Optimal Tilt Angle for Fixed PV Panels for Annual Maximum Energy Output in Cyprus Condition

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ABSTRACT

Solar panel technology system utilizes solar radiation to generate electricity, and it is very important to absorb and capture maximum energy output. This study aims to find the yearly optimal tilt angle to maximize the cumulative energy output. This study was conducted in Cyprus, and the solar panel true in the south, because Cyprus is in the Northern Hemisphere, and the solar panel should be in the south. During the research, several methods considering different conditions such as clearness index, extraterrestrial radiation on a tilted surface, ground reflection were discussed, and then the results of each method based on Cyprus latitude is observed. The Rhino 3D program and the Grasshopper plug-in program have been used to find maximum solar radiation and the optimum tilt angle. The data for this study were collected from the Energy Plus Weather data website. The data are used to calculate and evaluate the beam and diffuse and ground-reflected solar radiation and total solar radiation for different tilt angles between 0° and 90° and the value of 180° for azimuth angle by Tilt and Orientation Factor component inside the Grasshopper. By using the program, the total maximum solar radiation is about 2075 $kWh/m^{2,}$ and the optimum tilt angle is approximately 29°.

Keywords: Solar Panels, Optimum Tilt Angle, Solar Radiation, Azimuth

ÖZ

Güneş enerjısi teknoloji sistemleri güneş ışığını kullanarak elektrik enerjisi üretirler. Azami enerji çıktısı için Güneş enerjısi yakalayabilmek çok önemlidir. Bu çalışmanın amacı yıllık toplam enerji çıktısının azami olabılmesi için gerekli optimal panel açısını belirlemektir. Bu çalışma Kıbrıs için yapılmıştır. Güneş paneli gerçek güneye bakacak şekilde sabitlenmiştir. Araştırma sırasında, netlik endeksi, eğim yütyine düşen güneş ışığını, zemin yansıması gibi faktörler ele alınmıştır. Rhino 3D programı ve Grasshopper program eki kullanılarak gerekli hesaplamalar yapılmış, optimal eğim açısı bulunmuştur. Bu çalışmanın verileri "Energy Plus Weather" veri web sitesinden toplanmıştır. Yerden yansıyan, direk ve dağınık güneş ısığı 0º ile 90º derece eğim açıları ve 180º azimuth açıları için hesaplanmıştır. Bu çalışma neticesinde en çok enerji çıktası alınabilen (2075 kwh/m^2) panel eğim açısının yaklaşık 29º olduğu hesaplanmıştır.

AnahtarKelimeler: Solar panel, Optimal eğim açısı, Güneş ışığını, Azimuth

DEDICATION

To my family

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My thanks go to my friends who helped and encouraged me during the period of my studies and this thesis, such as Mr. and Mrs. Negar Amjadi and Naser Amjadi, Mr. and Mrs. Farideh Kordbacheh, Gediz Bakay. Many thanks go to Djordje for his crucial contribution to this study.

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Chapter 1

INTRODUCTION

This chapter provides information about the concepts of the sun path, sun position, and solar power, and the optimum tilt angle.

The world is divided into two parts by equator. The north part of the world is known as the northern hemisphere, and the south part of the world is called the southern hemisphere. The Earth orbits on its vertical axis with a slope of between 23.45º to -23.45º (declination angle) around the Sun, leading to the day and night phenomenon (Figure 1). The Earth requires 23hrs 56mins to complete one true rotation around the Sun. In the summer that happens around June 21, the North Pole is pointing towards the Sun at an angle of 23.5°. However, during the winter season that occurs around December 21, the North Pole is pointing away from the Sun at an angle of negative 23.5° [1].

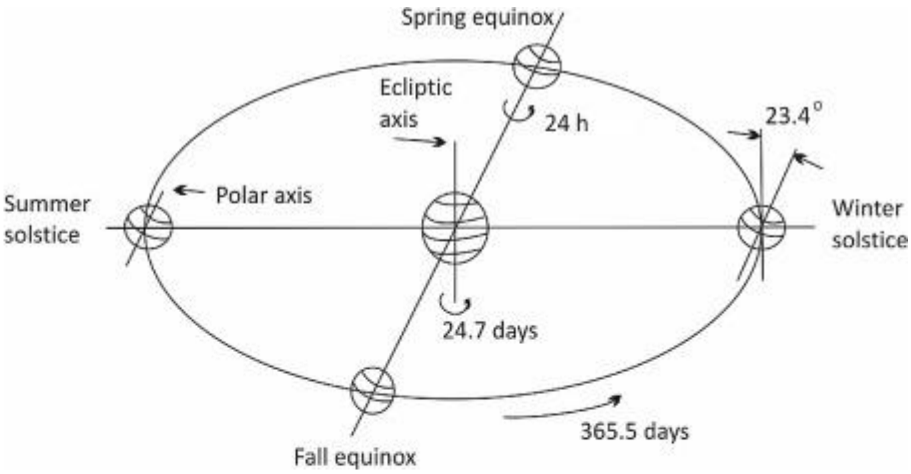


Figure 1: The earth rotation around the Sun [1]

The duration of the day and night depends upon the time of the year and the latitude of the location., the shortest solar day and the longest solar day occurs around December 21, known as the winter solstice, June 21 known as the summer solstice, respectively for locations in the northern hemisphere (Figure 2).

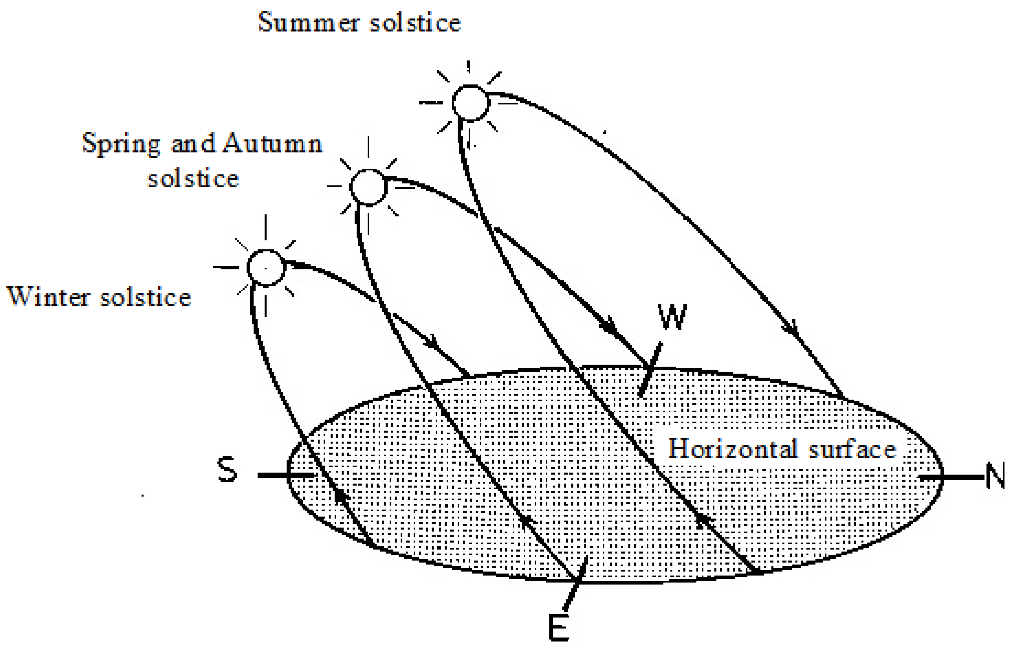


Figure 2: Sun path diagram [2]

Seasons occur on the earth axis that is slope by 23.5^{o}, which impacts the distribution of the Sun's energy around the planet's surface. As the Earth orbits the Sun every 365.5 days, the axis is always pointing in the same direction into space, with the north pole toward Polaris, the north star. Around June 22, the northern hemisphere faces the Sun and receives the most beam irradiation and the highest energy. This is the beginning of astronomical summer in the northern hemisphere and winter in the southern hemisphere. In December, the Earth completes half a revolution around the Sun. The northern hemisphere is now faced away from the Sun and receives lower energy than the southern hemisphere; this is the start of summer in the southern hemisphere and winter in the northern hemisphere. From north to south, the consequences of the distribution of solar energy can be seen in changing temperatures, animal behaviors, and day length.

The Sun does not exactly rise in the east and does not exactly set in the west. It depends on the position that we are living in. To know the exact position is determined by the latitude and longitude coordinates. The amount of latitude is varying between 90º (north) and 90º (South); when the latitude equals zero that the object is in the equator.

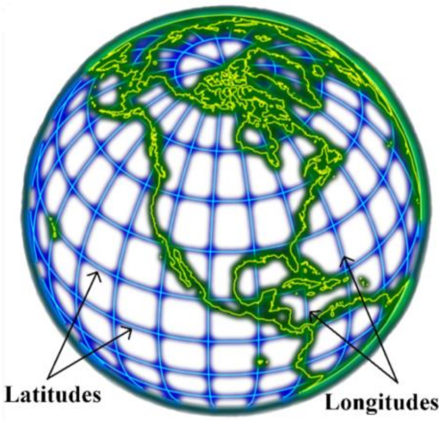


Figure 3: Latitude and longitude [3]

The position of the Sun can be defined as sun vectors denoted with regards to an altitude and azimuth angle of the Sun [4] (Figure 3). The azimuth angle is the angle in the horizontal plane to the horizontal projection of the Sun’s rays [5]. Elevation (altitude) angle can be defined as the angle between the horizontal plane of the location and at a point on the Earth’s surface, a default line connecting the point on the Earth and the sun [5] (Figure 4).

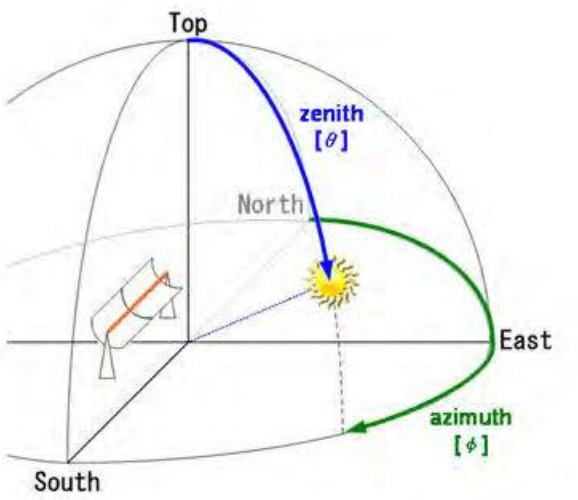


Figure 4: Altitude and azimuth [4]

Solar energy is a renewable energy source, which is often referred to as clean and sustainable energy, comes from natural sources and constantly replenished processes. Solar energy plays an important role as a fossil-fuel-free energy source. One of the reasons is the reduction in the burning of fossil fuels for energy production, leading to the reduction in CO2 emissions. Another reason is that amount of solar radiation that falls on the Earth's surface is about 20 GW of power to each person, which shows that solar energy has the potential to meet the requirement of energy usage of the human [6]. The amount of energy for the Sun that reaches Earth can be captured and converted into heat and electricity. One of the applications consists of electric power generation with the help of photovoltaic panels [7].

Photovoltaic panels (PV) installed capacity growth around the world. Top countries by cumulative solar PV capacity included China, Japan, Germany, and the United States [8]. Solar panel installations were developed to be used especially in Cyprus in recent years, where there is a great source of solar energy [9]. Nevertheless, most of the companies install the panels at an inappropriate tilt angle. It leads to the percentage of solar radiation absorbed by photovoltaic (PV) panels decreased and, therefore, decreased energy output. It is essential to find the optimum tilt angle to capture more energy and maximize the cumulative energy output.

Due to the problem regarding finding the optimum tilt angle for the solar panels, some research is selected, and each research proposed a method with considering different conditions and parameters such as clearness index, extraterrestrial radiation on a tilted surface, ground reflection in order to find the optimum tilt angle.

The methodology of this thesis is to use a program and an auxiliary program in order to find the optimal tilt angle for Cyprus and then compared the results with the results that obtained by different research and method. The algorithm is used to calculate the optimum tilt angle for maximizing solar radiation collection based on the Energy Plus Weather file (EPW). Each of the algorithms has its properties, and each algorithm is useful for some parts of the project. The optimum tilt angle is calculated by the Tilt and Orientation factor component inside the auxiliary program. The data are used in the auxiliary program is from the Energy Plus Weather website. The data were collected from more than 1200 locations, especially from Cyprus, and the data contains 8760 hours of weather files such as beam, diffuse solar radiation on a horizontal surface. After that, the data are used in order to find total solar radiation and followed by maximum solar radiation. Finally, the optimum tilt angle is found with respect to the maximum solar radiation point. It means that at that point, the solar panel can be mounted.

The main objective of this study is to identify the optimum tilt angle for fixed photovoltaic panels for Cyprus's conditions for maximum annual energy yield. The project's goal is to propose a model to find the optimum tilt for the photovoltaic panels and the results that the PV installers can use within the country's market.

The thesis is organized as follows. Chapter 2 describes and discusses several methods for calculating annual optimum angles as a function of latitude, as well as their results and disadvantages of the methods, followed by evaluating the most recent methods. Chapter 3 presents the methodology and the data used to obtain the total maximum solar radiation and followed by the annual optimum tilt angle for the photovoltaic panels. Chapter 4 presents the results of five different methods and compared the results with the result of the proposed method. Chapter 5 discusses and describes the results of this thesis work and the main conclusions.

Chapter 2

LITERATURE REVIEW

This chapter describes the new comprehensive and valid approaches of computing optimum tilt angle for photovoltaic (PV) panels, which considers different factors. Moreover, this chapter presents the equations in the previous part to determine the yearly optimum angle point under Cyprus conditions.

2.1 Approaches Used in Calculating Optimum Tilt Angle for Solar Panels

The performance and efficiency of a solar panel are affected by its tilt and azimuth (orientation) angles. These two parameters change the amount of solar energy absorbed by the surface of the solar modules.

It is important to evaluate the optimum tilt angle at which maximum solar radiation is absorbed. The yearly optimum tilt angle is influenced by different factors such as the latitude of the location and the weather condition, shading, and air pollution, and in an urban application, can be affected by the surrounding obstacles [10]. . The best way to capture more solar energy is to use the solar tracking system. In the solar tracking system, the panel follows the direction of the Sun and collects the maximum radiation when the angle of Sun’s ray has to be orthogonal with the surface of the panel.

In 1990's, researchers have developed lots of methods to compute the optimum tilt angle for photovoltaic (PV) panels. According to Duffie and Beckman [11], in the northern hemisphere, solar panels should always face true Sou. The optimum tilt angle is associated with the day of the year, the local latitude. Duffie and Beckman recommended that $\beta_{opt} = (\phi+15^o) \pm 15^o$, Heywood [12]suggested $\beta_{opt} = \phi-10^o$, Lunde [13] and Garge [14] presented $\beta_{opt} = \phi\pm15^o$. There is another equation that was introduced by Lewis [15]. Lewis considers the optimum tilt angle as $\beta_{opt} = \phi\pm8^o$. Where β_{opt} and ϕ are optimum tilt angle and latitude of the location, respectively. In those formulas plus sign represents winter, and the minus sign means summer. Where β_{opt} is the optimal tilt angle and ϕ is the latitude of interest.

Nevertheless, those methods do not consider some important parameters such as clearness index, surface azimuth angle, diffuse radiation, hour angle related to sunrise and sunset, ground reflection.. It is very important that pay attention to precision and validation of the equation to find the optimum tilt angle. It means that a suitable method with considering all parameters leads to maximize solar energy collection and precise the optimum tilt angle.

2.2 Most Recent Methods

There is a wide range of mathematical methods and equations, and simulation packages to evaluate the optimum angle of a photovoltaic (PV) panel.

Stephanie White Quinn and Brad [16] demonstrated a simple, accurate approach to estimate optimum tilt angle for both fixed-tilt photovoltaic (PV) system and dual-axis tracking system. A particular feature of using this method considers the importance of the clearness index on the optimum tilt angle evaluation. This is because climatic conditions especially cloudy days and air pollution, can affect the value of the optimum tilt angle. A formula for this method is valid for every time in a day and on any day or month, or season of the year.

This straightforward equation is based on latitude, orientation known as surface azimuth angle, hour angle, transmittance absorptance product of the reflected and diffuse radiation stream, the reflectance of ground, declination angle, and clearness index. The optimum tilt angle for single-axis and fixed photovoltaic (PV) panels can be calculated by series of formulas. Also, these formulae are helpful for countries are in the northern hemisphere, and the panel regulates monthly, and likewise, for the fixed solar panels, the formula can be useful for primary installation.

In this method for proving accuracy and validation of the formula, Quinn and Brad [16] used Typical Meteorological Year (TMY3) that are accessible by National Renewable Energy Laboratory (NREL). The database contains hourly data of direct beam irradiation, diffuse horizontal irradiance, temperature, wind direction, wind velocity, and clearness index for over 300 geographic locations worldwide, with latitudes from 70◦ north to 70◦ south for over a 15-year period [17], [18].

This method suggested using the tracking and tilt angle formula for absorbing more energy. In addition, the method is recommended especially for the locations which sky cover with clouds, and the results for yield energy are more considerable in comparison with sunnier locations. For sunnier sites, it is proposed solar tilt angle and tracking formula is in accordance with the tilt angle equation.

In Quinn and Brad's study, the mathematical model for evaluating the optimum tilt angle was proposed. After calculation and consideration, the values of solar radiation, diffuse radiation, reflected radiation in the tilt angle formula (β), the optimal tilt angle formulas for different types of PV panel are shown in Table 1. Quinn and Brad defined solar radiation as the summation of the beam radiation and reflected radiation, diffuse radiation.

Equation 1 represents the yearly optimum tilt angle for the fixed tilt angle of a solar panel without any tracking. In the formula, the optimum tilt angle depends upon orientation, the latitude of the location and ground reflection, correlation of $g(k_T)$, and the transmittance-absorptance products for the diffuse and reflected irradiance.

$$\tan\beta_{opt,yearly} = \cos\gamma \ \tan(\varphi) \left[\frac{1}{1+\frac{((\tau\alpha)_d\, g(k_T) - (\tau\alpha)_r \rho g)}{2\,(1-g(k_T))}}\right] \quad (1)$$

where;

$\beta_{opt,\ yearly}$ = yearly optimal tilt angle (degrees),

γ = surface azimuth angle (degrees),

φ = latitude of the site (degrees),

ρ_g = ground reflection,

$(\tau_\alpha)_d$ = transmittance-absorbance product of the diffuse radiation stream,

$(\tau_\alpha)_r$ = transmittance-absorbance product of the reflected radiation stream,

$g(k_T)$ = the ratio of diffuse irradiance to global horizontal irradiance.

In equation (1), the 1 in the numerator and denominator should be replaced by the beam irradiance's transmittance-absorptance product. With assuming the transmittance-absorptance products for the beam, diffuse, and reflected irradiance components are all 1 [19], then this correction will not affect the calculation.

The authors supposed that there is no azimuth tracking, and it is particularly acceptable for south-facing solar panels. The equations follow the definitions presented in Duffie & Beckman's [11]. For a solar panel facing due South, Duffie & Beckman's convention is that the surface azimuth angle is 0 degrees. Other textbooks may use a different convention (that is, 180 degrees). Also, the authors assumed the average of yearly earth declination angle δ equals zero in equation (1).

Furthermore, the researchers consider the fixed-tilt south-facing solar panel and used the mean annual insolation clearness index, and the value of the albedo (ground reflection coefficient) is assumed to be 0.2 for all months during which the ground is free of snow. The value of 0.2 is the albedo value for the surface which is covered with less than one inch of snow or no snow, and the value of 0.2 is adequate for the majority of latitudes <60° and >-60° [20].

It is essential to consider the correlation between global solar radiation and its beam and diffuse components in order to obtain the clearness index. Therefore, the method [19] has been used, and the method is based on the regression analysis. Regression analysis of the measured hourly and daily for solar data shows the linear relationships for the diffuse fraction ($g(k_T)$) and clearness index (k_T) correlations. The attempt has been made to correlate the direct normal with the clearness index via third-order polynomial functions. Three k_T, have been considered, namely $0.15 \geq k_T$, $0.15 < k_T \leq 0.7$, and $k_T > 0.7$, and the values represent cloudy, partly cloudy, and clear sky conditions, respectively. The model has been developed for three periods of a year. In addition, the method suggested that diffuse correlation could be used for the cloudy sky (i.e. $0.15 \geq k_T$), and clear (i.e. $k_T > 0.7$) sky conditions, and for the partly cloudy sky, for $k_T \leq 0.5$ correlations between direct normal and the clearness index should be used to estimate the direct component, and for $k_T > 0.5$ linear correlations between diffuse fraction and the clearness index, can be used to estimate the diffuse component from global radiation. correlation of $g(k_T)$ is:

$$g(k_T) = \begin{cases} 0.977 & for\ k_T \leq 0.15 \\ 1.237 - 1.361k_T & for\ 0.15 \leq k_T \leq 0.7 \\ 0.273 & for\ k_T \geq 0.7 \end{cases} \quad (2)$$

Hourly clearness index (k_T) is defined as the hourly irradiation ratio on a horizontal surface (I) to the extraterrestrial irradiation on a horizontal surface for an hour period (I_0). For the clearness index k_T in (2), Quinn and Brad have gotten results using the annually-averaged insolation clearness index values given by the NASA Surface Meteorology and Solar Energy (SSE) [21]. In addition, the value of the clearness index depends on the location and is varies between 0 to 1.

Another method is introduced by Hassane Darhmaoui and Driss Lahjouji [22]. The purpose of Darhmaoui and Lahjouji's method is to find a relationship between yearly optimal tilt angle for solar panel and latitude of the site. In the Darhmaoui and Lahjouji's [22] study, both mathematical and computer modeling have been proposed by [22] for evaluating the optimal tilt angle. The authors have developed a model for computing the optimum tilt angle for maximizing the total amount of radiation hitting the surface of the photovoltaic (PV) panels by using the value of global radiation incident on a horizontal surface. In addition, another model is based on computer programming. It is used in calculating the optimum tilt angle under 35 countries in the Mediterranean Region.

At first, the researchers used Reindl's model to approximate solar radiation. This is because Reindl's model considers most of the important parameters that influenced global solar radiation, such as scattering aerosols and diffuse and beam radiation.

After considering beam, ground reflection, and diffuse radiation on an inclined surface parameter, the overall radiation incident that arrived at the surface is given by the following mathematical model:

$$H_T = (H_g - H_d)R_b + H_g\rho\frac{1-\cos\beta}{2} + H_dR_d \quad (3)$$

Where H_g,H_d, R_b,ρ, R_d, β are the monthly mean daily global and diffuse radiation on a horizontal surface, the ratio of the mean daily beam radiation on a tilted surface to that on a horizontal surface, the solar reflectivity, the ratio of the mean daily diffuse radiation on the surface and tilt angle, respectively.

For finding the value of daily global radiation, the authors used the NASA Climatology Resource [21]. The computer program (Mathematica 8.0) was used for estimating the yearly optimum tilt angle based on the point that solar radiation is maximum for each of the 35 countries. Therefore, the quadratic regression model has been used to determine the annual optimum tilt angle for absorbing maximum solar energy based on the latitude of the sites.

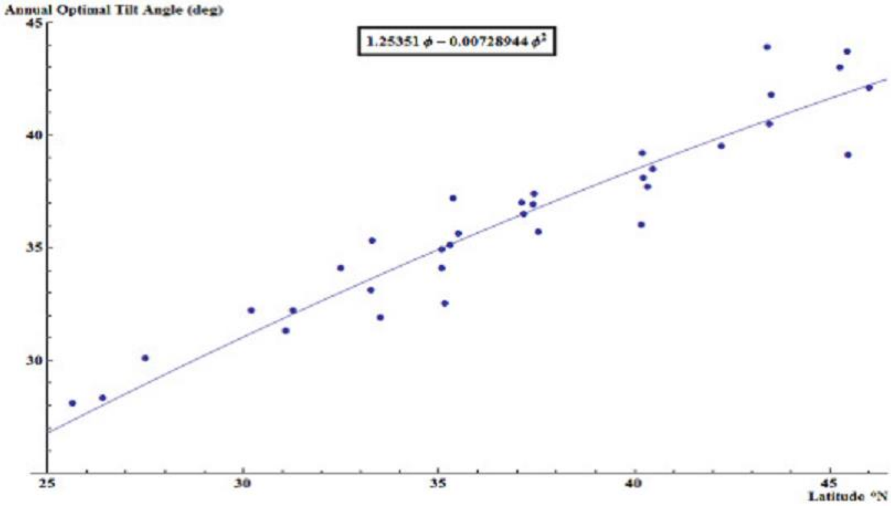


Figure 5: Scatterplot of the yearly optimum tilt angle with regards to the latitude of the location and plot the quadratic model [22]

Figure 5 indicates a scatterplot of the relationship between the annual optimum tilt angle and latitude of the location. As it can be seen, the data points are not set and close to the line. However, the points follow the line with a slow curvature. There is a quadratic dependency between the annual optimum tilt angle and latitude of the site. The usage of using a quadratic model is to match the data points with the line.

The quadratic regression model for predicting yearly annual optimum tilt angle regarding the latitude of the sites is given by:

$$\hat{Y} = 1.25351\phi_i - 0.00728944\phi_i^2 \quad (4)$$

where;

$\hat{Y}$ = the predicted yearly optimum tilt angle (degrees);

ϕ_i = the latitude of the location (i);

and the coefficient for the latitude of the sites means the orientation and slope of the curvature.

Equation (4) is suitable for the ranges of latitude between 25ºN and 46ºN.

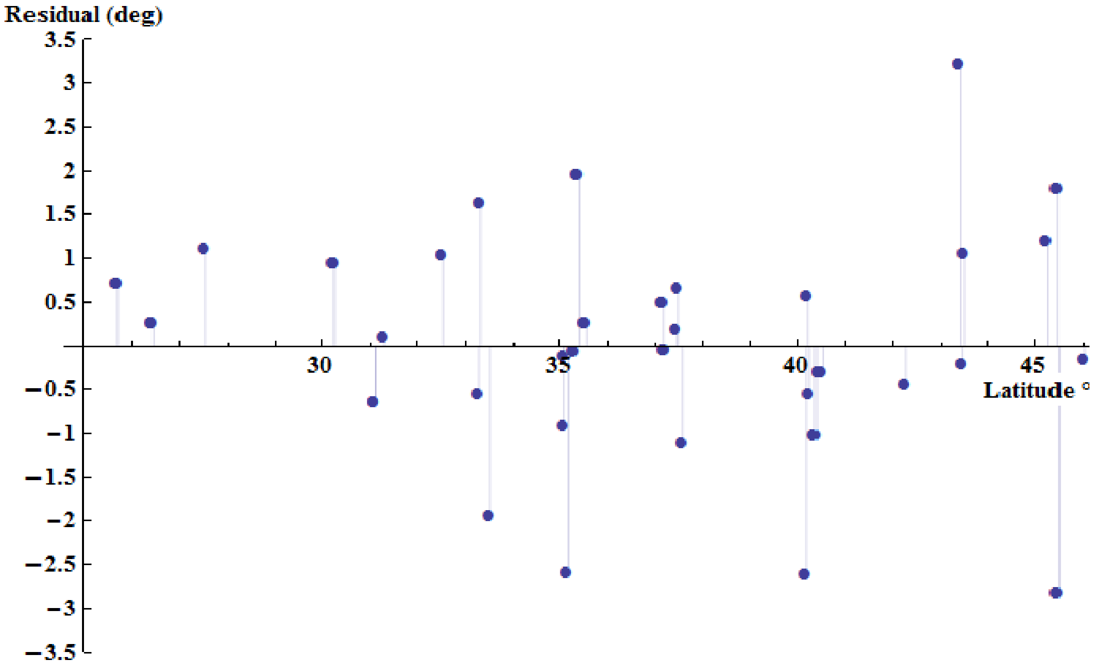


Figure 6: Optimum tilt angle residual plot

Figure 6 shows that the residual of the predicted optimum tilt angle from the real optimal tilt angle based on location's latitude for the 35 countries in the Mediterranean Region. The residuals change the values between 0.2º and 3.2º. It means that the model can estimate the appropriate value for the optimum tilt angle for maximizing solar radiation in the 35 sites.

In conclusion, the authors inspected a mathematical as well as a quadratic regression model to evaluate both real and predicted optimum tilt angle and obtained a precise prediction of the optimum tilt angle with the mean residual value of just 0.96º.

In Kemal Skeiker's [23] research, one of the most important factors for calculating the optimal tilt angle is extraterrestrial radiation for different latitudes as well as Syria. This is because in order to obtain the optimum tilt angle is necessary to maximize the amount of extraterrestrial radiation.

Kemal Skiker estimated one formula in accordance to the extraterrestrial radiation captured by a solar pane, and it is given by the following equation:

$$I_d = \frac{24}{\pi} I_0 \left[1 + 0.034 cos\left(\frac{2\pi n}{365}\right)\right] . [cos(\emptyset - \beta)cos(\delta)sin(h_{ss}) + h_{ss}sin(\emptyset - \beta)sin(\delta)] \quad (5)$$

where;

I_d = total extraterrestrial radiation on a tilt surface,

ϕ = latitude of the site,

β = tilt angle,

δ = earth declination angle,

h_{ss} = sunset hour angle.

After derivation and substitution, all parameters in the (5) with the exception of β parameter because all parameters are constant except tilt angle. Through the formula, the daily, monthly optimum tilt angle ($\beta_{opt,\,m}$) were calculated and given by:

$$\beta_{opt,d} = \emptyset - \tan^{-1}\left[\frac{h_{ss}}{sin(h_{ss})} tan(\delta)\right] \quad (6)$$

$$\beta_{opt,m} = \emptyset - \tan^{-1}\left[\frac{\sum_{n=n_1}^{n=n_2} \frac{24}{\pi} I_0 \left[1 + 0.034 cos\left(\frac{2\pi n}{365}\right) sin(\delta) h_{ss}\right.}{\sum_{n=n_1}^{n=n_2} \frac{24}{\pi} I_0 \left[1 + 0.034 cos\left(\frac{2\pi n}{365}\right) cos(\delta) sin(\delta)\right.}\right] \quad (7)$$

In equation (6), $\beta_{opt,d}$ is the daily optimum angle, and in equation (7), $\beta_{opt,m}$, n_1, and $n_2$are monthly optimum tilt angle and the first day and last day of the month, respectively.

A computer program used created by [23], and using (5 - 7) to find yearly, monthly, yearly optimal tilt angle for a solar panel as well as total extraterrestrial radiation. The annual total, monthly, daily extraterrestrial radiation on a surface is computed at β=0 and $\beta=\beta_{opt}$.

Also, Kamal Skiker compared the results were calculated by the software with another method developed by Nijegorodov et al. Nijegorodov et al presented that the clearness index has a significant influence on the optimal tilt angle in comparison with other weather condition. Nijegorodov considers β_{opt} equals zero for cloudy days. It means that there is no direct radiation on cloudy days, and the only thing that exists is diffuse radiation that can also be ignored because of its small value.

The yearly optimum tilt angle has a constant value, and different latitude has a different yearly optimum slope. Kemal Skiker calculated the yearly optimum slope as well as extraterrestrial radiation for Ssouth-facing solar panels and between the latitude of 0 – 60 degrees north, with the step of 5.

To be concluded, the value of solar radiation that is absorbed by the fixed tilt angle of the solar panel at the annual optimal tilt angle decreased with the amount of 12% in comparison to the monthly optimum slope. Moreover, by comparing two different methods, results show that in the Nijegorodov methods, the value of the optimal tilt angle is higher than Kemal Skiker's model. The reason is Nijegorodov method did not consider all parameters, especially for solar radiation.

Another method is developed by Arbi Gharakani Sirkani, and Pragasan Pillay [24] . The aim of the method is to improve the accuracy of the optimal tilt angle by taking into account lots of factors such as effects of shading, ground reflection radiation, sky blocking, and clearness index. Furthermore, the relationship between latitude and the optimum tilt angle was discussed with respect to the effects of the abovementioned factors. The method is suitable for the location is surrounded by trees or buildings and exposed to cloudier days.

Sirkani and Pillay improved and extended the Hay, Davis, Klucher, Reindl's (HDRK) model to obtain shading and sky blocking coefficients for direction and diffuse radiation formulas. The amount of sky blocking is calculated accurately with a computer program.

In [24] study, the relationship between the latitude of the desired location and the optimal tilt angle discussed, and it proved that with the small amount of latitude of the sites, the yearly optimal tilt angle is very close to the site's latitude, but the higher latitude leads to the smaller optimal tilt angle.

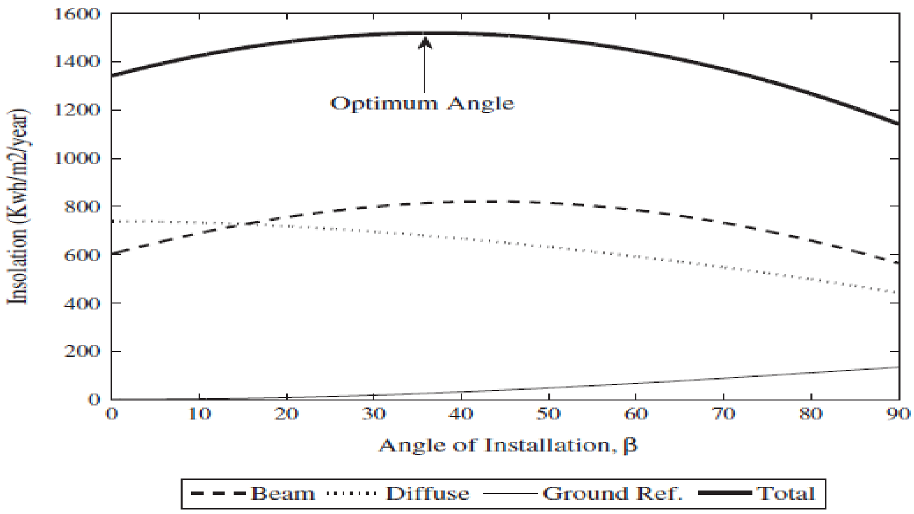


Figure 7: The participation of total radiation values ϕ=15º, k=0.5

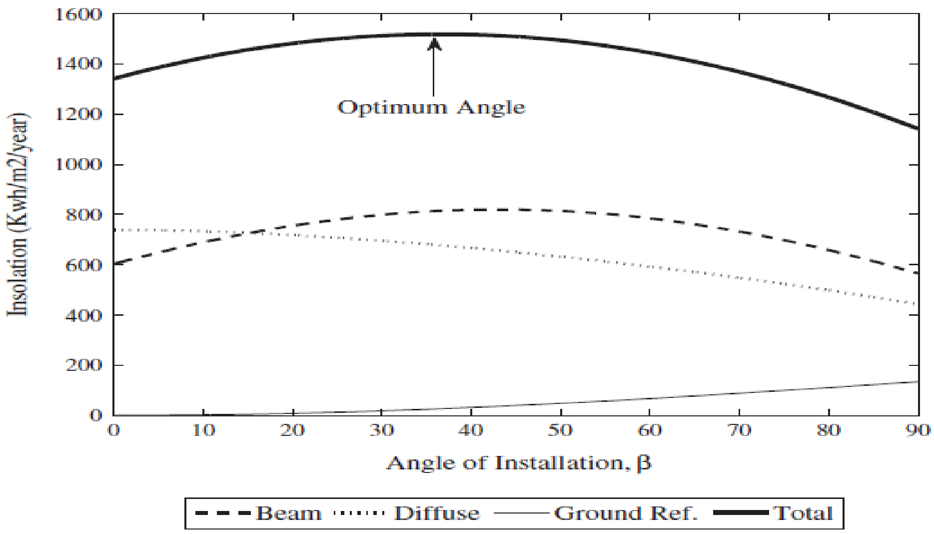


Figure 8: The participation of total radiation for ϕ=45º, k=0.5

Figure (7-8) shows that the participation of three different types of solar radiation. The maximum beam radiation is close to the optimal tilt angle. The summation of diffuse and direct radiation creates the dominant part of the total radiation. It means that the optimal tilt angle is smaller than latitude.

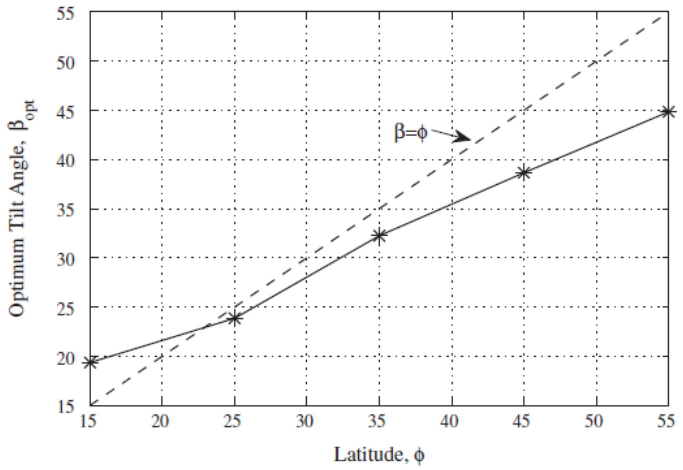


Figure 9: The relationship between latitude and the optimum tilt angle

Figure (9) indicates the relationship between the latitude of the interest location and the optimal slope with respect to the real climatic conditions. Also, it reveals that with increasing the latitude value, the amount of the optimal tilt angle declined with the exceptional value of 15º for latitude.

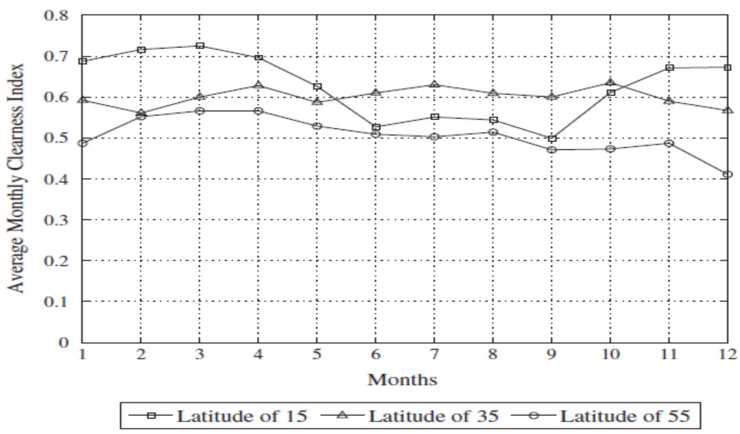


Figure 10: The plot of values of clearness index for three different latitudes

Figure (10) illustrates that for the latitude of 35º, the amount of mean monthly clearness index is approximately monotonous, and researchers propose that where monthly clearness index are approximately the same during a whole year, the optimal tilt angle can be equal to the latitude of the site. But for the latitude of 15 and 55 degrees, there is some fluctuation. It means that the amount of weather condition is very important, and can affect the value of the optimal tilt angle. Figure (11) compared the optimal tilt angle assuming two different conditions. The first condition is based on unshaded solar panels, and the optimal tilt angle is shown as $\beta_{op1,}$ and the second one is based on shaded solar panels.

The results reveal that the importance of considering obstacle coefficients in the beam and diffuse radiation formula.

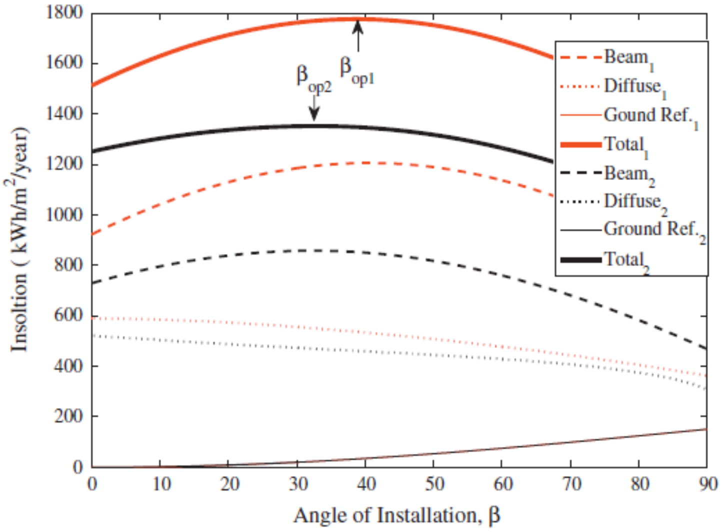


Figure 11: Influence of the obstacles on the optimal angle for ϕ=45º

Another method is introduced by Carolina Nicolas-Martín, David Santos-Martín, Monica Chinchilla-Sanchez [20] in order to find the annual optimum tilt angle. The method considers a series of global models to evaluate the annual optimum tilt angle as a function of three variables (latitude, diffuse fraction, and albedo). The models are based on the hourly radiation data of different sites spread worldwide from the One

Building database. The One Building database includes the meteorological data for 14,468 sites worldwide, from latitudes 83.5° to -90° [25]. The data consists of latitude, longitude, elevation, global horizontal irradiance (GHI), the direct (DNI) and diffuse (DHI) components.

The methodology of the study is a research-based model to evaluate the annual optimum tilt angle for each site around the world. In addition, the study investigated the impacts of several variables (latitude, diffuse fraction, and albedo) on the annual optimum tilt angle for a given site. The impact that the different variables have on the optimum tilt angle is identified by means of using robust linear-squares regression.

At the beginning of the study, the annual optimum tilt angle for every site with available data is calculated following a search-based model shown in Figure 12.

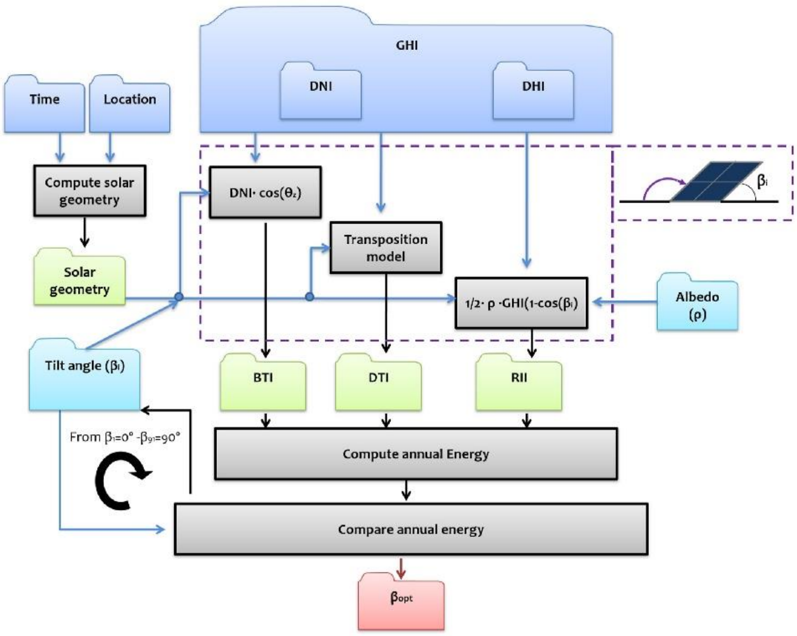


Figure 12: Search-based approach to obtain the annual optimum tilt angle [20]

Figure (12) illustrates that the input data is presented in blue, and the intermediate variables are green, and the outputs are red. The input data is taken from the One Building Database. The solar geometry data is evaluated based on the time and location values. The beam tilted irradiance (BTI) is computed through the solar geometry. Diffuse tilted irradiance (DTI) is calculated by using a diffuse transposition model, which was proposed by Perez [26]. Reflected incident irradiance (RII) is calculated as a function of the default albedo value which is considered 0.2 in the study. The annual energy can be obtained from the summation of BTI, DTI, RII for every angle between 0 to 90 degrees for a year. Finally, the tilt angle with a maximum resulting yearly energy is chosen as the annual optimum tilt angle.

Once the annual optimum tilt angle for the desired site is calculated, the study aims to find the mathematical model for the optimum tilt angle and the effect of the variables (latitude, diffuse fraction, and albedo) on it. Therefore, the study investigated the impact of each variable separately and described it as follows. Finally, the study proposed the worldwide model for the annual optimum tilt angle as a function of latitude, annual diffuse fraction, and annual albedo.

First of all, the study examines the influence of the latitude of the location on the optimum tilt angle. Polynomial regression is proposed in the study, and polynomial regression for northern latitudes (positive), southern latitude (negative), and both are considered. Finally, equation (8) is proposed as a mathematical model for worldwide applications for calculating the optimum tilt angle (β_{opt}) as a function of latitude (L).

$$\beta_{opt} = \begin{cases} -0.007021|L|^2 + 1.091|L| + 2.132, \; if \; -50° \leq L \leq 90° \\ 3.194 \times 10^{-5}|L|^2 - 0.008649|L|^2 + 1.099|L| + 1.891, \; if \; L \leq -50° \end{cases} \quad (8)$$

Secondly, the study determines the influence of diffuse irradiance on the annual optimum tilt angle. The best way to represent the relative annual amount of diffuse irradiance and its effect on the regression is the diffuse fraction, k_d, and the clearness index (k_T). The values of k_d, and k_T were obtained using the One Building data. The results for the k_d, and k_T show that sites with the lowest values k_d, also had the highest k_T values. However, the study proposes that the use of k_d, gave a better correlation with the optimum tilt angle data.

The annual value of the k_d can be obtained from the following equation (9):

$$k_{d_{annual}} = \frac{1}{n}\sum_{i=1}^{n}\frac{DHI_i}{DHI_i} \quad (9)$$

Where DHI_i and GHI_i are the hourly values, and n is the total of hourly data values for a year. The value of k_d can be computed based on the One Building radiation data according to equation (9).

In order to find the effect of the annual k_d on the optimum tilt angle, a polynomial regression analysis is used to quantify this impact.

$$\beta_{opt} = min\{3.334 + 1.213|L| - 0.1223k_{d_{annual}} - 0.002226|L|^2 - 0.6043|L|k_{d_{annual}}90° \quad (10)$$

The model, which is presented in equation (10), can be useful if the irradiation data for the annual k_d is available in the One Building database, and the data can be found through [27] for the desired location. Figure (13) shows that the geographical location and annual diffuse fraction values from the One Building data sites. As it can be seen in figure (13), there is a higher percentage of the annual diffuse radiation in the northern hemisphere than for those in the southern hemisphere.

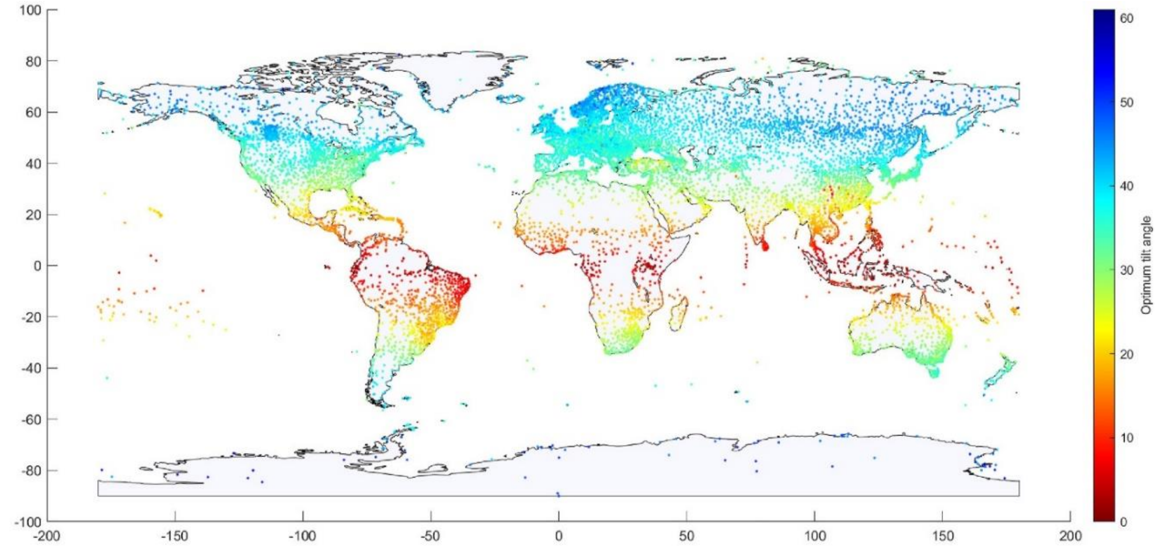


Figure 13: World plot of One Building sites and their diffuse fraction [20]

Thirdly, the study investigated the impact of albedo on the annual optimum tilt angle. Albedo is the measure of diffuse reflection of solar irradiation out of the total solar irradiation and is measured on a scale from 0 to 1. There is no specific value for the albedo in the One Building data set, and it is set to be 0.2 as default. This is because the albedo value is particular to each site. However, the real can significantly impact the value of the optimum tilt angle as well as annual energy yield.

The dependency of the optimum tilt angle on albedo and latitude has been examined by means of a polynomial surface regression, and the worldwide model is proposed in order to calculate the optimum tilt angle (β_{opt}) as a function of albedo (ρ) and the latitude and it is equation (11):

$$\beta_{opt} = -2.333 + 1.157|L| + 12.22\rho - 0.008627|L|^2 + 0.2766|L|\rho \qquad (11)$$

There is monthly data for the albedo value which is used to provide a reference for the annual albedo value map for the whole word shown in Figure (14).

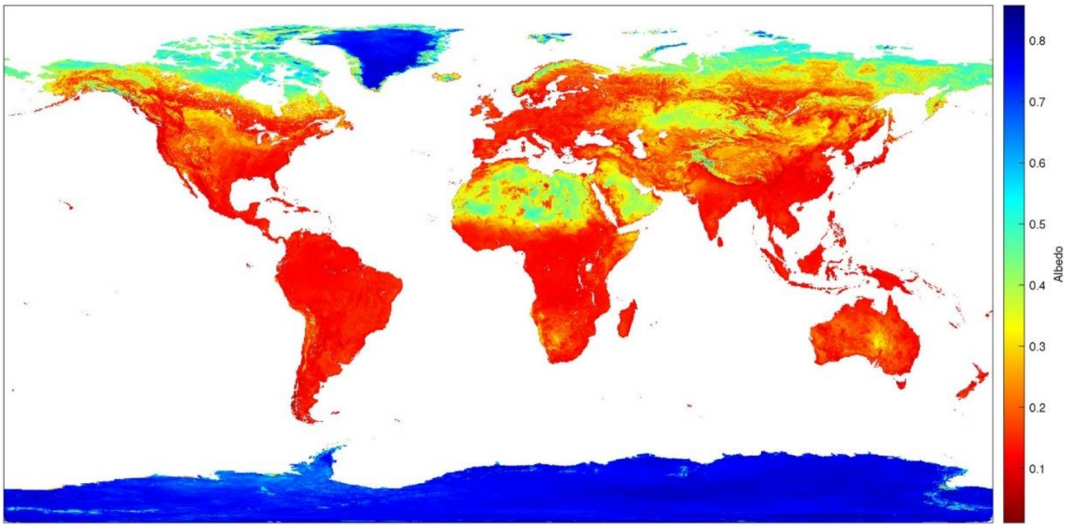


Figure 14: Annual albedo values [28]

As it can be observed from Figure (14), the default value of 0.2 for the albedo can be enough for the large part of the latitudes between <60° and >-60°.

Finally, the study proposed the final worldwide model for the annual optimum tilt angle, including all three variables (latitude, annual diffuse fraction, and albedo) in equation (12) and Table 1.

$$\beta_{opt} = P_{200}|L|^2 + P_{020}k_d^2 + P_{002}\rho^2 + P_{100}|L| + P_{010}k_d + P_{001}\rho + P_{110}|L|k_d + P_{101}|L|\rho + P_{011}k_d\rho \quad (12)$$

Table 1. Regression coefficients for the worldwide model

Regression coefficient									
P_{000}	P_{200}	P_{020}	P_{002}	P_{100}	P_{010}	P_{001}	P_{110}	P_{101}	P_{011}
-6.1038	-0.0045	-44.3249	11.5031	1.0660	37.0889	- 0.0101	-0.1735	0.2292	4.3645

Table 2 represents the comparison of five different methods considering the different conditions and with different parameters. Table 1 also reveals that the difference between the methods is very small except for Quinn and Brad [16] method. In addition, it shows that the optimum tilt angle by Hassane Darhmaoui and Driss Lahjouji [22], Kamal Skeikers [23], Arbi Gharakani Sirkani, and Pragasan Pillay [24] methods are very close to the latitude of Cyprus. The latitude of Cyprus is 35 degrees, and it means that the methods of Hassane Darhmaoui and Driss Lahjouji [22] and Carolina Nicolas-Martín, David Santos-Martín, Monica Chinchilla-Sanchez [20] are too close to the latitude of Cyprus.

Table 2. Comparing the optimum tilt angle by five different methods

Method	Parameters used	Latitude (Degree)	Optimum tilt angle (Degree)
Quinn and Brad [16]	Clearness index	35	25.64
Hassane Darhmaoui and Driss Lahjouji [22]	Global solar radiation	35	34.94
Kamal Skeikers [23]	extraterrestrial radiation	35	32
Arbi Gharakani Sirkani, and Pragasan Pillay [24]	Shading, ground-reflected, clearness index	35	31.94
Carolina Nicolas-Martín, David Santos-Martín, Monica Chinchilla-Sanchez [20]	Latitude, diffuse fraction, albedo	35	34.37

Chapter 3

METHODOLOGY

The main objective of this thesis is to find the optimum tilt angle of PV panels for Cyprus in order to maximize the yearly cumulative energy output for Cyprus. The solar panel is assumed to be unshaded, as a fixed tilt angle, and faces the south.

3.1 Data

In this project, it is necessary to consider most of the conditions such as clearness index, the latitude of the location, direct normal radiation, diffuse horizontal radiation, global solar radiation, longitude, elevation (altitude), time zone, solar angles that influence the optimum tilt angle. If the number of parameters can affect results increased, the accuracy of the results also increased. The most important factors that influence the optimal tilt angle is clearness index, humidity, wind speed, types of application such as off-grid or on-grid, shaded or unshaded photovoltaic (PV) array.

It is very important to use appropriate and accurate data files for the project. The data file must include clearness index, humidity, wind speed, types of application such as off-grid or on-grid, shaded or unshaded photovoltaic (PV) array condition. Over the past 20 years, several researchers developed hourly weather data sets. Energy simulation programmers have lots of weather data from which to select from locally recorded weather data to preselected ‘typical’ years.

In the last five years, several researchers and organizations have designed new or updated typical weather data sets. Each of these data sets includes a whole year of hourly data (8,760 hours) combined to show long-term statistical trends and patterns in weather data for a longer period of record. Each designer developed its data sets to meet a particular need, such as typical weather patterns, solar radiation. All groups consider their weather data sets to be available with energy performance simulation programs.

There are many sources for obtaining the weather data files. Some of the most used sources of the data are the Energy Plus website [29] has gathered together simulation weather data from different sources around the world and converted them to a single standard weather data format (EPW), another source is ASHRAE [30] ASHRAE has collected weather data from the International Weather For Energy Calculation (IWEC) and converted to a single data format (CSV), the third one is Typical Meteorological Year 3 (TMY3), TMY3 has collected weather data through the National Renewable Energy Laboratory (NREL) web site and the weather data is useful just for sites in the United States. Also, other organization and designers have created their own weather data files.

The data files used in the project are through the Energy Plus weather (EPW) Data website [29]. The EPW data file was designed by the US Department of Energy (DOE) to be a standard weather data format to that multiple other data formats could be converted. The DOE provides a collection of thousands of weather files from throughout the world on their website [29].

In Energy Plus weather [29], Weather data for more than 2092 places are now accessible. The EPWs were made by converting the source data into the EPW format. The data is covered 1042 sites in the USA, 71 sites in Canada, and more than 900 places in 100 other countries around the world. The weather data are ordered by the World Meteorological Organization Region and Country. The EPW is also considered for use in software or another programmed computer.

3.1.1 Energy Plus Weather

The EPWs are series of data every hour of values of meteorological elements and solar radiation annually. The EPW weather file includes weather data for all 8760 hours of a whole year. The reason for and validation of using [29] as references of the project is the weather data is derived from 20 different and valid sources based on each country.

All the data collections are based on real recordings from official weather stations throughout the world coming back up to 25 years and stored as the Integrated Surface Hourly Database (ISD) by the U.S. National Center for Environmental Information (NCEI). Widespread processing equivalent in scope to the TMY3 files resulted in complete weather files with total solar radiation, daylight illuminance, moreover to the standard factors of temperature, relative humidity, air pressure, wind speed, wind direction, etc.

The Energy Plus weather data files (EPW) include hourly data for the values of weather data such as wind speed and relative humidity, etc., the values of weather data files the immediate measurements at 1:00 am, and 2:00 am, 3:00 am, and so on. This is because one hour in Energy Plus is less than one hour because of using zone time steps. These amounts are linearly interpolated for every time step. The data values reported from Energy Plus at a time step frequency set the data file one the time step hourly on the hour, and it means that weather data reported at the hourly frequency shows that the mean of values over one hour. Consequently, they will not set the immediate value in the weather data file.

The values of the solar radiation in the weather data file are integrated total values for one hour. So, the total radiation in-unit Wh/m^2 is used as a mean rate for the hour in-unit W/m2. Also, this average is supposed to be the amount at the midpoint of the hour, and linear interpolation is used to evaluate the amount for each time step. The stated solar values in the output will set the amount in the weather data file on the half-hour.

In addition, the Energy Plus weather (EPW) is suitable for the project because EPW consists of most of the parameters that influence the optimum tilt angle of a fixed solar panel, such as humidity, relative humidity, wind speed, wind direction, direct normal radiation, diffuse horizontal radiation, global solar radiation, clearness index (total sky cover).

Furthermore, EPW data provides information about the location of interest (latitude of a location, longitude, elevation (altitude), time zone, solar angles).

3.2 Methodology

In order to find the yearly optimal tilt angle for a fixed solar panel for maximum solar radiation collection under Cyprus conditions, a method is proposed for this project.

The method is based on an algorithm, and a program is developed to find the annual optimal tilt angle for maximizing energy output.

In this method, a computer program is used to design 3-D modeling with the help of one auxiliary or plug-in program. It means that 3-D modeling programs and auxiliary programs are designed to combine geometrical subjects with an algorithm to solve some design issues. The algorithm is created in the auxiliary program, and the outputs of the algorithm run within the 3-D program.

In the auxiliary program, there are two types of objects. One of them is parameters can usually store data, and another one is components perform some action such as making curves or surfaces.

The algorithm is used to calculate the optimum tilt angle for maximizing solar radiation collection based on the Energy Plus Weather file (EPW). Each of the algorithms has its own properties, and each algorithm is useful for some parts of the project. The algorithms create by dragging and dropping the components or parameters onto a canvas. Some objects draw stuff and generate data; some of them control and handle an already existing geometry or data. Parameters are objects that represent data and store it like a point. The objects can be drawn by relevant parameters, or they can be defined as manually from drawn objects of 3-D program’s workplace. The outputs of each algorithm are connected to the inputs of the subsequent algorithm. After connecting the components, the results will be run within the 3-D computer application.

In the method, most of the conditions that influence the optimal tilt angle is taken into account based on the values inside the Energy Plus weather (EPW), such as latitude of the location, humidity, wind speed, and direction, diffuse and beam radiation. It means that the results should be more accurate and precise.

3.2.1 Tilt Orientation Factor Algorithm (TOF)

Tilt and Orientation Factor is the solar radiation at the real tilt and azimuth divided by the solar radiation at the optimum tilt and azimuth.

The tilt and Orientation Factor (TOF) component is used in order to find the annual optimum tilt angle for PV modules. TOF component does not use a single formula to evaluate its optimum tilt or azimuth angles. TOF component computes the optimum tilt and azimuth based on annual incident solar insolation.

In order to find the diffuse parameter of the annual incident solar insolation for each point, the Perez [31] modified model. The equation is given as follows:

$$D_c = D_h[0.5(1 + cos(\beta))(1 - F_1) + F_1(cos(AOI)/\, cos(Z)) + F_2\, sin(\beta)] \qquad (13)$$

where;

D_c = Diffuse radiance incident on a tilted surface (kWh/m^2),

D_h = Diffuse radiance on the horizontal surface from EPW file,

β = Plane tilt angle (degree),

AOI = Incidence angle on the tilted plane,

F_1 = Original circumsolar brightness coefficient,

F_2 = Original horizon brightness coefficient,

Z = Solar zenith angle (degree).

The coefficients (F1 and F2) were obtained from the least square fitting of equation (13) to real data recorded on the sets of sloping pyranometers [31]. Moreover, beam (direct) solar radiation is the part of the total incident solar radiation, which is the capture from the Sun without atmospheric scattering. The value of direct radiation on a tilted surface from the horizontal surface and rotated from the north to south axis is calculated by multiplying the horizontal beam irradiation by the incidence angle [32].

$$I_b = E_b \cos AOI \tag{14}$$

where;

I_b = Beam radiation (kwh/m^2),

E_b = Beam radiation on a horizontal surface from EPW file (kWh/m^2),

AOI = Incidence angle.

Furthermore, the ground reflected component of the annual incident solar radiation for each point is calculated by the following equation [33]:

$$I_r = \rho(E_b \cos Z + D_h)\frac{(1-\cos\beta)}{2} \tag{15}$$

where;

I_r = Ground reflection (kwh/m^2),

ρ = Albedo (ground reflectance),

E_b = Beam radiation on a horizontal surface from EPW file (kwh/m^2),

Z = Sun zenith angle (degree),

D_h = Diffuse irradiance from EPW file (kwh/m^2),

β = Tilt angle (degree).

In equation (14,15), the values of AOI (incidence angle) can be defined as the angle between direct radiation and a line normal to the surface. The value of the AOI can be obtained by the following equation. AOI is a function of the surface and sun azimuth-tilt angle.

$$a = \sin Z \cos(\gamma - \gamma_s) \sin \beta_s + \cos Z \cos \beta_s$$

$$AOI = \begin{cases} \pi & if\ a < -1 \\ 0 & if\ a > 1 \\ arccos a & if -1 \leq a \leq 1 \end{cases} \tag{16}$$

where;

AOI = Incidence angle,

Z = Zenith angle (degree),

γ = Sun azimuth angle (degree),

γ_s = surface azimuth angle (degree),

β_s = surface tilt angle (degree).

In equation (16), surface tilt angle and azimuth tilt angle values for a fixed panel is given as follows:

$$\beta_s = \beta_0$$

$$\gamma_s = \gamma_0$$

where β_0 is tilt angle and γ_0 is azimuth angle.

The total solar radiation on the surface is the summation of beam diffuse and ground-reflected solar radiation:

$$I = I_b + D_c + I_r$$

After considering all parameters for total incident solar radiation, TOF creates a grid of points. Each point represents the computed annual radiation on the surface for a single tilt and azimuth angle. Each point is then elevated with regard to the annual insolation values. The mesh is made from that grid of points. The contribution of the mesh, which is the highest, represents the optimal tilt and azimuth angles. So, with increasing the precision, the more points in a mesh it will have as well as the more accurate the final optimum tilt angle will be.

TOF component yield is pretty accurate results because for crystalline silicon modules (which is what Auxiliary Program Photovoltaics components support) the generation of AC energy depends mostly on the solar radiation. But, the AC energy output also depends upon air temperature and wind direction, and speed. A smaller percentage of the solar radiation will be converted to AC energy output while the rest will be converted into heat and increase the temperature of the photovoltaic (PV) module. The higher this temperature means the smaller the AC energy output. This is why low air temperature and high wind speed can help photovoltaic (PV) modules to cool down and increase the final AC energy. So, basically, even though solar radiation plays an important role in the determination of the optimal PV surface angles, air temperature and wind speed can too, to some degree. It assumes this happens in specific locations where there is a significant diurnal temperature and wind speed variation. For example, in the morning, in the arid, desert-like locations, maybe gorges. But air temperature and wind speed are likely to affect the optimal azimuth, then tilt. The TOF component will find the optimal azimuth to be 181.5. While the optimal one maybe 180.5, gravitating towards the east and the cool and windy morning. Still, the differences are really small.

Figure (15) indicates the process of finding the optimum tilt angle in order to maximize the cumulative energy output for Cyprus. There are two main stages in the process, beginning with the EPW data file about the weather. This information is then evaluated and prepared by TOF in order to find maximum total solar radiation and finally optimal tilt angle.

As is observed from the flowchart, at the first stage of the process, the outputs of the EPW file include information of the beam and diffuse solar radiation on a horizontal surface and hourly data file. The hourly data file contains 8760 hours of data, and the data are used for finding azimuth and zenith angle.

In the second stage of the process, the data are fed in the beam and diffuse and ground-reflected solar radiation in order to calculate total solar radiation with respect to different tilt angles between 0 to 90 degrees by TOF.

The final information was analyzed to know the maximum value of total solar radiation with respect to a different angle, and according to that point, the optimum tilt angle can be found.

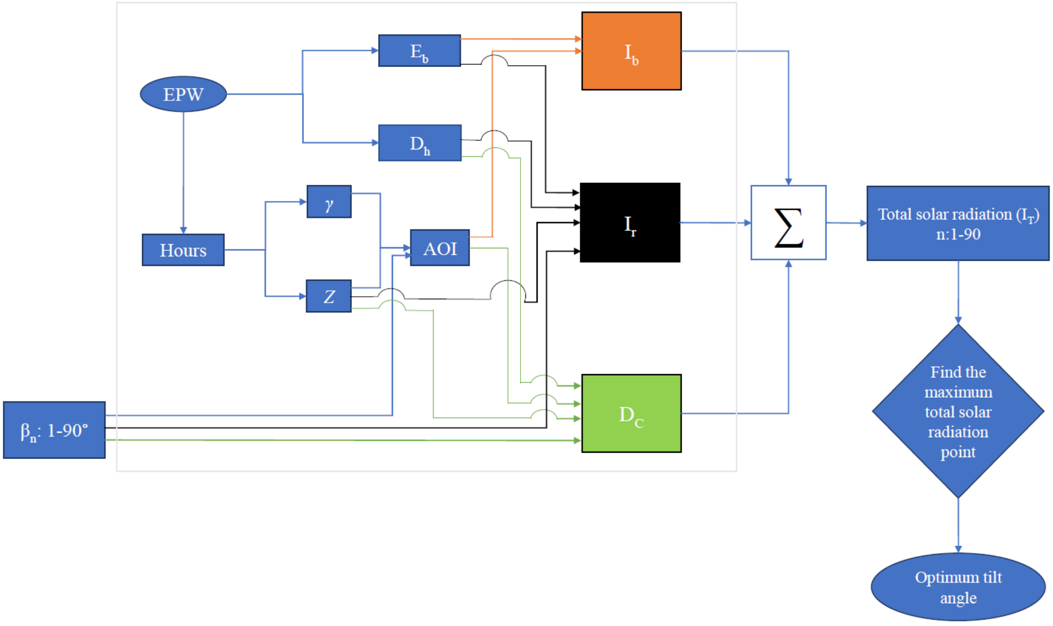


Figure 15: The process of finding optimum tilt angle in order to maximize the cumulative energy output

3.2.2 Implementation of the TOF Algorithm

The program and auxiliary programs that are being used in this project are Rhino 3d, Grasshopper, Ladybug. Rhino 3d is a platform that can make, edit, render, animate, and translate Non-Uniform Rational B-Splines (NURBS) curves, point clouds, polygon meshes, surfaces, and solids with no limits on complexity, degree, or size. Rhino is a free-form Non-Uniform Rational B-Splines (NURBS) surface modeler, and it is based on NURBS mathematical model. NURBS are mathematical representations of 3-d geometry that can describe any shape from a simple 2-D line, circle, arc, or curve to the most complex 3-d organic free-form surface or solid.

Grasshopper is a plug-in for Rhino 3d, and it is a graphical and visual algorithm editor tightly integrated with Rhino's 3-D modeling tools. It means that Rhino creates and works on real 2d/3d geometries while the Grasshopper program works on the algorithm behind those real geometries. In addition, Ladybug is an open-source environmental plug-in for Grasshopper 3d and a parametric environmental plug-in for Grasshopper to help designers and engineers create an environmentally conscious design. Furthermore, Ladybug imports the energy plus weather data (EPW) files in Grasshopper and provides a variety of 2D/3D designer-friendly interactive graphics.

There lots of components and parameters in the Grasshopper and Ladybug program, that each of them has its own usages. The parameters and components that are used in order to obtain the optimum tilt angle for maximizing the energy output in the project are further as follows discussed.

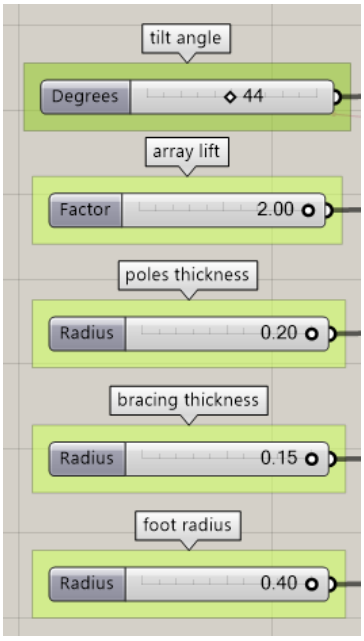
3.2.3 Solar Panel Algorithm

There are different types of objects to create the solar panel. In this project, most of the useful and practical components are considered, and each algorithm and the properties of each of them is discussed step by step in detail. At the end of each step, the component or parameter icon is shown. The main screen of the plug-in software (Grasshopper), which has all these components, is shown in Appendix A.

Step 1: The first parameter that is used in the project is Number Slider. A slider is a special jointing parameter that allows for the quick setting of individual numeric values. The values of the number slider can be changed through the slider editor, such as changing the slider types (integers, odd or even numbers) or changing numeric values and domain. The slider has just one output.

Five number sliders are used in the project. The sliders are tilt angle, array lift, poles thickness, bracing thickness, foot radius. The tilt angle slider is various between 0 to

90 degrees, and it was used in changing the slope of the solar panel. , The array lift slider is for changing the height of the panel with the values of between 0 to 2 meters. Poles and bracing thickness are used for changing the leg's thickness of the panel with the amount of between 0 to 0.2 and 0 to 0.15, respectively. The foot radius slider is for changing the radius of the panel's foot with values between 0 to 0.40 meters.



Step 2: The object is created in the 3-D model program and then set on boundary representation (Brep). Brep gives a full description of an object by associating topological and geometric information. In this case, objects are described by their boundary. For instance, an edge lies on a curve and is bounded by two vertices. Figure (16) shows the data structure of brep for topological and geometric information.

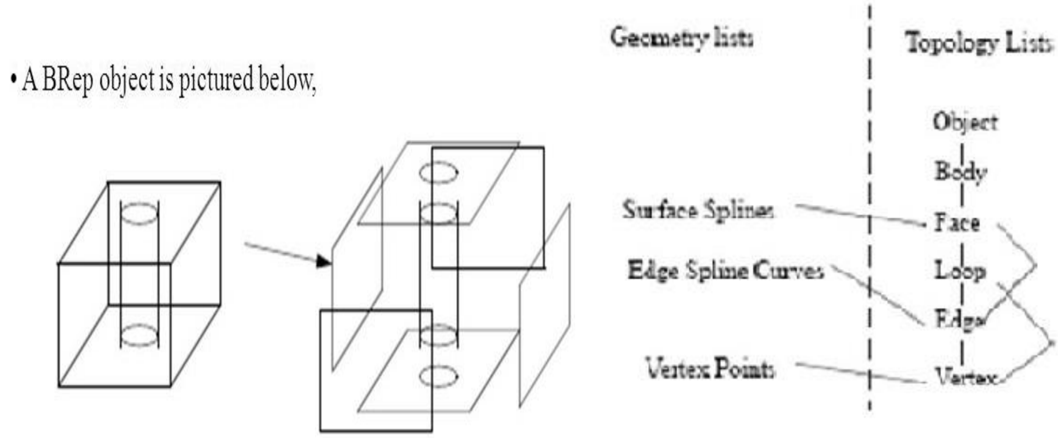
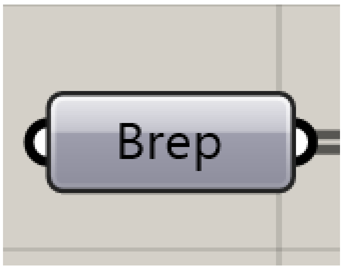
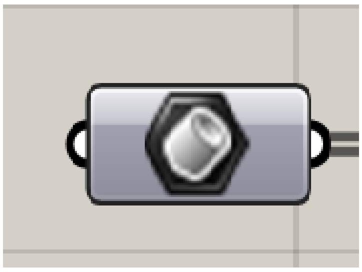
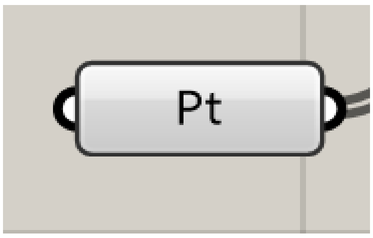


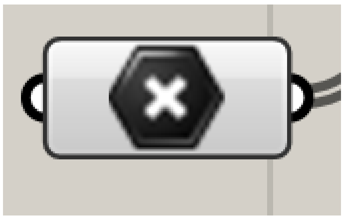
Figure 16: Brep object sample



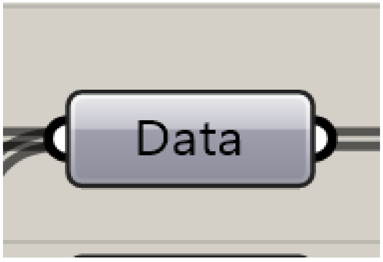


Step 3: in this step, the point parameter data is used for storing the data. The parameter is defined by any sort of information, and it represents a set of 3D point coordinates. Point parameters are able to store persistent data.

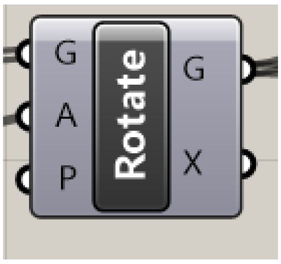


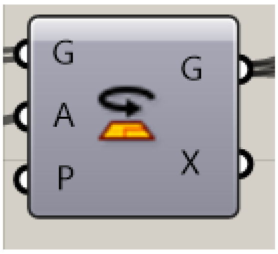


Step 4: The outputs of the Brep and point parameter goes into the input data parameter. The reason why data parameters are used is to collecting both brep and point parameter information into a data parameter.

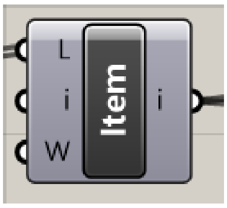


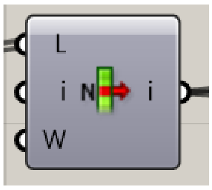
Step 5: After collecting the data, the outputs of the data parameter are connected to the input of rotate component. The rotate component cannot store the data, and it only performs some action. The component is used by rotating the object on a plane. There are three inputs and two outputs in the component. The inputs include geometry (G) that is connected by the output of data parameter, number (A) represents the angle of rotation, and plane (P) represents a set of plane primitives. Planes can be defined by an origin point and three-axis vectors. The outputs of the components include rotated geometry (G) and transformation data (X) that represent a collection of 3-D linear transforms.





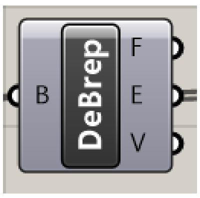
Step 6: The outputs of the rotate component are connected to two components. The first component is discussed in this step, and another one is discussed in step 9. The list item tool is a very useful tool to organize and list the important information that needs outputs or in other words recalling a specific item from a list. The list item component consists of three inputs as well as one output. The inputs are generic data (L), integer (i) that represents a set of integer numeric amount and Boolean (W) that represent a set of true or false values. The output of the component is generic data (i) or a list of important information that needs.

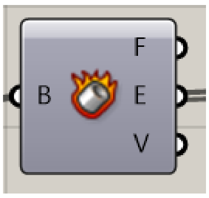




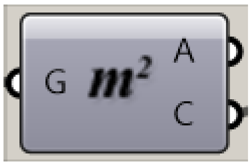
Step 7: The output of the list item component is divided into two parts. The first part is connected to the input of deconstructing brep, and the second one is connected to the input of the area component. Deconstruct Brep is used for deconstructing the brep into its constituent parts such as edges or surfaces, or vertices. And the component has one input, namely brep (B), and three outputs, namely surface (F), curve (E), point (V). Also, the area component is used for centroid the area of the brep.

Deconstruct Brep





Area

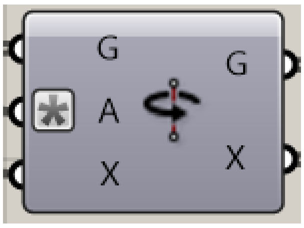


Step 8: After considering and choosing the edge in Deconstruct Brep, the output of the component connected to the input of list item component to choose some information that needs to be in the outputs. The output is a line like a curve, and it is used for step 9. Then the output of the list item is branched into three parts. One of them is the preview component that is used for customizing geometry previews, and there is no output for this component. There are two inputs, namely geometry (G) that is used for preview the geometry and shader (S). Usually, the preview component is just for affecting visual elements of the program, and this component can be used to add color or text to geometry generated into the 3-D program. The second one is the rotating axis that is discussed in step 9.

Step 10: In this step, with the help of a component, the panel is going to be rotated. The component is Rotate Axis that can be defined as rotating an object along an axis. The component has three outputs and two inputs. The inputs are geometry (G) that is linked by the output of a rotate component in step 5. The second input is the angle (A)

that is connected by the output of the number slider (tilt angle) in step 1, and the radians component is used between the rotate and number slider to convert degree to radians. The third one is the axis (X) represents a set of line primitives that are connected by list item in step 9. The outputs are geometry (G), and transform parameter (X) represents a set of three-dimensional linear transforms.

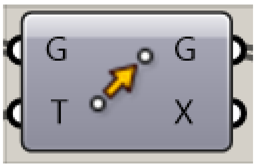
Rotate Axis



Radians

Step 11: The thing that is needed in this step is to rotate the panel along a plane. Because the panel is facing true the south. The component is Rotate, and it is used for rotating the panel. The inputs are geometry and plane which are connected by the output of geometry in the rotation axis (step 10) and area centroid (step 7). The outputs are geometry and transform.

Step 12: The position of the panel is not exactly on the legs. The element that can change the position of the object is the Move component. The inputs are geometry and motion (V), which are linked by the output of rotate component (geometry) in step 11 and number slider (array lift) in step 1, and between the number slider and motion, the unit element is used to move the panel along the z-axis. The outputs are geometry and transform.



Step 13: After moving the panel along the z-axis, in this step, the values of Brep and integer number are separated by the Split component. The component has two outputs and two inputs. The inputs are list (L) and splitting index (i), which are adjoined by the output of the move component (geometry) and the integer number, respectively. The outputs are list A and list B, which separate the Brep values and integer values.

Step 14: in this step, the purpose is to create poles of the panel. Firstly, circle and deconstruct component are used for creating circle by base plane as well as the radius of the circle and deconstructing points into its component parts (X,Y,Z), respectively. The inputs of circle components are plane radius parameters which are connected by

split component (list B) in step 13 and number slider (poles thickness) in step 1, respectively, and the output is the resulting circle. Deconstruct component has one input, namely point (P), and three outputs, namely component parts (X,Y,Z). In the end, for creating the poles of PV panel, a extrude modifier is used for extruding the curves and surface along a vector. A unit vector (Z) is used.

Figure (17) shows the steps as well as the parameters and component's icon for creating the poles of the photovoltaic (PV) panel.

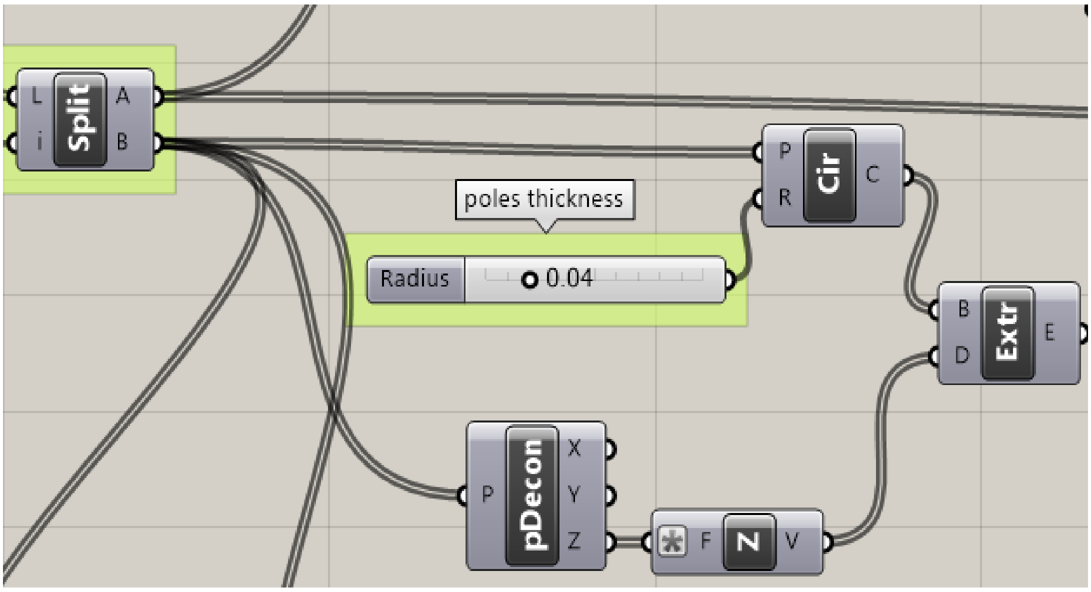


Figure 17: The steps of creating poles of PV panel

Step 15: In this step, the bracing of the photovoltaic (PV) panel is created by some components and algorithms. The first step is adding a project component to project the panel on a plane. After projecting, the values of z=0. The component inputs contain geometric that is connected by the output of split component (list B) and projection plane. The outputs are projected geometry and transformation data.

Then, splitting the values by connecting the input of the split component (list B) in step 13 to the input of two new split components. Both of the new components have the same values of three for integer numbers. But, the difference between them is in the input. The first split component is directly connected to the output of the split component (list B) in step 13, while the second split component is connected by the output of the project component (projected geometry).

After splitting, the values by two different split components, the output of the first split component is connected to the input of the line component (line start point A), and the second one is linked to the input of the line component (line end pint B). According to the inputs of the line component, the output is a line segment.

After creating the line, the brace of photovoltaic (PV) panel is made by pipe component. The component consists of three inputs, namely curve (C), pipe radius (R), integer (E).

The curve is connected to the output of the line component, and the radius is linked to the output of the number slider (bracing thickness). The output is the resulting pipe that is a brace of the solar panel.

Figure (18) indicates the process of creating a photovoltaic (PV)’s brace.

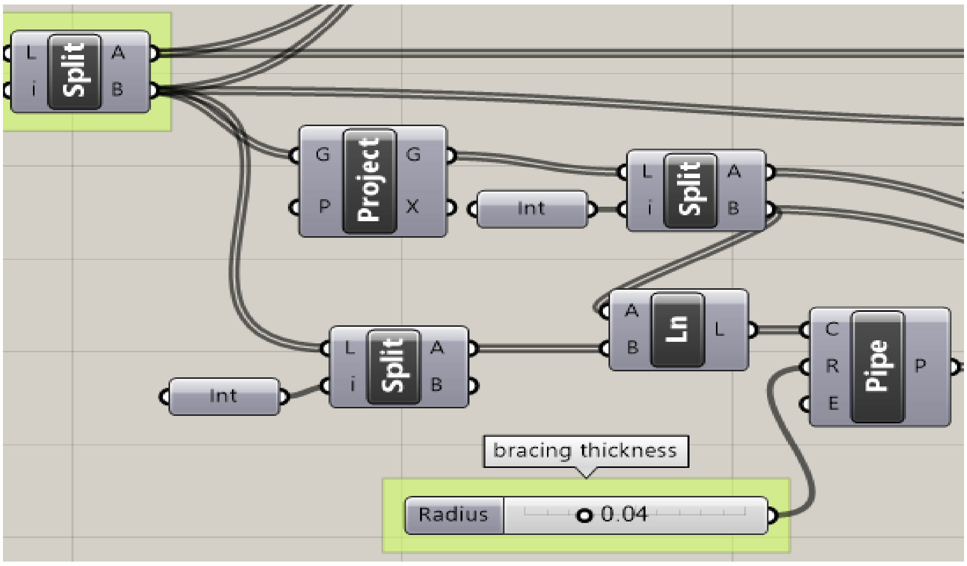


Figure 18: Creating braces of PV panel

Step 16: In this stage, the panel's foot is created by a different algorithm. The components are circle, boundary surfaces, unit vector, and extrude.

First, circle component is used to create eight circles, and it has two input which is connected to the outputs of the split component as well as slider number (foot radius) for changing the thickness of panel's foot.

The output of the component, namely the resulting circle, is linked to the input of the boundary surface (boundary curve (E)) parameter. The usage of this parameter is to make planar surfaces from a set of boundary edge curves. The result of the parameter is the trimmed surface. After that, the results of the boundary surface parameter go into the input of extruding modifier to create the panel's foot. Another input is linked by a unit z-direction vector to change the foot's height. The result is eight circles, namely solar panel's foot.

Figure (19) illustrates the stages of creating a solar panel’s foot.

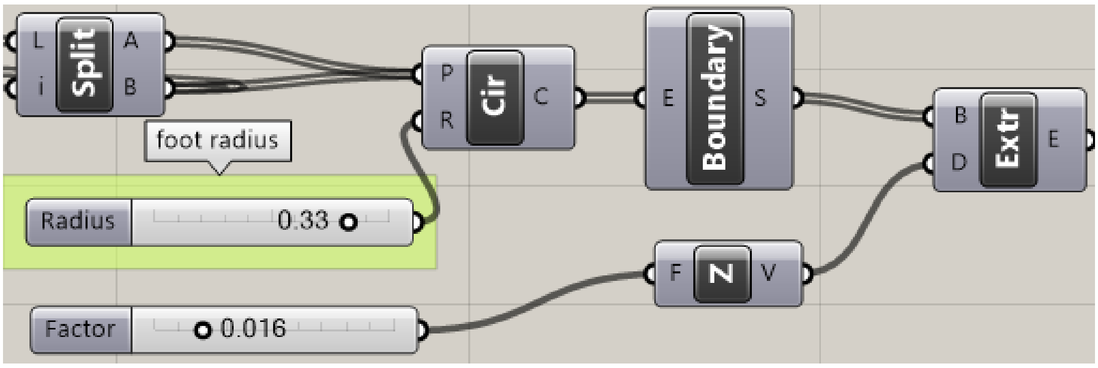


Figure 19: The process of creating solar panel's foot

Step 17: in this step, the direction of the panel is created by item and evaluation surface components. Evaluate the surface component calculate the surface based on the panel’s surface and UV coordinate. The result (output) is a point and a vector that represents the PV panel’s direction. The layout of the software for the solar panel is shown in Appendix B.

3.2.4 Tilt and Orientation Factor (TOF) Algorithm

The TOF component is available in Ladybug, and it is used to find optimum tilt angle in order to maximize energy output. Moreover, the TOF calculates the optimum tilt angle for a whole year. It works based on the Energy Plus Weather (EPW) files, and for running the EPW files, the Boolean Toggle is used. Also, the TOF component calculates the optimum tilt angle with regards to the EPW files and photovoltaic surface that is created already. Programming codes for the total annual solar radiation and the TOF components are added in Appendix C.

Furthermore, there is a component inside the TOF that allows increasing the accuracy of the results. The component is Precise, and it represents that the higher precision input leads to more points in a mesh as well as the more precise final optimal tilt and azimuth.

Chapter 4

RESULTS AND DISCUSSIONS

In this chapter, the results of the data analyzed are presented and discussed. The data were analyzed and evaluated, and it processed by TOF component to obtain total solar radiation and followed by maximum solar radiation as well as the optimum tilt angle.

Furthermore, according to the stages of calculating total solar radiation and the optimum tilt angle in figure 15, the results of each stage is discussed.

Figure (20-21) illustrates the information about both average monthly beam and diffuse solar radiation from the output of the EPW file for Larnaca. The information is related to the beam and diffuse solar radiation on a horizontal surface. The information was collected for 8760 hours.

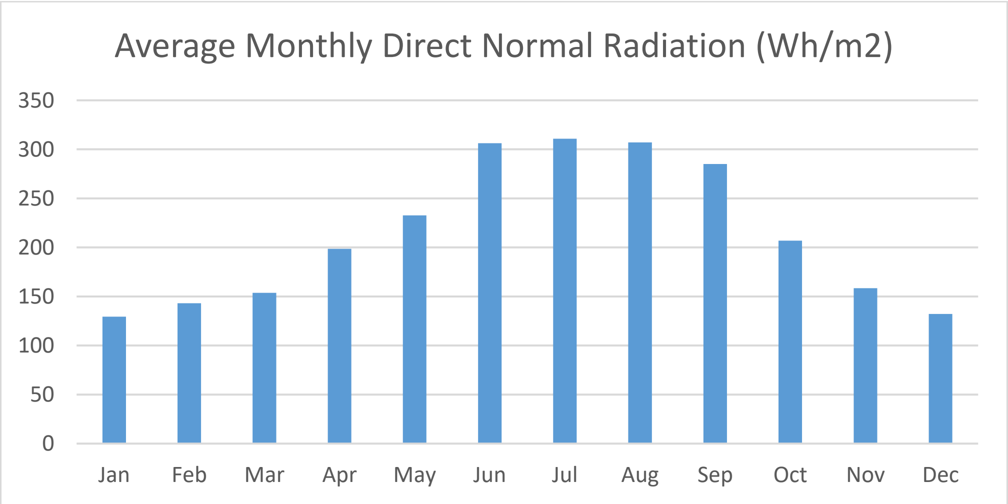


Figure 20: Beam Solar Radiation on a horizontal surface

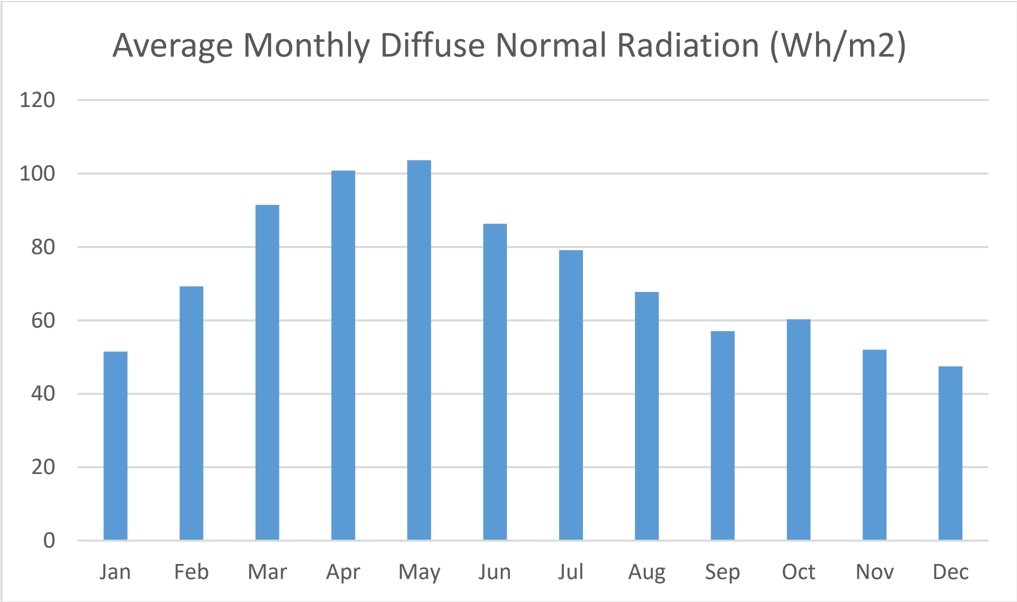


Figure 21: Diffuse Solar Radiation on a horizontal surface

In addition, the data inside the EPW file were used for computing azimuth and zenith angle. Figure (22) shows the sun path and azimuth and zenith angle for three different days of the year in Cyprus. Moreover, it shows the relation between the hours and zenith, azimuth angle. Each day and each hour have different values of zenith angle and azimuth angle.

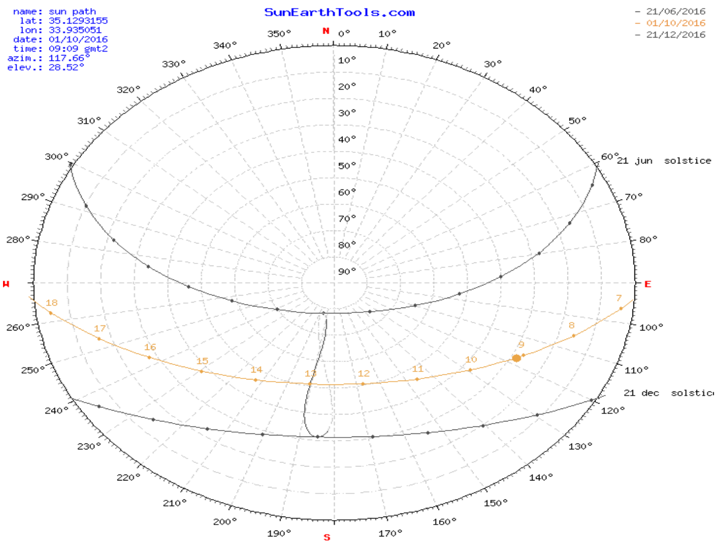


Figure 22: Relation between hours and azimuth and zenith angle

The values of azimuth and angle are passed into the AOI to calculate the angle of incidence. Then, the values of beam solar radiation and angle of incidence, and tilt angle are fed into the beam solar radiation on a tilted surface. And then, the values of beam solar radiation are computed for each hour of one year at each angle between 0 to 90 degrees with considering the amount of beam solar radiation on a horizontal surface from EPW file and angle of incidence and tilt angle and zenith angle.

Figure (23) indicates the total values of beam solar radiation for different tilt angles (0-90 degrees). The figure reveals that the highest amount of total beam solar radiation is approximately 1405 kWh/m^2 at a tilt angle of 29.3^o, and the lowest amount occurs at the tilt of 90^o with a value of around 683 kWh/m^2.

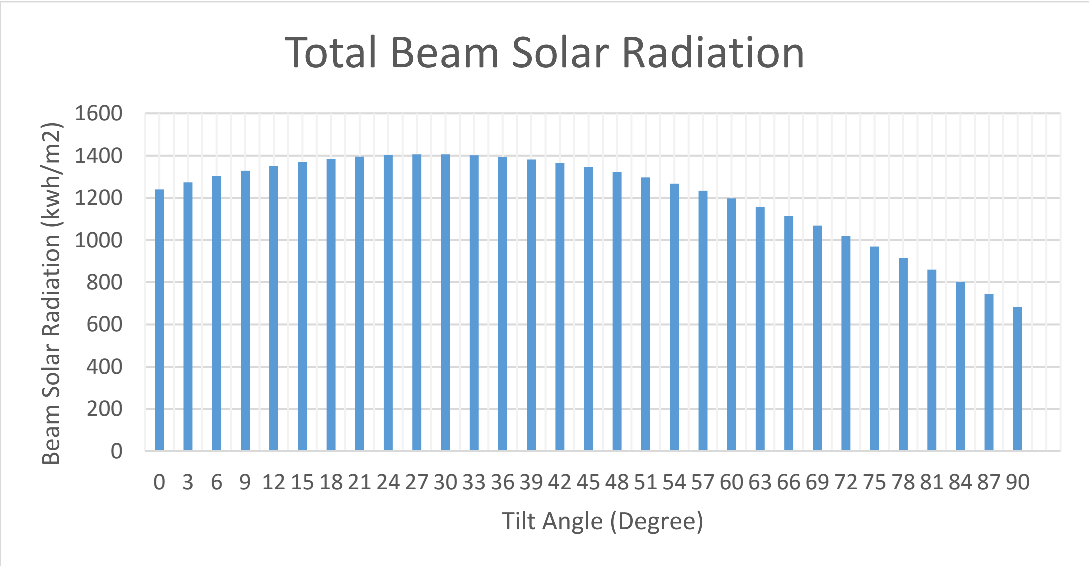


Figure 23: Total beam solar radiation

Furthermore, the values of diffuse solar radiation and angle of incidence and tilt angle are fed into the diffuse solar radiation on a tilted surface, and then the values of diffuse solar radiation are calculated hourly in one year at each angle between 0-90 degrees with considering the amount of diffuse solar radiation on a horizontal surface form EPW data file and angle of incidence and tilt angle and zenith angle.

Figure (24) represents the amount of total diffuse solar radiation on a tilted surface for different tilt angles between 0 to 90 degrees. As it can be seen, the highest and lowest amount is approximately 653 kWh/m^2 at 21º and 335 kWh/m^2 at 90º, respectively.

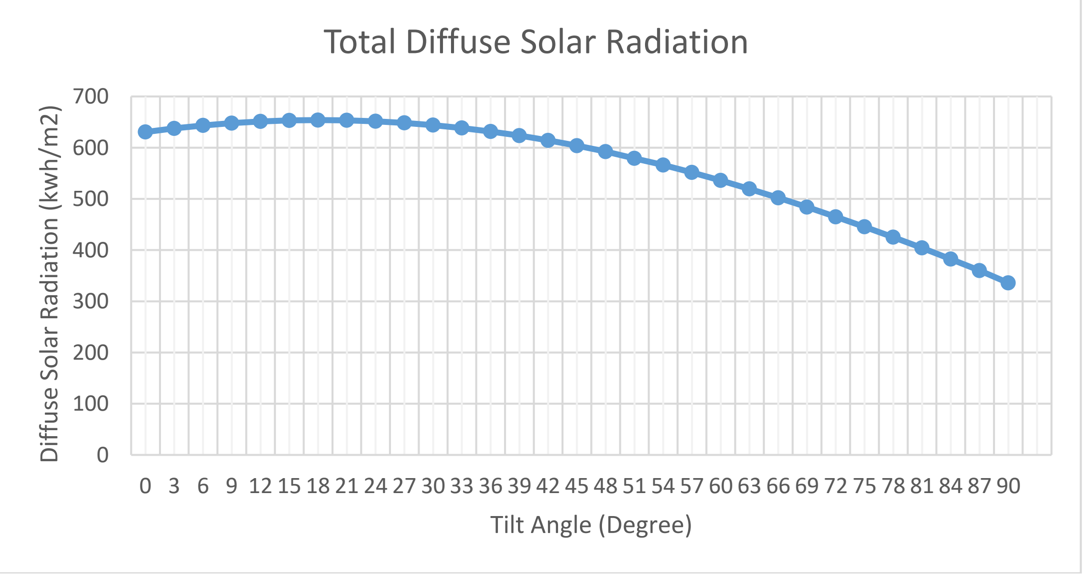


Figure 24: Total diffuse solar radiation

Moreover, the values of diffuse solar radiation and beam solar radiation and tilt angle and zenith angle are fed into the ground-reflected solar radiation on a tilted surface, and then the values of ground-reflected solar radiation are evaluated hourly in one year at each angle between 0-90 degrees with considering the amount of diffuse and beam solar radiation on a horizontal surface form EPW data file and zenith angle and tilt angle.

The figure below shows the value of total ground-reflected solar radiation on an inclined surface for different tilt angles between 0 to 90 degrees. According to the figure, the ground-reflected level increased sharply between 0 to 90 degrees. Starting at 0º with the amount of 0 kWh/m^2 and finishing at 90º with a value of around 156 kWh/m^2.

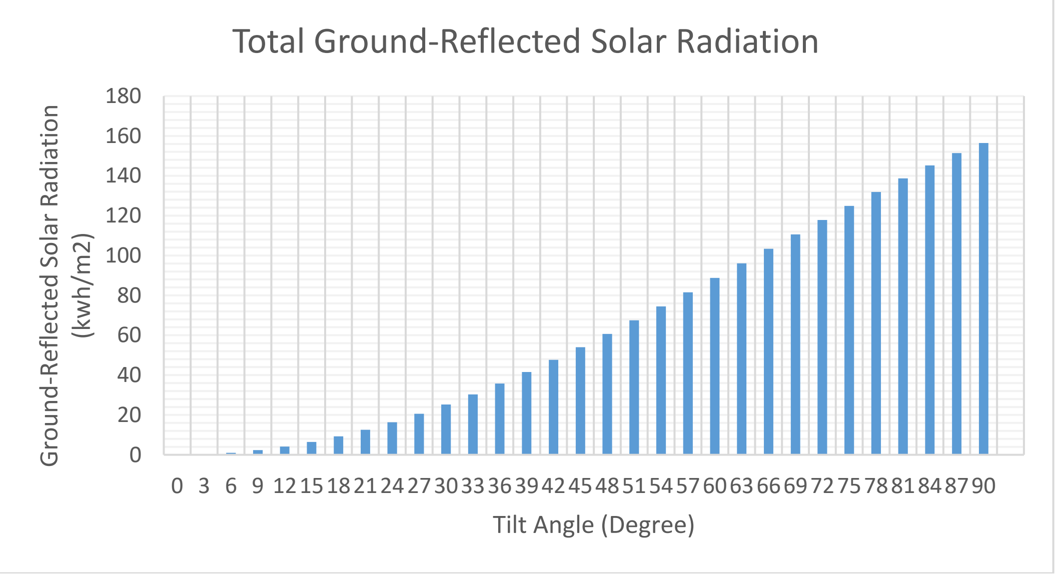


Figure 25: Total ground-reflected solar radiation

Finally, the total solar radiation values are obtained by summation of the total beam and diffuse and ground-reflected solar radiation on a tilted surface. Also, considering the results of the summation for each hour at each angle, total solar radiation for each angle is obtained.

Figure (25) illustrates the amount of total solar radiation on a tilted surface for different tilt angles between 0 to 90 degrees. Based on the figure, the value of total solar radiation starts at approximately 1870 kWh/m^2 in 0º, and it reaches the highest point at about 2074 kWh/m^2 in about 30º, then it decreases and reaches the lowest point at around 1161 kWh/m^2 in 90º.

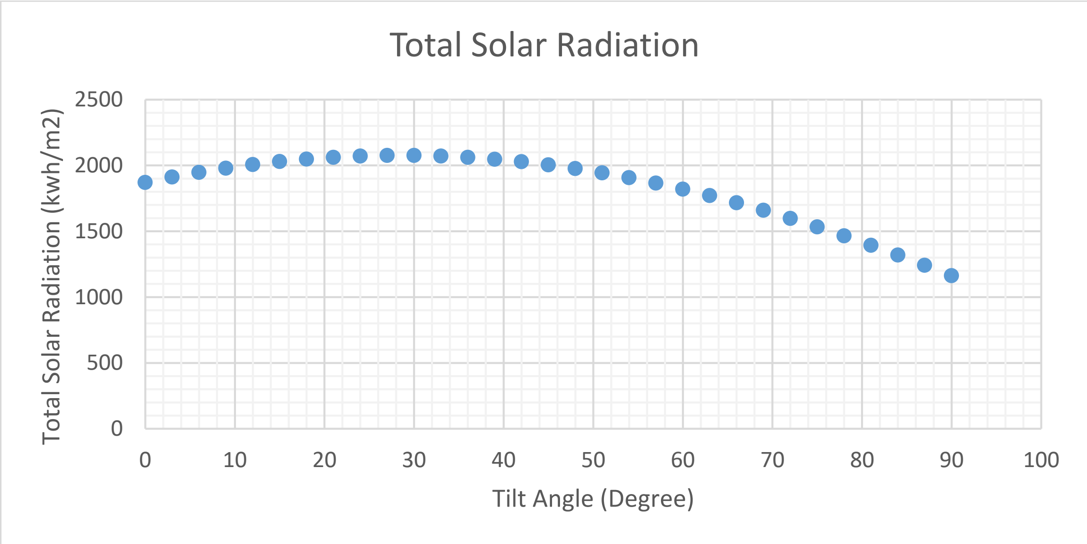


Figure 26: Total solar radiation

As it can be seen from figure 26, between 20 to 30 degrees, the amount of total solar radiation is very close to each other. For instance, the difference between the amount of total solar radiation at 25º and total solar radiation at 30º is 1.25 percent.

It means that the maximum solar radiation can be captured by photovoltaic (PV) panels, and solar panels can be installed at the ranges of between 20º and 30º.

Finally, considering all values of total solar radiation for different tilt angles, the total maximum solar radiation is about 2075 kWh/m^{2}at an angle of about 29.3 degrees. So, the optimum tilt angle is 29.3 degrees under Cyprus condition.

4.1 Comparing Five Different Methods with the Proposed Method

After finding the optimum tilt angle with the proposed method, the five different methods with the proposed method are discussed in table 2. Each of the proposed methods in table 2 is used from the results of chapter 2.

Each result is based on the latitude of Cyprus and calculates based on Cyprus condition. It means that the results are appropriate for the places with a latitude of 35º. For each method, some conditions and some parameters are considered in order to find the maximum solar radiation and, after that, find the optimum tilt angle.

After finding the optimum tilt angle photovoltaic panel can be installed at that point, and at that point, maximum energy during the year can be absorbed by a photovoltaic (PV) panel, and the amount of energy output will be maximum in comparison to the panels that install without knowing the exact optimum tilt angle for each country around the world especially for Cyprus.

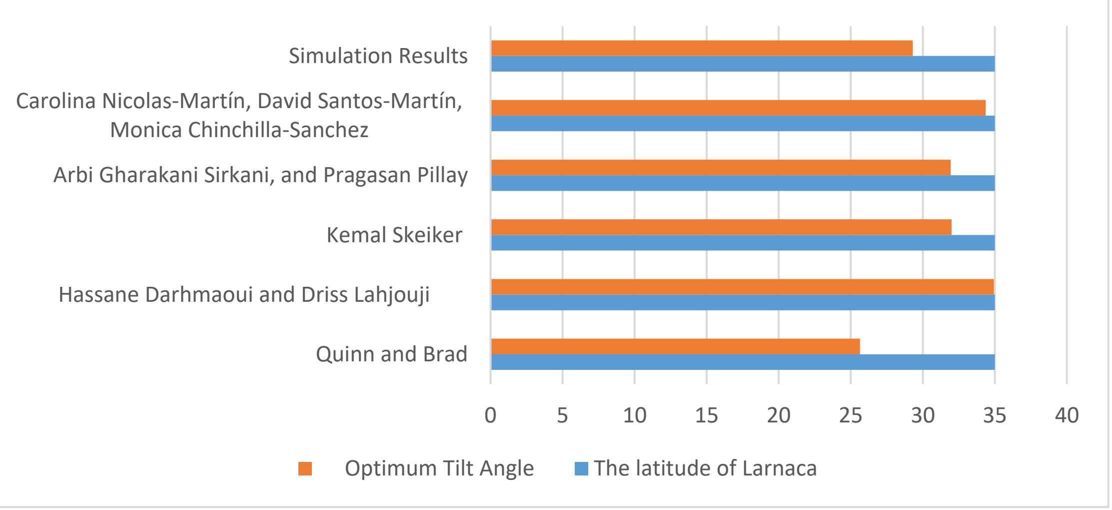


Figure 27: Comparing the optimum tilt angle by five different methods and the proposed method

Figure 27 indicates the comparison between five different methods in chapter 2 with the proposed method in this chapter.

Based on the table, the values of the optimum tilt angle for five different methods and the proposed method are close to each other except Quinn and Brad's [16] methods. All optimum angle values except 25.64 are close to the latitude of Cyprus. However, based on the simulation results and figure (23), we can conclude that photovoltaic (PV) panels can be mounted at ranges between 20 to 32 degrees. So, according to the table, the angle of 25.64º and 31.94º and 32º, as well as the simulation results, are acceptable, and at those points, the maximum solar radiation can be absorbed by photovoltaic (PV) panels. The future work can consist of using the same method for this thesis for the other countries in the world and compare the method’s results with the most recent literatures.

Chapter 5

CONCLUSIONS

The main aim of this study was to find the yearly optimum tilt angle in order to maximize cumulative energy outputs for Cyprus.

Five different methods were discussed, and each method proposed different conditions and different parameters such as clearness index, extraterrestrial radiation on a surface, ground-reflected solar radiation, shading, and global solar radiation to find the optimum tilt angle. In the end, five different methods were compared, and the optimum tilt angle for Cyprus is suggested.

The methodology of this thesis is to use a program and an auxiliary program in order to calculate and estimate the total solar radiation and followed by maximum solar radiation and the optimum tilt angle. By using the Tilt and Orientation factor component inside the auxiliary program, total solar radiation is calculated, and the optimum tilt angle can be found. The data that was used in the auxiliary program was from the Energy Plus Weather website. Based on the weather data outputs (hours and beam and diffuse solar radiation on a horizontal surface) and considering azimuth angle and zenith angle as well as the angle of incidence and different tilt angle, the total solar radiation can be calculated.

Regarding the amount of total solar radiation and different tilt angle, the highest value of total solar radiation for a tilt angle can be found, and followed by the optimum tilt angle can be observed. The value of optimum tilt angle was 29.3º. It means that at that point, the photovoltaic (PV) panel should be installed.

Finally, the simulation results are compared with five different method's results. The comparison reveals that photovoltaic (PV) panels can be installed at the ranges between 20º to 30º to absorb maximum solar radiation in Cyprus. In addition, the solar panels can also be mounted in the ranges of 0 to 90 degrees, and still, the panels absorb the solar radiation and produce the energy; however, The impact in terms of energy loss due to deviation from optimum tilt angle needs to be considered. Furthermore, it is essential to understand how much of the annual energy loss is expected in large-scale systems compared to the small-scale system. The impact of the deviation from the optimum tilt angle is mostly on the large-scale system, where the percentage of the annual energy lost will be higher in comparison to the small-scale systems. Moreover, the effect in terms of energy loss due to deviation from a location's optimum tilt angle needs to be taken into account. This is because latitude has a clear influence on energy loss when deviating from optimum tilt.

REFERENCES

[1] H. Kambezidis, Comprehensive Renewable Energy, Association of American, 2012.

[2] J. Alan and A. Kadhem, "Design and Construction of a Tracking Device for Solar Electrical Systems," *Journal of Scientific and Engineering Research,* pp. 225-236, 2018.

[3] L. Wang, S. Zhu, B. Wang, X. Tan, Y. Zou and S. L. Shuai Chen, "Latitude-and-longitude-inspired three-dimensional auxetic," p. 16, 2020.

[4] G. Prinsloo and R. Dobson, solar tracking, sun position, sun following, sun tracking, Stellenbosch, 2015.

[5] S. Ray1, "Calculation of Sun Position and Tracking the Path for a Prticular Geographical Location," *International Journal of Emerging Technology and Advanced Engineering,* vol. 2, no. 9, pp. 81-84, 2012.

[6] T. Letcher, Future Energy: Improved, Sustainable and Clean Options for Our Planet, Third Edition, Elsevier, 2020.

[7] D. B. Singh, A. Mahajan, D. Devli, K. Bharti and S. Kandari, "A mini review on solar energy based pumping system for irrigation," *Materials Today: Proceedings,* 2020.

[8] N. Belyakov, Sustainable Power Generation: Current Status, Future Challenges, and Perspectives, Elsevier, 2019.

[9] M. Şenol, S. Abbasoğlu, O. Kükrer and A. Babatunde, "A guide in installing large-scale PV power plant for selfconsumption mechanism," *Solar Energy,* pp. 518-537, 2016.

[10] A. G. Siraki and P. Pillay, "Study of optimum tilt angles for solar panels in different latitudesfor urban applications," *Solar Energy,* pp. 1920-1928, 2012.

[11] Beckman, J. A. Duffie and W. A., Solar Engineering of Thermal Processes, New York, 1991.

[12] H. Heywood, Operational experience with solar water heating. J Inst Heat Vent, 1971.

[13] P. J. Lunde, Solar thermal engineering, New York, 1980.

[14] H. P. Garg, Treatise on solar energy. Fundamentals of solar energy, vol. 1., New York, 1982.

[15] G. Lewis, Optimum tilt of solar collector. Sol Wind Energy, 1987.

[16] S. W. Quinn and Brad, "A Simple Formula for Estimating the," p. 8, 2013.

[17] M. Chinchilla, D. Santos-Martín, M. Carpintero-Rentería and S. Lemon, "Worldwide annual optimum tilt angle model for solar collectors and photovoltaic systems in the absence of site meteorological data," *Applied Energy*, 2021.

[18] NREL, "Energy Plus database," National Renewable Energy Laboratory, 2018. [Online]. Available: https://energyplus.net/weather/sources.

[19] J. C. Lam and D. H. Li, "Correlation between global solar radiation," *Building and Environment*, vol. 31, no. 6, pp. 527-536, 1996.

[20] C. Nicolas-Martín, D. Santos-Martín and M. Chinchilla-Sanchez, "A global annual optimum tilt angle model for photovoltaic generation to use in the absence of local meteorological data," *Renewable Energy*, pp. 722-735, 2020.

[21] A. S. D. Center, "NASA Surface Meteorology and Solar Energy," 24 March 2012. [Online]. Available: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov.

[22] D. L. Hassane Darhmaoui, "Latitude Based Model for Tilt Angle Optimization for Solar," *Energy Procedia,* pp. 426 - 435, 2013.

[23] K. Skeiker, "Optimum tilt angle and orientation for solar collectors in Syria," *Energy Conversion and Management,* pp. 2439-2448, 2009.

[24] P. P. Arbi Gharakhani Siraki, "Study of optimum tilt angles for solar panels in different latitudes for urban applications," *Solar Energy,* p. 1920–1928, 2012.

[25] D. Crawley and L. Lawrie, "Development of global typical meteorological years (TMYx)," September 2019. [Online]. Available: http://climate.onebuilding.org/.

[26] R. Perez, P. Ineichen, R. Seals, J. Michalsky and R. Stewart, "Modeling daylight availability and irradiance components from direct and global irradiance," *Solar Energy,* vol. 44, no. 5, pp. 271-289, 1990.

[27] C. Nicolas-Martín and Jun, "Diffuse fraction from location," 2020. [Online]. Available: https://zenodo.org/badge/DOI/10.5281/zenodo.3874373.svg .

[28] NASA, "NEO webpage," NASA Earth Observations, 2015. [Online]. Available: https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MCD43C3_M_BSA&date=2014-12-01. [Accessed November 2019].

[29] DOE, "weather data," the U.S. Department of Energy, [Online]. Available: https://energyplus.net/weather.

[30] ASHRAE, "Weather Year for Energy Calculations," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2013. [Online]. Available: https://www.ashrae.org/resources--publications/bookstore/climate-data-center.

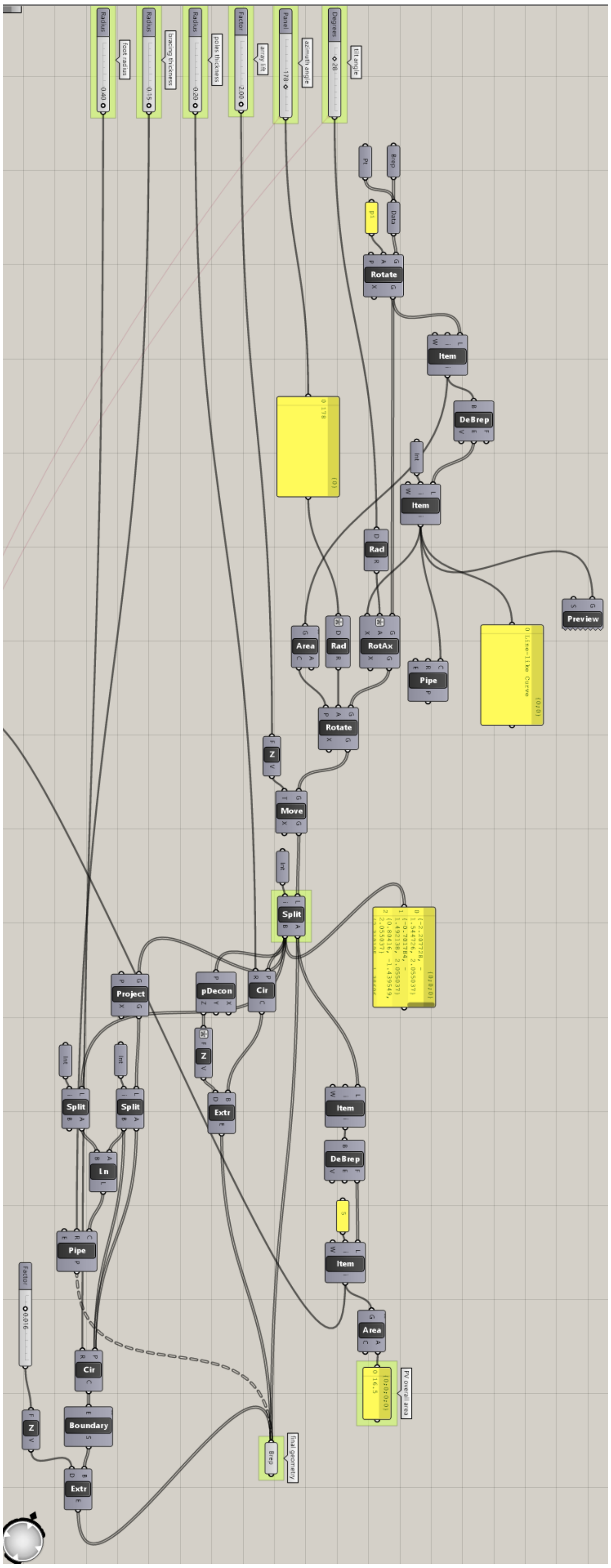
[31] R. Perez, "A new simplifed version of the Perez diffuse irradiance model for tilted surfaces," *Solar Energy*, vol. 39, pp. 221-231, 1987.

[32] P. Gilman, "SAM Photovoltaic Model Technical Reference," National Renewable Energy Laboratory, Colorado, 2015.

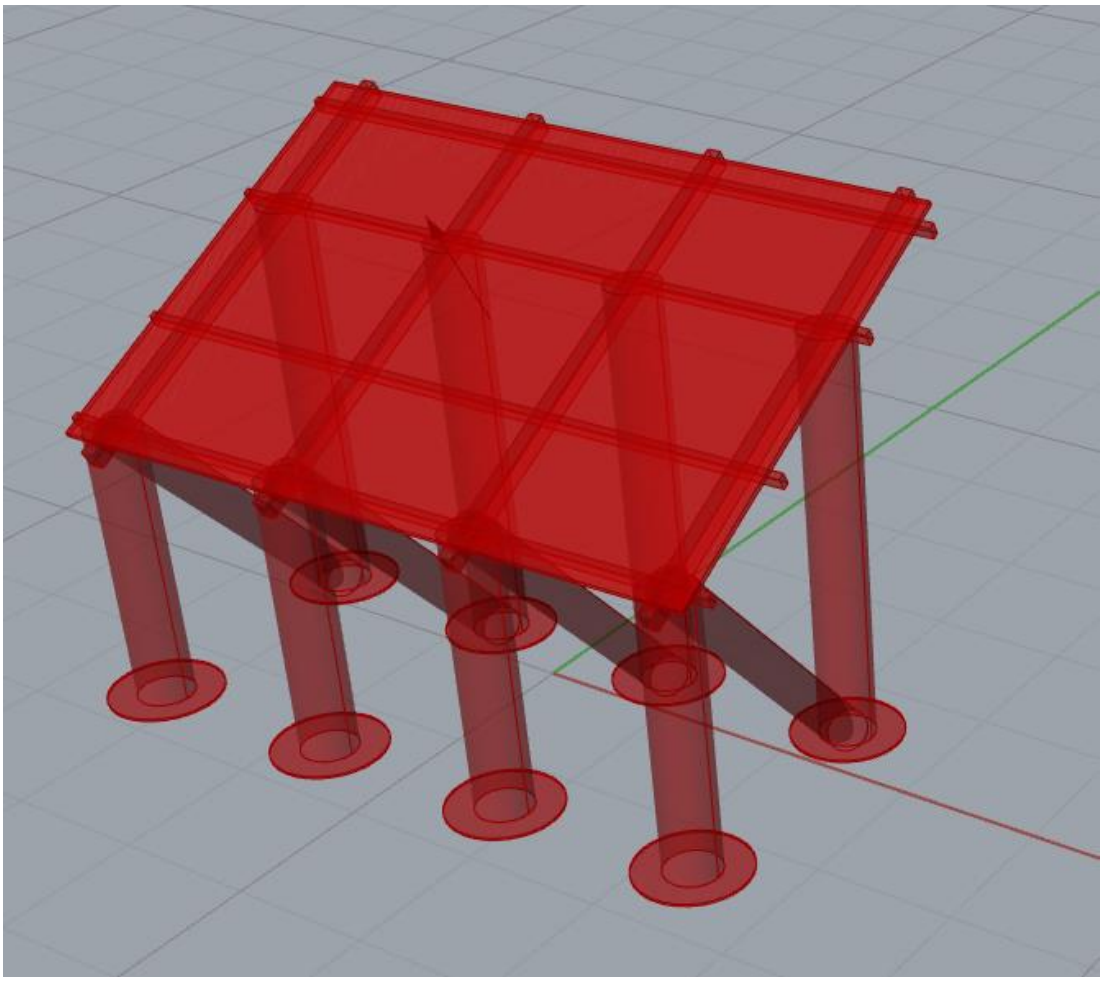
[33] T. Muneer, solar radiation and daylight models, Edinburgh, 2004.

APPENDICES

Appendix A: The Software Parameters and Components



Appendix B: The Layout of the Software



Appendix C: The Annual Solar Radiation and the TOF Codes

```
    # totalRadiationPerYear of the inputted (analysed) surface
    totalRadiationPerYear = 0
    for i,hoy in enumerate(HOYs):
        sunZenithD, sunAzimuthD, sunAltitudeD = 
lb_photovoltaics.NRELsunPosition(latitude, longitude, timeZone, years[i], 
months[i], days[i], hours[i]-1)
        Epoa, Eb, Ed_sky, Eground, AOI_R = 
lb_photovoltaics.POAirradiance(sunZenithD, sunAzimuthD, srfTiltD, srfAzimuthD, 
directNormalRadiation[i], diffuseHorizontalRadiation[i], albedoL[i])
        totalRadiationPerYear += Epoa  # in Wh/m2

    # TOF, TSRF of the inputted (analysed) surface
    TOF = round((totalRadiationPerYear/maximalTotalRadiationPerYear)*100 ,1)  # in 
percent
    if TOF > 100:
        TOF = 100
    TSRF = round(TOF * ((100-annualShading)/100) ,1)  # in percent
```