirrors must be quite large in certain parts of the rings to be able to make the shading zero; however, in this case, the land cannot be used optimally. Especially considering the winter days when the solar radiation is very inclined and weak, leaving the mirrors more spaced than necessary by taking into account the gaps in the field during the summer days when the radiation is intense will cause them not to be used enough. This is a matter of preference, but it would be reasonable and appropriate to consider periods of radiation intensity. In addition, in most applications, it is more convenient to distribute the mirrors evenly in the ring to compensate for losses at different times. Moreover, if desired, the geometric approximation of the distance between mirrors according to the angle of incidence of solar radiation in a heliostat ring can be arranged by considering the notation given in **Figure 5**. Considering the states of the mirrors, the distance between the mirrors standing next to each other can be given with an approximate expression depending on the local azimuth and the azimuth angles of the sun (Equation (8)).

$$s \approx w_m \left[1 + \left| \sin\left(\phi_A - \omega \right) \right| \right] \tag{8}$$

where w_m is the width of the mirror, ϕ_A is the azimuth angle of the mirrors relative to the tower, and ω is the hour angle.

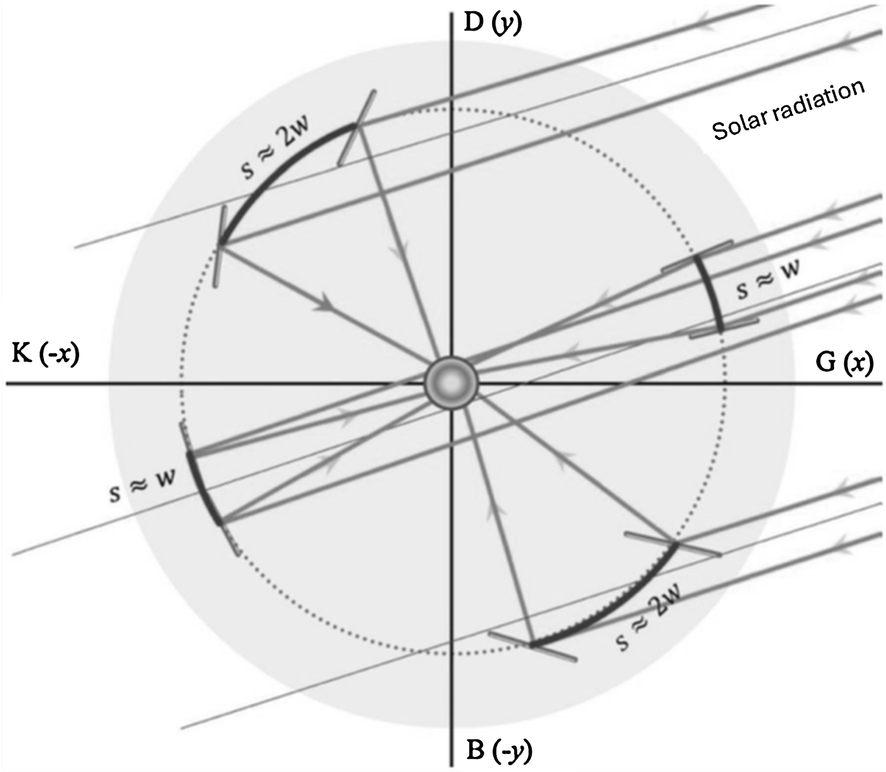

Figure 5. Representation of the distance between mirrors arranged side by side in a heliostat ring [25].

2.5. Total Power Collected by Mirrors in Heliostat

Thanks to the orientation of the collector mirrors of it, a heliostat will collect the solar radiation, coming from different angles, in the heat exchanger-receiver of the tower on each day of the year and at every moment of the day.

The power reflected by the mirrors to the top of the tower will be found by the direction of solar radiation (*i.e.*, the scalar multiplications of the normals of the mirrors and the solar radiation vectors).

The mirror normals, where A_0 is the surface area of each mirror, are determined based on Equation (9).

$$\boldsymbol{A}_{pq} = A_0\left[\sin(\theta_N)_{pq}\cos(\phi_N)_{pq}\,\hat{\boldsymbol{i}} + \sin(\theta_N)_{pq}\sin(\phi_N)_{pq}\,\hat{\boldsymbol{j}} + \cos(\theta_N)_{pq}\,\hat{\boldsymbol{k}}\right] \quad (p = 1,2,3,\cdots,M;\ q = 1,2,3,\cdots,N_i) \tag{9}$$

Intensity vector of power flow of incident solar radiation per unit area is determined as follows:

$$\boldsymbol{I} = \frac{I_0}{(AM)_n}\left[\sin\theta_z\cos\beta\hat{\boldsymbol{i}} + \sin\theta_z\sin\beta\hat{\boldsymbol{j}} + \cos\theta_z\hat{\boldsymbol{k}}\right] \tag{10}$$

where $(AM)_n$ is the air mass, I_0 is the insolation, and θ_z is the zenith angle of the radiation.

The strength of the radiation that each mirror reflects on the tower in this case will be as follows:

$$\begin{aligned} P_{pq} &= \boldsymbol{I}\cdot\boldsymbol{A}_{pq} \\ &= \frac{A_0 I_0}{AM_n}\Big[\sin(\theta_N)_{pq}\cos(\phi_N)_{pq}\sin\theta_z\cos\beta \\ &\quad + \sin(\theta_N)_{pq}\cos(\phi_N)_{pq}\sin\theta_z\sin\phi_N + \cos(\theta_N)_{pq}\cos\theta_z\Big] \\ &\quad (p = 1,2,3,\cdots,M;\ q = 1,2,3,\cdots,N_i) \end{aligned} \tag{11}$$

The sum of the reflected powers of each mirror is the total power reflected by the heliostat to the heat exchanger. Total power reflected on the tower is calculated as in Equation (12).

$$P_T = \frac{A_0 I_0}{AM_n}\sum_{p=1}^{M}\sum_{q=1}^{N_i} P_{pq}, \quad (p = 1,2,3,\cdots,M;\ q = 1,2,3,\cdots,N_i) \tag{12}$$

2.6. Required İnputs For Heliostat Calculation

The necessary input values for the design and calculation of the heliostat created by the developed algorithm are given below [25]:

- The day of the year and the time of day when the heliostat will be installed (These variables should be determined in advance).
- The day and time of the calculation (These variables should be given separately).
- Coordinates of the land where the heliostat will be installed.
- The dimensions of the land where the heliostat will be installed.
- The location of the tower on the land (the tower can be on one side or in the middle of the land).
- The height of the tower. This height should be within the limits of technology. Being too high is not preferred due to the problems such as insulation or pumping that may occur in the transfer of the hot storage material. On the other hand, the shortness of the tower will cause the number of mirrors to be small and therefore the collected power to be low. Ideal tower height should be determined by thermodynamic calculations.
- The radius of the rings. The first ring of the heliostat should be determined on an optional basis. The radii of the other rings can be found based on the expressions given in Equations (1)-(8).

- Width and height of each mirror (These values should be compatible with the size of the heat exchanger).
- The noon time of the relevant geographical region (*i.e.*, the time when the Sun is directly overhead). Although this time is mostly given as 12:00, it may differ by location regarding daylight saving time and the state of being away from the time zone.
- Sunrise and sunset times. Although the time when the heliostat will start production by receiving sufficient solar radiation can be determined depending on the sunrise and sunset times, these times vary depending on the days of the year. Therefore, the altitude angle of the Sun after sunrise and before sunset can be determined in advance.
- In this calculation, only the collected solar power is taken into account. The CSP system and its efficiencies are out of this study.
- In addition, to be able to make some interventions when it is desired, the distances between the rings and the distances between the mirrors in each ring should be adjusted to a certain extent.

2.7. Geographical Location of Adana Province and Meteorological Data

Adana Province is located in the Mediterranean Region, between approximately 35˚ - 38˚ north latitudes and 34˚ - 36˚ east longitudes. Adana is divided into two parts as mountainous and lowland in terms of landforms. A large part of the lowland area is the geographical structure known as Çukurova, and this region is under the influence of the Mediterranean climate, which is warm in winter, and humid and hot in summer. The mountainous regions are cooler and receive more rain Summers are dry and hot, winters are warm and rainy, and the precipitation in the region is generally caused by the combination of slope precipitation and mobile air masses. The average precipitation is 769.9 mm, and an average of 74 days of the year are rainy (**Figure 6**) [26].

3. Findings and Discussions

3.1. Heliostat Calculations for Adana Province

Figure 7 shows the calculations related to power generation performed by using solar energy in Adana's Aladağ (37˚19'N; 35˚33'E), Yumurtalık (36˚44'N; 35˚35'E), Tufanbeyli (38˚17'; 36˚14'E), Pozantı (37˚23'N; 34˚48'E), Karaisalı (38˚17'N; 35˚00'E), and Karataş (37˚04'N; 35˚11'E) districts. All calculations were carried out on the 21[st] of each month for a year. The calculations were made based on a land of 400 m × 400 m and a tower with a height of 64 m.

When two types of powers (Pincoming and Pcollected) obtained by the months for these six regions were compared, it was observed that the values were close to each other as expected, but the highest power value was obtained in Yumurtalık. **Table 2** gives the meteorological average of Adana province from 1991 to 2020, and it is seen that the data is suitable for CSP or other solar energy systems.

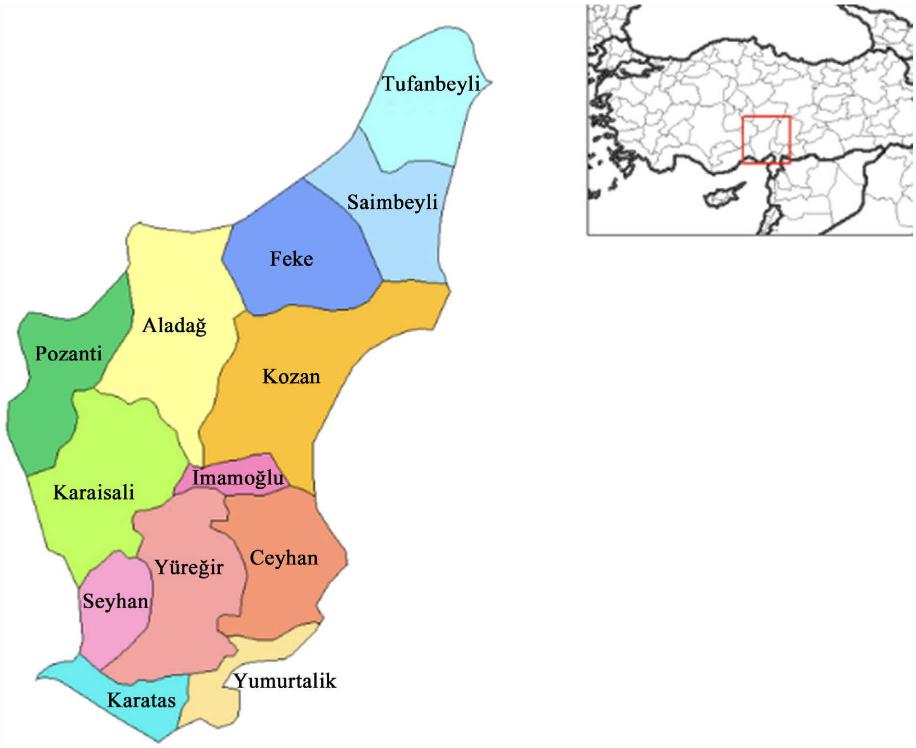

Figure 6. Location and geographical structure of Adana province and its districts where calculations were made [27].

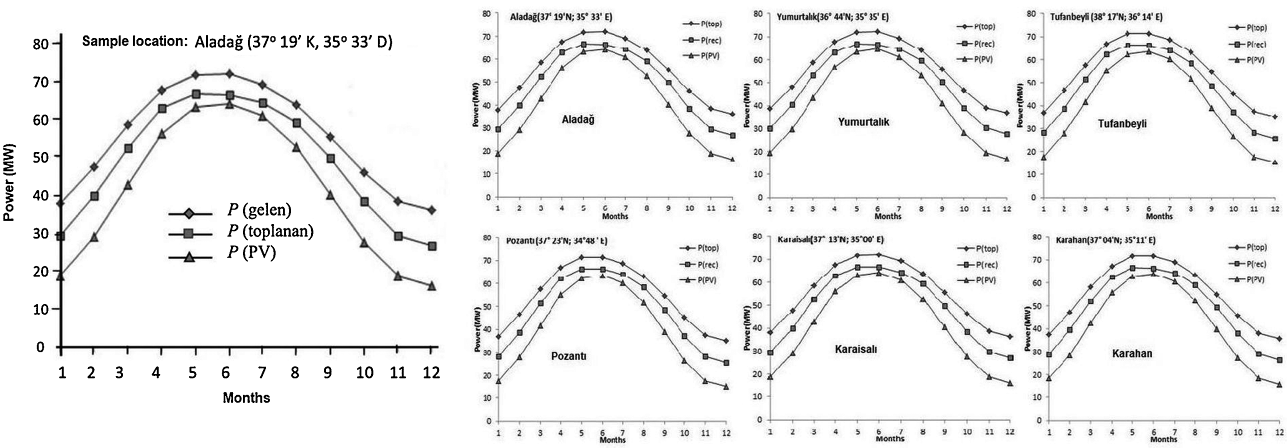

Figure 7. Power values generated from the solar energy by months in six districts of Adana province (The graph of Aladağ, Yumurtalık, Tufanbeyli, Pozantı, Karaisalı, Karahan District is given as an example on the left. These values were obtained on the 21st of each month).

Changes in values of energy generated from the sunlight on the 21st of each month for a year are given in **Figure 8**. It is seen that these generated energy values are also close to each other for the six districts. The fact that both power and energy values are close to each other for six districts is due to the fact that all days were open and the latitudes where the districts are located are close to each other. The southern and northern regions of Türkiye are between 37˚ and 41˚ north latitudes. A latitude of 4˚ does not make a serious difference for exposure to sunlight.

When the energies obtained for these six regions were compared by months, it

Table 2. Seasonal normals for Adana province between 1991 and 2020 retrieved from [28].

ONTHS	Average temperature (˚C)	Average highest temperature (˚C)	Average lowest temperature (˚C)	Average sunshine duration (hours)	Average number of rainy days
January	9.5	15.0	5.6	4.3	10.10
February	10.7	16.6	6.3	5.2	9.33
March	13.9	19.9	8.9	5.9	9.07
April	17.7	24.1	12.4	6.9	8.67
May	22.1	28.4	16.6	8.6	6.40
June	25.9	31.7	20.8	9.9	2.83
July	28.6	33.9	24.3	10.1	1.17
August	29.2	34.9	24.7	9.4	0.77
September	26.6	33.2	21.4	8.7	3.07
October	22.4	29.5	16.9	7.2	5.27
November	15.8	22.6	11.0	5.7	6.17
December	11.1	16.8	7.3	4.0	9.03
Yearly	**19.5**	**25.6**	**14.7**	**7.2**	**71.9**

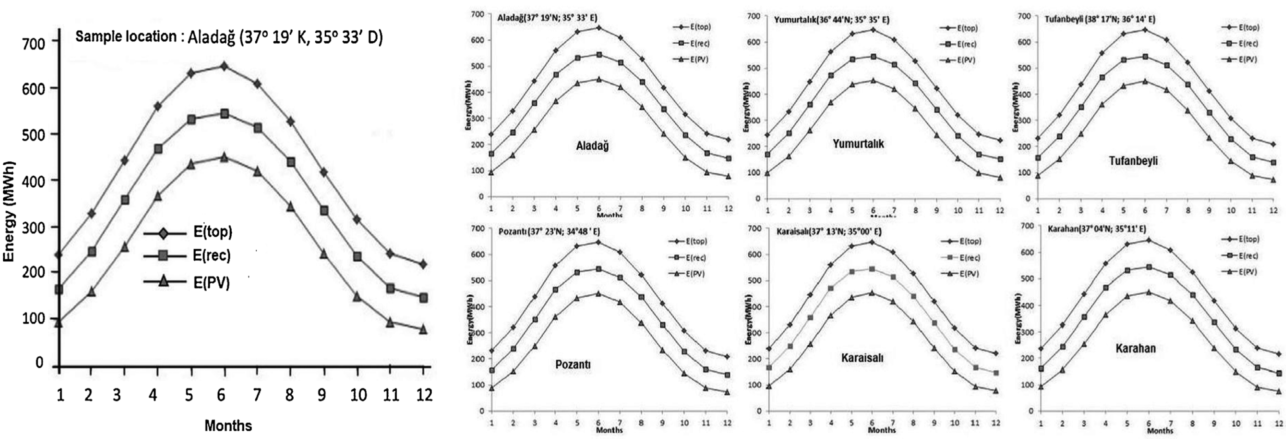

Figure 8. Energy values generated from the solar energy by months in six districts of Adana province (The graph of Aladağ ,Yumurtalık, Tufanbeyli, Pozantı, Karaisalı, Karahan District is given as an example on the left. These values were obtained on the 21st of each month).

was seen that they were close to each other. However, the highest energy value in terms of both energy types (E(incoming) and E(collected)) collected in the tower by the mirrors was obtained in Yumurtalık. This is because the district of Yumurtalık is in the south where the sunlight comes more steeply.

3.2. Variation of Mirror Number by Tower Height

First of all, the change in the number of mirrors by the height of the tower in a certain location and in a certain area was calculated on a 400 m × 400 m land sample at 35˚N and 11'E position in the Aladağ district. The variation of the number of mirrors by the tower height values between 20 m and 120 m is given in Figure 9. All calculations were made on the 21st of June at 12:00 to be able to compare them. As seen in the figure, the number of mirrors first increases rapidly depending on the tower height, but then increases more slowly in an almost linear manner. The figure reveal that if the height of the tower increases further, the number of mirrors will most probably remain constant as expected. This variation is taken into account when determining the optimal tower height and, thereby, the number of mirrors for a given land.

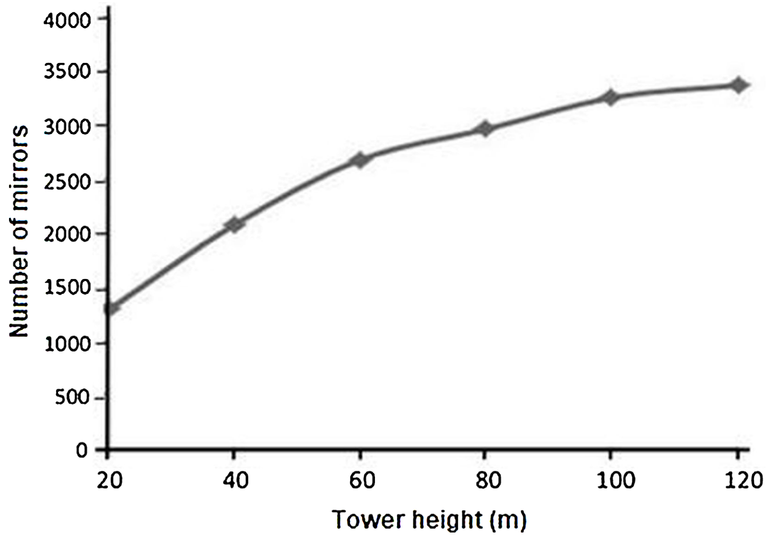

Figure 9. Variation of the number of mirrors by different tower heights in the same geographic location (Yumurtalık, 36˚44'N; 35˚35'E).

3.3. Variation of the Number of Mirrors by the Circle of Latitude

In the study conducted to see the variation in the number of mirrors by the latitude circle for fixed tower height and fixed land, it was observed that the number of collector mirrors decreased from 2663 to 2652 between the latitudes of 36˚, which is the southern border of Adana province, and 38˚, which is the northern border. As seen, this variation is insignificant. Based on this, it can be said that the difference in the number of mirrors between south and north latitudes on the scale of Türkiye is about 100, and the importance of this may vary depending on the investor. If it is desired to increase the number of mirrors and, accordingly, power generation, the tower height and the appropriate dimensions should be determined within the framework allowed by the land and technology.

4. Conclusions and Discussions

In this study, a CSP system suitable for six districts (Aladağ, Yumurtalık, Tufanbeyli, Pozantı, Karaisalı, and Karataş) of Adana province located in the south of Türkiye was developed by the help of an algorithm created to increase the efficiency of the heliostat collecting solar energy and software created accordingly.

Thanks to this software, it is possible to make a design for a land selected in any latitude circle both in the Northern hemisphere and in the Southern hemisphere by using many inputs such as the dimensions of the land, the height of the tower, the design time (as the day of the year) and the time of day, and the mirror dimensions. This software provides some data as outputs, such as the positions of the mirrors in the field, the instantaneous power they receive from the Sun and reflect on the heat exchanger at the top of the tower, the daily energy production, and the orientation angle values that the Sun tracker will need for each mirror at any time of the day. While designing the algorithm, the equations related to the motion of the earth were taken from astronomy sources and used in such a way that the heliostat would receive maximum solar energy for all days of a year and collect it in the heat exchanger in the tower. For comparison purposes, it was assumed that all days of the year and every moment of the day were clear and cloudless.

In the context of the study, exemplary designs and calculations were made for the six districts by keeping all parameters same except the geographical locations. Firstly, the power changes by the months were calculated and results were discussed. To be able to make a comparison, calculations were made for the 21st day of each month. When the power and energy values obtained for these six districts by the months were compared, it was observed that they were quite close to each other, but the values for both power and energy in Yumurtalık were higher than the other districts, albeit a little. The main reason for this is that Yumurtalık is in the south. Among these six districts, the most suitable one for heliostat design would be the district with the highest sunshine day, however, this issue is out of the scope of this study.

In addition, the total solar power received by the photovoltaic panel, which had the same surface area but with a fixed 23˚ orientation, was also added to the calculations. In these calculations, the total power received from the Sun was determined, and the efficiency of the panel (not the production of the photovoltaic panel) was evaluated separately. In this way, the power collected by the heliostat and the photovoltaic panel could be compared. Results of the study revealed that the power and, thereby, the energy obtained from the photovoltaic solar panels was lower compared to the power and energy obtained from the heliostat with the same surface area. The reason for this is that the heliostat mirrors have a sun-tracking mechanism and the photovoltaic panels are fixed orientation, which is technically necessary for the heliostat sun-tracking mechanism.

In the calculation, Results also showed that the number of mirrors changed by the height of the tower, while the size of the land remained constant. It was concluded that the number of mirrors increased depending on the height of the tower, but tended to remain constant above 100 m. This situation can be considered true for Türkiye's southern and northern borders, that is, between latitudes 36˚ and 42˚.

CSP is an alternative renewable energy technology that does not require high technology in areas with plenty of sunlight and that many countries can do with their own means. It is important in terms of providing some of the energy for instant use when there is sunlight and storing some of it as heat and continuing to produce energy when there is no sunlight. Today, Spain, the USA, India, China, and North African countries, which receive plenty of sunlight, are widely using and developing the CSP systems. Türkiye, which has sun-drenched regions, suitable lands, and sufficient technology, should give the necessary importance to the CSP systems. The heliostat designed and performed in this study is the most important element of the CSP system. The most suitable regions can be determined, and the most suitable heliostat designs can be made by making preliminary calculations with the software developed for different regions or with similar software.

Acknowledgements

I am grateful to Prof. Recep Tapramaz for his continuous support and feedback throughout the research process.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Kesselring, P. and Selvage, C.S. (1986) The IEA/SSPS Solar Thermal Power Plants—Facts and Figures. Final Report of the International Test and Evaluation Team (ITET). Springer.

[2] Alaphilippe, M., Bonnet, S. and Stouffs, P. (2007) Coupling of a Parabolic Trough Concentrator and an Ericsson Engine. Low Power Thermodynamic Solar Energy Conversion. *International Journal of Thermodynamics*, **10**, 37-45.

[3] Romero-Alvarez, M. and Zarza, E. (2007) Handbook of Energy Efficiency and Renewable Energy—Concentrating Solar Thermal Power. Platforma Solar de Almeria CIEMAT, Taylor & Francis LLC.

[4] Wei, X., Lu, Z., Lin, Z., Zhang, H. and Ni, Z. (2007). Optimization Procedure for Design of Heliostat Field Layout of a 1mwe Solar Tower Thermal Power Plant. *SPIE Proceedings*, Beijing, 15 January 2008. https://doi.org/10.1117/12.755285

[5] Da Rosa, A.V. (2010) Fundamentals of Renewable Energy Processes. 4th Edition, Elsevier Academic Press.

[6] Wei, X., Lu, Z., Wang, Z., Yu, W., Zhang, H. and Yao, Z. (2010) A New Method for the Design of the Heliostat Field Layout for Solar Tower Power Plant. *Renewable Energy*, **35**, 1970-1975. https://doi.org/10.1016/j.renene.2010.01.026

[7] Jagoo, Z. (2013) Tracking Solar Concentrators. A Low Budget Solution. Springer.

[8] Zhang, H.L., Baeyens, J., Degrève, J. and Cacères, G. (2013) Concentrated Solar Power Plants: Review and Design Methodology. *Renewable and Sustainable Energy Reviews*, **22**, 466-481. https://doi.org/10.1016/j.rser.2013.01.032

[9] Zhu, G. (2013) Development of an Analytical Optical Method for Linear Fresnel Collectors. *Solar Energy*, **94**, 240-252. https://doi.org/10.1016/j.solener.2013.05.003

[10] Zobaa, A.F. and Bansal, R.C. (2011). Handbook of Renewable Energy Technology. World Scientific Publishing Co. Pte. Ltd. https://doi.org/10.1142/9789814289078

[11] Benammar, S., Khellaf, A. and Mohammedi, K. (2014) Contribution to the Modeling and Simulation of Solar Power Tower Plants Using Energy Analysis. *Energy Conversion and Management*, **78**, 923-930. https://doi.org/10.1016/j.enconman.2013.08.066

[12] Bhatia, S.C. (2014) Advanced Renewable Energy Systems. Part-1. Woodhead Publishing.

[13] Zhou, Y. and Zhao, Y. (2014) Heliostat Field Layout Design for Solar Tower Power Plant Based on GPU. *IFAC Proceedings Volumes*, **47**, 4953-4958. https://doi.org/10.3182/20140824-6-za-1003.01581

[14] Heller, P. (2017) The Performance of Concentrated Solar Power (CSP) Systems. Analysis, Measurement and Assessment. Woodhead Publishing (An imprint of Elsevier).

[15] Chandra, L. and Dixit, A. (2018) Concentrated Solar Thermal Energy Technologies Recent Trends and Applications. Springer Proceeding in Energy. 1st Edition, Springer.

[16] Chen, R., Rao, Z. and Liao, S. (2018) Determination of Key Parameters for Sizing the Heliostat Field and Thermal Energy Storage in Solar Tower Power Plants. *Energy Conversion and Management*, **177**, 385-394. https://doi.org/10.1016/j.enconman.2018.09.065

[17] Collado, F.J. and Guallar, J. (2019) Quick Design of Regular Heliostat Fields for Commercial Solar Tower Power Plants. *Energy*, **178**, 115-125. https://doi.org/10.1016/j.energy.2019.04.117

[18] Giostri, A., Binotti, M., Sterpos, C. and Lozza, G. (2020) Small Scale Solar Tower Coupled with Micro Gas Turbine. *Renewable Energy*, **147**, 570-583. https://doi.org/10.1016/j.renene.2019.09.013

[19] Bayraktar, F.S., Yazıcı, M. and Köse, R. (2023) Yoğunlaştirilmiş Güneş Enerjisi (CSP) Teknolojileri Ve Türkiye'de Csp'ye Yönelik Politikalar. *Journal of Scientetic Reports-B*, **7**, 1-13.

[20] International Energy Agency (2014) Technology Roadmap: Solar Thermal Electricity—2014 Edition.

[21] Leutz, R. and Suzuki, A. (2001) Nominating Fresnel Lenses, Design and Performance of Solar Concentrators. Springer.

[22] Sabonnadière, J.C. (2007) Renewable Energies. Wiley.

[23] Şen, Z. (2008) Solar Energy Fundamentals and Modeling Techniques. Atmosphere Environment. Climate Change and Renewable Energy. Springer.

[24] Srilakshmi, G., Ramaswamy, M.A. and Thirumalai, N.C. (2016) Design of Solar Field and Performance Estimation of Solar Tower Plants. Center for Study of Science, Technology and Policy (CSTEP).

[25] Nazari, A.J. (2021) Helıostat Desıgn and Calculatıons for Concentratıng Solar Power Towers in Türkiye and Afganistan. Master's Thesis, Ondokuzmayıs University.

[26] Adana İli (2023) 2023 Çevre Durım raaporu. https://webdosya.csb.gov.tr/db/ced/icerikler/adana-ilcdr-2023-20240918144837.pdf

[27] https://www.uyduharita.org/adana-haritasi-resimleri

[28] Turkish State (2023) Meteorological Service. https://www.mgm.gov.tr/