THE REPUBLIC OF TURKEY
BAHÇEŞEHİR UNIVERSITY

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

INDUSTRIAL ENGINEERING

# INVESTMENT ANALYSIS OF SOLAR ENERGY SYSTEMS

**Master's Thesis**

**GÖKÇE ÖZDEMİR**

**Thesis Supervisor: PROF.DR. MUSTAFA ÖZBAYRAK**

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Assoc.Prof.Dr. Tunç BOZBURA

Graduate School Director
Signature

This is to certify that we have read this thesis and we find it fully adequate in scope, quality and content, as a thesis for the degree of Master of Arts.

| Examining Comittee Members | Signature |
|---|---|
| Prof.Dr. Mustafa ÖZBAYRAK | |
| Prof.Dr. M. Akif EYLER | |
| Assist.Prof.Dr. Ahmet BEŞKESE | |

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# ABSTRACT

## INVESTMENT ANALYSIS OF SOLAR ENERGY SYSTEMS



Gökçe Özdemir

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The energy consumption increases rapidly due to the growth on population, concerns of countries regarding economical advancements and unexpected improvements of the technology. The price of conventional energy reserves is rising day by day. Since the traditional energy resources are limited by nature, it is inevitable that all the countries in the world have been affected from this economically, politically and environmentally. The solar energy is a powerful alternative to the traditional energy resources and has a great potential to solve as well as eliminate above mentioned problems. In this study, it is aimed to create an engineering economy based investment analysis and generate a guideline for solar energy investments.

Four different areas in Turkey that are suitable to implement the photovoltaic energy systems are selected and system's size is assumed to be 10 MW for each installation. First, an analysis of solar radiation concept is introduced and several financial investment techniques are presented in the use of evaluation of the feasibility of photovoltaic energy systems. The irradiation rates of selected sites on inclined surfaces are determined, annual energy productions and required number of panels to provide planned energy amount are calculated by considering irradiation rates and average solar hours of the related areas.

The viable capital budgeting techniques are used to evaluate the financial investments of the projects. The total life cycle method, the return on investment method and the payback period method are used for each of the four selected areas. The payback periods are estimated based on geographical condition of the regions considered in this study and applied technology efficiency rates. Through the obtained results, it is intended to create a guideline for the solar energy investors as well as the researchers in photovoltaic energy applications and provide a source of financial characteristics of solar energy systems. A set of conclusions are drawn based on the findings of this thesis, which are believed to be a useful source for both investors and academics.

**Keywords:** Photovoltaic Energy, Irradiation, Energy Projects Investments, Total Life Cycle Cost, Return on Investment

# ÖZET

## GÜNEŞ ENERJİSİ SİSTEMLERİNİN FİNANSAL ANALİZLERİ

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Ülkelerin ekonomik kalkınma endişeleri, artan nüfus ve ilerleyen teknolojik gelişmeler enerji tüketimini artırıcı unsurlardır. Klasik enerji kaynakları kısıtlı kaynaklardır ve fiyatlar her geçen gün artmaktadır. Bu durum dünya ülkelerini ekonomik, politik ve çevresel açıdan yakın zamanda etkileyecek duruma gelecektir. Bu bağlamda güneş enerjisi klasik enerji kaynaklarına karşı güçlü bir alternatiftir ve sözü geçen problemleri elimine etmek için büyük bir potansiyele sahiptir. Bu çalışmada, mühendislik ekonomisi temelli bir finansal analiz gerçekleştirmek ve güneş enerjisi yatırımları için bir kılavuz oluşturmak amaçlanmıştır.

Türkiye fotovoltaik enerji sistemlerinin uygulanabilirliği açısından potansiyel bir ülkedir. Bu potansiyeli açıklayabilmek amacıyla, Türkiye'de bulunan ve fotovoltaik enerji sistemlerinin uygun olduğu dört farklı bölge seçilmiş ve bu bölgelere kurulacak olan sistemin büyüklüğünün her bölge için 10 megavat olacağı farz edilmiştir. Fotovoltaik enerji sistemlerinin Türkiye'ye uygulanabilirliğini değerlendirmek için güneş radyasyonu ve finansal yatırım teknikleri konusunda detaylı bir araştırma yapılmıştır. Seçilen alanların eğimli yüzeydeki güneş radyasyonu değerleri ve yıllık enerji üretim miktarları hesaplanmıştır. Bölgelerin radyasyon oranları ve ortalama güneşlenme saatleri baz alınarak, hesaplanan üretilebilecek enerji miktarını karşılamak için ne kadar panel gerektiği belirlenmiştir.

Projeleri finansal açıdan değerlendirebilmek için, uygulanabilir temel bütçeleme teknikleri kullanılmıştır. Her bölge için toplam maliyet, yatırımın geri dönüş oranı ve geri ödeme zamanı hesaplanmıştır. Geri ödeme süresi tahmininde bölgenin coğrafi özellikleri ve kullanılan teknolojinin verimlilik oranı göz önünde bulundurulmuştur. Elde edilen sonuçlara dayanılarak, enerji yatırımcılarını fotovoltaik enerji sistemleri konusunda bilgilendirmek ve güneş enerjisi sistemlerinin finansal özellikleri konusunda bir kaynak oluşturmak amaçlanmıştır.

**Anahtar Kelimeler:** Fotovoltaik Enerji, Radyasyon, Enerji Üretimi, Enerji Proje Yatırımı, Geri Ödeme Süresi

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## LIST OF ABBREVIATIONS

AC : Alternative Current

AM : Air Mass

CdTe : Cadmium Telluride

CIGS : Copper Indium Gallium Diselenide

CIS : Copper Indium Selenide

DC : Direct Current

FIT : Feed-in-Tariff

IRR : Internal Rate of Return

kWh : Kilowatt hours

kW : Kilowatt

MW : Megawatt

NPV : Net Present Value

O&M : Operation and Maintenance

PV : Photovoltaic

PVUSA: Photovoltaics for Utility Scale Applications

ROI : Return on Investment

SPB : Simple Payback Period

STC : Standard Test Conditions

TLCC : Total Life Cycle Cost

W : Watt

## LIST OF SYMBOLS

| | | |
|---|---|---|
| Albedo irradiation reflected from the ground to the inclined surface | : | $R_\beta$ |
| Analysis period | : | N |
| Annual discount rate | : | d |
| Clearness index | : | $K_T$ |
| Cost in period n | : | $C_n$ |
| Daily extraterrestrial irradiation on a horizontal surface | : | $B_0$ |
| Geographical latitude angle of the area on the Earth's surface | : | $\phi$ |
| Inclination angle of the panel to the horizontal surface | : | $\beta$ |
| Minimum of $w_s$ and $w_s'$ | : | $w_0$ |
| Monthly average daily beam irradiation on a horizontal surface | : | B |
| Monthly average daily beam irradiation on an inclined surface | : | $B_\beta$ |
| Monthly average daily diffuse irradiation on a horizontal surface | : | D |
| Monthly average daily diffuse irradiation on an inclined surface | : | $D_\beta$ |
| Monthly average daily global irradiation on a horizontal surface | : | G |
| Monthly average daily global irradiation on an inclined surface | : | $G_\beta$ |
| Number of the day of the year | : | n |
| Reflectivity value of the ground | : | $p$ |
| Solar constant | : | S |
| Solar elevation angle | : | θ |
| Solar declination angle | : | $\delta$ |

| | | |
|---|---|---|
| Solar hour angle | : | $\mathbf{w}$ |
| Sunrise hour angle | : | $\boldsymbol{w_s}$ |
| Sunrise hour angle on the tilted array | : | $\boldsymbol{w_s'}$ |

# 1. INTRODUCTION

The limited resources of the Earth present a massive threat for the future of growing population. Increase on the consumption of fossil fuels damages the environment due to the effects of greenhouse gases and carbon dioxide emissions. The price of fossil fuels are rising day by day other than being a limited energy resource and all the countries in the world are to be effected economically, politically and environmentally in the near future. To eliminate these problems, solar energy is a powerful alternative source of energy because sun's energy is free, available, adequate for satisfying the world's energy demand and nondestructive for the environment.

In recent years, the importance of renewable energy systems was realized by the countries and incentive mechanisms were constituted to stimulate the solar energy investments. In this study, it is aimed to clarify the investment analysis techniques for solar energy projects to determine the correlation of the profitability, solar power and payback period. The investment opportunities and drawbacks are compared by applying various capital budgeting techniques which are payback period method, life cycle cost method and return on investment method.

In this study, a review of literature is made in chapter 2 to clarify the research areas with respect to solar energy technologies and economic views on renewable energy systems. In chapter 3, solar energy concept and common terms on the subject are expressed. The sun's geometry and angles that are essential to be considered in the systems' implementation are explained. The required components to generate a PV system are represented in detail and design considerations of PV technologies are explained by considering industry standards. The characteristics of existent photovoltaic energy technologies are discussed, benefits and drawbacks of these technologies are represented. In chapter 4, the calculation methodology of irradiation on inclined surfaces is explained. The techniques to calculate annual energy production and the number of panels needed to match the energy production capacity are clarified. The applied capital budgeting procedures and government incentives for solar energy systems are represented in chapter 5. The calculations and results for photovoltaic system application of four different areas are given in chapter 6. Finally, discussion is made in chapter 7 and conclusions are represented in chapter 8.

In order to make the required financial investment calculations, four convenient areas in terms of geographical location which are Denizli, Niğde, Karaman and Van in Turkey are chosen to practice 10 MW photovoltaic power plant assumption. An analysis of photovoltaic technologies and applications is made to determine the most feasible PV technology to install to the chosen sites. The effects of solar energy flux to the tilted surfaces based on monthly average daily irradiation values of four chosen area is studied to determine yearly optimum photovoltaic panel angle positions. The obtained data are used to calculate annual energy production capacity of each area. Also, the required numbers of panels to match the energy capacity of per site are calculated by considering the average solar insolation hours. The obtained results are used to support the financial calculations.

In the financial phase of the study, the costs of the projects are calculated based on the methodology of life cycle cost. The return on investment after one year and payback periods for each project are estimated based on irradiation rates of the areas, solar insolation hours and the efficiency of the technologies that are used in the process. The results for four selected area are compared and the most acceptable project to implement is determined.

# 2. LITERATURE REVIEW

## 2.1 INTRODUCTION

The attributes of sun had been a significant investigation subject from the beginning of the world until today. Even though, sun is visible from the Earth every day, the discovery of the characteristics and benefits of the solar energy is a continuing research area.

In this chapter, several published academic and non-academic literature are presented to review the developments in the field of solar energy, considering the framework and context of this thesis.

## 2.2 THE BRIEF HISTORY OF SOLAR ENERGY

The history of solar energy shows that the first sundials were built in 1800 BC and the relationship between the sun and the Earth was started to be seen by the mankind through the shadows. This discovery had led people to understand the geometry of the sun but until Kepler's studies Astronomia Nova and Harmonice Mundi that explains the spatial movements in the 17th century, any significant discovery had been existed. After that, there had been various antitheses to Kepler's study but it is known at the present day that Earth revolves around the sun on an elliptical path (Lorenzo 2003).

After the discovery of the relationship between sun and the Earth, the methods for converting sunlight to electricity became the research subject. The scientist of the 19th century had discovered that some objects generate electricity under sunlight (Boxwell 2012). The first solar cell originated in 1893, started to be used in many areas and the evolution of solar power had been continued. [1]

[1] *History of Solar Energy*.2012. http://exploringgreentechnology.com/solar-energy/history-of-solar-energy/

The production of solar cells led countries to improve the existing technology, reduce the production costs, investigate the contribution of solar energy to the economies and develop the solar energy technologies for being suitable and effective from every household to every corporation. Many studies that were made for that purpose are as follows:

The prediction of photovoltaic energy production is very important for the enlargement of the industry. Marion et al. examined the performance parameters which are final PV system yield, reference yield, performance ratio and PVUSA rating that simplifies the comparison of grid-connected photovoltaic applications which can be different from each others on the subjects of design, technology or geographic location. It was indicated that these four performance parameters can be used to identify the system performance on energy production, solar resource and effects of system losses (Marion et al. 2005). The report of Detrick et al. have the similar results and the photovoltaic modules and systems' classification were studied for establishing required standards in the world. The report also suggests that accurate energy estimation is crucial and photovoltaic industry is in the need of a standardized, comprehensible approach for module and system rating, performance predictions and evaluations (Detrick et al. 2005). Menegaki also introduced a review of assessment of renewable energy systems and expressed the methods which are used in the evaluation process such as preference techniques, revealed preference techniques, portfolio analysis and emergy analysis (Menegaki 2008). A broad review of 102 articles with respect to grid-connected and stand-alone energy systems for decentralized power was also made by Kaundinya et al. to clarify the engineering and institutional design aspects of the mentioned systems (Kaundinya et al. 2009).

## 2.3 ECONOMIC ASPECTS OF SOLAR ENERGY

As financial side of the photovoltaic projects based on the country's' economic stability, various studies exist in the literature with respect to large scale photovoltaic applications and small scale residential building integrated photovoltaic projects. Lazou et al. investigated the effectiveness of stand-alone residential PV systems on 23 Europe and Mediterranean locations based on the classic medium sized houses with four family members. It was claimed that stand-alone PV systems meet the energy needs of these families and the system is sized to reach the optimal minimum life cycle cost. The analysis shows that the system which is implemented in year 1998 is more expensive than conventional system. According to a simulation process based on same system but in 2005 shows that PV battery stand-alone systems have a life cycle cost about 80 percent of that of systems installed in year 1998 but the cost is still quite expensive (Lazou et al. 2000). As a similar study, was practiced by Spanos and Duckers which is an economic analysis of building-integrated photovoltaic systems based on United Kingdom and Greece. In the project, the medium sized houses with four people inhabiting were considered and the comparisons between photovoltaic system and grid power electricity were made in terms of costs. To make the required calculations, a program called PVSYST software was used. It was found that the cost for PV is 40 percent greater in United Kingdom and the PV system for both countries are not attractive in comparison with conventional electricity. According to the sensitivity analysis, PV systems will be effective in the future alleging the period of 2009–2013 for both of the countries (Spanos and Duckers 2004). However, the study of Dalton et al. shows that renewable energy systems can supply 100 percent of the demand of a large hotel which is located in Queensland, Australia and technically feasible in proportion to a conventional diesel generator. Nevertheless, it was also found that the wind energy systems are more feasible than photovoltaic applications as renewable energy supply to meet the large hotels' energy demand because of the high cost of the PV system which is four times the cost of a wind energy system (Dalton et al. 2008).

The feasibility of photovoltaic systems with regard to country characteristics is also a required issue to be considered. According to Diarra and Akuffo, solar energy is a feasible option to meet the energy demand for a country that receives approximately 12 hours of sunshine. Mali further overexploits the wood fuel and imported fuels such as petroleum whereas the free resource solar energy utilization is very low. The reason grounds on the population's financial inadequacy and it precipitates the lack of utilization of PV systems. It was also noted that government of Mali applied a financial policy for solar systems in 1994 by eliminating all the taxes but the electrical wiring and fitting taxes to reveal the solar energy potential (Diarra and Akuffo 2002). A similar study was made by Hongxing and Yuyan to examine the operationability of photovoltaic systems to Hong Kong by explaining four implemented building-integrated photovoltaic projects. It was reported that photovoltaic applications are conducive to meet the energy demand of Hong Kong and the energy payback of building integrated photovoltaic system is 5 or 6 years whereas the economical payback is almost 20 years (Hongxing and Yuyan 2003). As a generic approach, Evrendilek and Ertekin investigated Turkey's potential of renewable energy sources. It was indicated that the electric power capacity in 2001 has to be doubled by 2010 and increased fourfold by 2020 to fulfill the energy demand. The renewable energy sources of Turkey which are hydropower, biomass, biogas, bio fuels, wind power, solar energy and geothermal energy were surveyed and it was suggested that approximately 90 percent of Turkey's energy demand can be met if Turkey pays importance to the implementation of renewable energy systems and the global and environmental problems will be diminished via renewable energy systems (Evrendilek and Ertekin 2003). The study of Kaya also introduces the potential of renewable energy in Turkey with the energy policies and organizations, incentive mechanisms and efficient applications of the renewable energy systems. It was mentioned about the renewable energy policies that several developments were made towards greater liberalization by introducing the notion of privatization to the Turkish constitution. Thus, legislation and gas market law was adopted in 2001 to allow competition in the electricity market. It was expressed that solar, geothermal and wind energies are the most supported energy types by financial mechanisms in Turkey (Kaya 2006). Fthenakis et al. examined solar energy in United States in a technical, geographical and economical view as well and future energy demands of U.S were estimated. They argued that 90 percent of the total energy needs of the U.S can be met by the solar energy systems and it is feasible to replace the fossil fuels with renewable energy systems as solar power in United States through the estimated results that the solar power plants are able to produce 69 percent of total US electricity generation until 2050 (Fthenakis et al. 2009).

The utilization of renewable energy on rural areas which is an advantageous way of satisfying the energy demand was analyzed by Mahmoud and Ibrik. They examined the viability of energy supply in rural areas in Palestine by considering three energy alternatives which are photovoltaic system, diesel generators and electricity grid. The costs of the PV system, diesel generators and electricity grid were determined through the financial calculation techniques. It was found that the PV systems are economically more feasible than diesel generators and electricity grid in the rural areas of Palestine (Mahmoud and Ibrik 2006). Shaahid and El-Amin also investigated the feasibility of off-grid hybrid photovoltaic-diesel-battery systems on a rural village in Saudi Arabia. It was mentioned that the energy needs of the village are met by a diesel system of 6.72 MW installed capacity but on the other hand it was found that 724 tons/year of carbon emissions can be eliminated by PV energy. It was indicated that the location with a considerable monthly average daily global solar radiation intensity which was selected for implementation of off-grid hybrid photovoltaic–diesel–battery power systems is an abundant potential spot to apply the PV system (Shaahid and El-Amin 2009). Another study on the field of rural applications was made by Deichmann et al. that investigates the importance of renewable energy systems in an economical view because of the incremental energy demand of developing Sub-Saharan Africa. On the contrary to preceding study, it was found that decentralized power systems are more costly than centralized power based on the unit costs and if industry reduces the cost of solar modules, the solar photovoltaic power may be cost competitive. It was also suggested that concentrating solar thermal power which is less costly than photovoltaics can be a good alternative for Africa (Deichmann et al. 2011).

The government policies, incentive mechanisms, feed-in-tariffs are significant issues to be considered before investing a solar energy project. Solangi et al. presented a review of solar energy policies based on the examples all around world to examine the existing renewable energy policies of specific countries by comparing the renewable energy policy status of Malaysia with other countries. It was also indicated that feed-in tariffs, renewable portfolio standards and incentives are the advantageous energy policies that are used all around the world (Solangi et al. 2011). Furthermore, Aste et al. also studied the energy policies through the inspection of three case studies which are funded under the national financing program Tetti Fotovoltaici, based on Subsidy Grant Scheme in Italy (Aste et al. 2007). The study of Couture and Gagnon is based on the feed-in tariffs as distinct from the preceding researches. The benefits and drawbacks of seven models of feed-in tariffs were introduced to remunerate a feed-in tariff policy through the analysis of two categories which are the remuneration is dependent on the electricity price and the remuneration is independent from the electricity price for renewable energy investments. It was indicated that feed-in tariffs are the most effective policy to support the renewable energy systems and the most used feed-in tariff policy is the market independent FIT policies (Couture and Gagnon 2010). A broad analysis of market barriers for renewable energy industry was made by Owen to state the externalities. The internalization of the externalities of power production was suggested for the renewable energy systems to create a cost advantage (Owen 2006).

The global irradiation rate of a region is an important parameter to build a photovoltaic system in a productive way. The study of Nouni et al. presents the photovoltaic projects which provide decentralized power supply in India by considering the cost of PV applications and required financial incentives. According to the calculated irradiation values of 18 selected locations, the most abundant areas were determined and taken into consideration (Nouni et al. 2006). Purohit and Purohit also studied the concentrating solar power generation in India with the references of two case projects which are located in Spain by using the monthly global and diffuse solar radiation data to predict the direct solar radiation. It was found that the locations which have more than 1800 $kWh/m^2$ annual direct solar radiation are the most appropriate for implementation of concentrating solar power systems (Purohit and Purohit, 2010). As a similar project, Al-Badi et al. investigated the economic probability of solar energy by using average daily global solar radiation and sunshine duration data of 25 locations with PV power plants in Oman. The best site with the highest solar irradiation was determined.
(Al-Badi et al. 2011).

The surveyed literature shows that the capital budgeting techniques are used to achieve the investment analysis of renewable energy projects as the study of Bakos et al. In the project, a grid-connected building-integrated photovoltaic system installation in the building of Environmental Education Centre was analyzed which is located in the Kastoria city of Northern Greece. This project was performed on the purpose of decreasing the electricity demand. The financial computations which are internal rate of return (IRR), year-to-positive cash flow, return of investment (ROI), net present value (NPV) and simple payback period (SBP) were used to evaluate the projects' viability.

According to the calculations, it was found that the initial cost of the project is high which is the main drawback of the photovoltaic technologies and it leads to a prohibitive factor for the implementation of the PV system (Bakos et al. 2003). As a similar practice, Horn et al. examined an integrated solar combined cycle system implementation in Egypt. At the economic phase of the project, the incremental cost of the project was calculated by the comparison of a conventional power facility and the feasibility and advantages of the project were evaluated. The net present values, incremental costs and levelized electricity costs were calculated and it was obtained that contrary to the previous study, an integrated solar combined cycle system is a very efficient and important opportunity for Egypt (Horn et al. 2004). Another solar combined cycle system implementation practice was made by Hosseini et al. The first integrated solar combined cycle system in Iran was examined technically and economically by considering capacity factor, environmental benefits, investment and operation and maintenance costs. It was expressed that the power plants' efficiencies are more than conventional power plants and integrated solar combined cycle system is a feasible project for Iran's first solar power plant (Hosseini et al. 2005). The research of Waldau also clarifies that there exists various obstacles on the implementation of renewable energy systems such as the high initial investments and the economic system based on conventional energy. The study covers Europe and suggests Europe a support policy for renewable energy market and reliable political framework conditions to enable return on investments and keep its position on the market (Waldau 2007). Dusonchet and Telaretti also used the required capital budgeting techniques to express the support policies in photovoltaic energy systems in western European Union countries, evaluate the effects of the policies in different countries and introduce the potential PV markets. It was found that all of the support policies can not be appropriate for the PV systems of all countries and different results can be obtained (Dusonchet and Telaretti 2010). As a different approach to the financial calculation mechanism of renewable energy systems, Verhelst et al. developed a calculation tool for private individuals and companies that make it possible to calculate the NPV and IRR to make the right decisions in respect of the effectiveness and viability of an investment in photovoltaic panels (Verhelst et al. 2010). A more improved calculation model that assists the user to calculate net present value, internal rate of return, payback period, discounted payback period, profitability index, yield unit cost, yield unit revenue and break-even turnkey cost was introduced by Audenaert et al. to assess the photovoltaic grid connected systems for companies in Belgium. The feasibility of the grid-connected PV systems to build in Belgium and the government subsidy policies were also discussed (Audenaert et al. 2010).

# 3. SOLAR ENERGY: PARAMETERS, CALCULATIONS AND INSTALLATIONS

## 3.1 INTRODUCTION

Solar energy calculations are basically part of the discipline of physics. It normally requires a considerable knowledge in the sciences of atmosphere, climatology and electrical engineering for the true calculation of sun power, irradiation and conversion of crude power into useable energy. In this section, some fundamental knowledge of solar energy calculation is provided besides the basic parameters needed in calculations as well as the instruments used in installation of such power systems.

## 3.2 SOLAR ENERGY

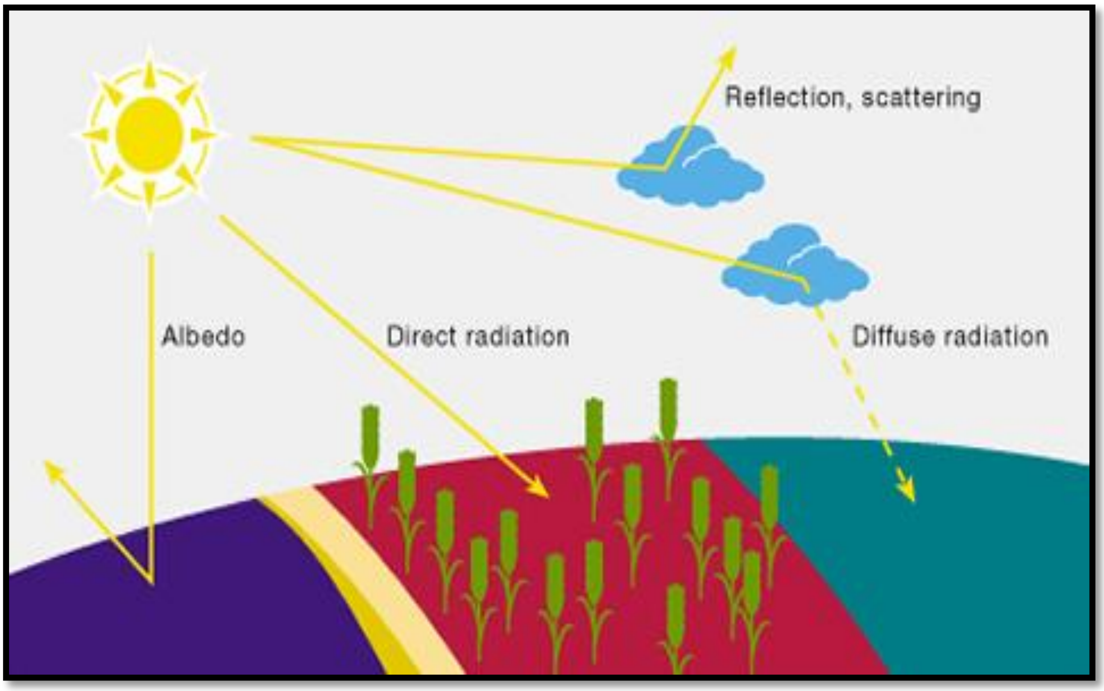
Solar energy is the most important and abundant energy resource for the Earth. The terms that are associated with solar energy are essential to be understood before investing these systems. The power of the sun is usually denoted as solar irradiance that is expressed in watts per square meter ($W/m^2$). On the other hand, solar irradiation includes time factor that is the measure of solar radiation in a given time that reaches to the Earth's surface. The solar irradiation is denoted in the unit of $Wh/m^2$.

The incoming energy from the sun also called insolation reaches the Earth in the form of infrared, ultraviolet and visible energy.[2] The atmosphere of the Earth affects the incoming energy by scattering, reflecting and absorbing. The scattered light reaches the Earth with different angles. This scattered light is diffuse radiation whereas the light that reaches to the Earth without scattering is direct radiation (Honsberg 2008).The scattering diminishes the quantum of energy that comes to the Earth.

[2] *Energy from the sun.* 2011. http://www.elmhurst.edu/~chm/onlcourse/chm110/outlines/sunenergy.html

The reflection of radiation occurs when the light from the sun strikes to an object usually clouds and returns back to the space by emitting zero insolation. The reflectivity of the Earth's surface is the albedo radiation that differentiates with regard to the type of the ground. [3]

**Figure 3.1: Irradiation types**




*Source:* *http://www.kalzip.com/solar/int/technical/solar_energy.html*

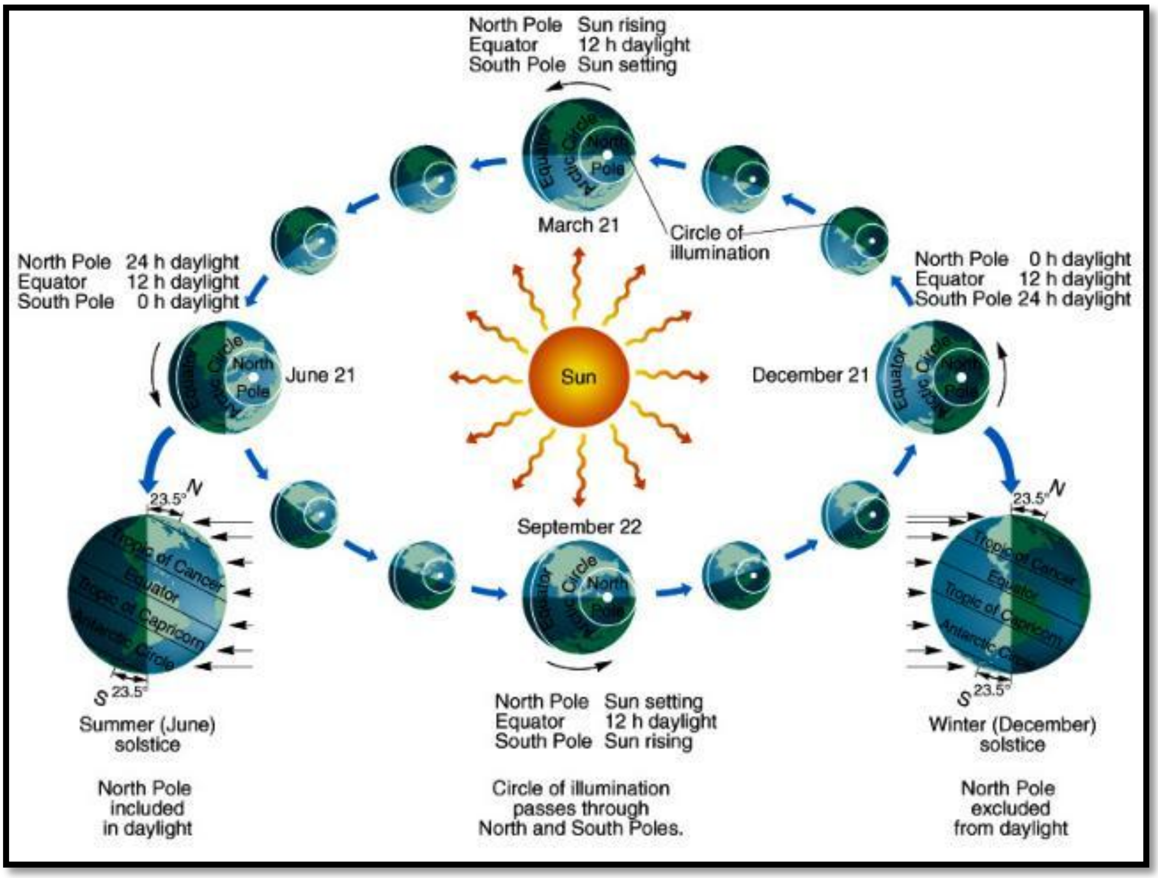
## 3.3 SOLAR GEOMETRY

It is crucial to comprehend the position of the sun and angle specifications to integrally perceive the solar radiation concept. The radiation is related with the sun's movement which means that changes with every motion. The position of the sun is determined through three angles which are declination angle, azimuth angle and elevation angle.

[3] Pidwirny, M., 2006, Atmospheric Effects on Incoming Solar Radiation. http://www.physicalgeography.net/fundamentals/7f.html .

The Earth rotates on its axis with a speed of approximately 467 meter per second and one rotation lasts 24 hours which is called a solar day. When the Earth finishes its cycle around the sun in 365.26 days, Earth revolution is completed which means one year occurs. [4]

**Figure 3.2: The cycle of Earth around the sun**

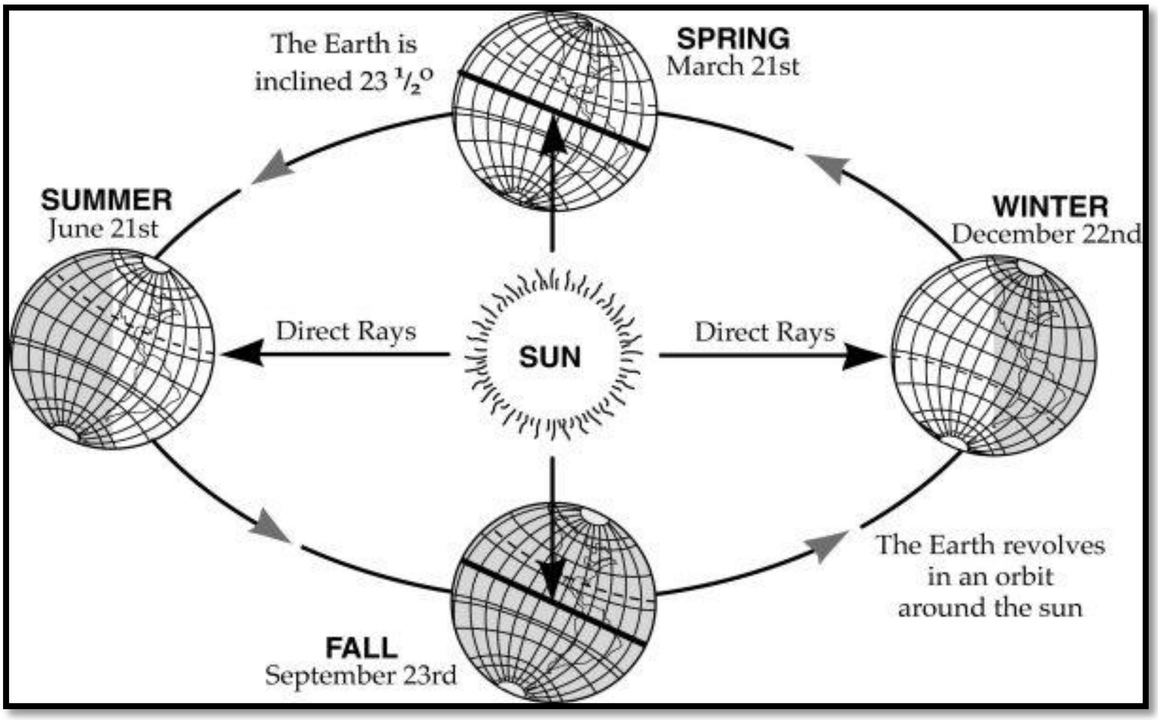



*Source: jwilson.coe.uga.edu*

In the northern hemisphere, summer and winter solstices starts with the first day of summer and winter which are accepted as 21st of June and 22nd of December. The time between sunrise and sunset hours of sun is the longest relatively all the days of the year in summer solstice whereas it is the shortest period of time in winter solstice. When the distance of sun to the North Pole and South Pole became equal, the equinoxes occur which means the night and daytime become also equal at that day. The spring equinox starts with 20th of March whereas it is 22nd of March for the autumn equinox.

[4]Pidwirny, M., 2006, Earth-Sun Geometry. http://www.physicalgeography.net/fundamentals/6h.html .

**Figure 3.3: Equinoxes and solstices**




*Source: http://benkolstad.net/?p=5431*

The daily and yearly movement of the Earth and the sun changes the solar radiation amount. The solar time which is the rotation characteristics of Earth to the sun is used to calculate these variations. In the course of 24 hours, a solar day occurs which means that Earth completes one rotation around its own axis with respect to the sun. When the sun is at its highest point on its own path on the local meridian, it is called the solar noon. The solar time and local time are different from each others. The local time which is the time that is a function of the local longitude should be converted to solar time to be able to make the required solar calculations (Heinemann 2000, pp. 19-20).

### 3.3.1 Position of the Sun

There exist specific angles between the sun's rays and the Earth's surfaces. The utilization of solar energy can be improved by understanding these angles and required explanations.

The terrestrial solar radiation is the radiation that reaches to the Earth's surface and it is designated with the air mass. The air mass is the volume of air that has specific properties which is obtained through staying at particular places in Earth for a long time.[5] The distance that light should take to reach to the Earth can be detected with the air mass factor.

$$AM = \frac{1}{\cos(\theta)} \quad \textbf{(3.1)}$$

where θ is the solar elevation angle, the formula 3.1 gives the air mass and elevation angle correlation.

It is essential to understand the calculations of the sun's position to introduce the solar energy mechanism. The three angles are important to determine the sun's position which is azimuth angle, elevation angle and declination angle.

The solar azimuth angle is the angle that is formed of the direction of the sun from south which is zero when the sun is at solar noon that means the sun is at true south. The angle between equatorial plane and the line that integrates the centers of the sun and the Earth is the solar declination angle. The declination angle of the sun is zero at the autumn and spring equinoxes and it reaches its maximum and minimum levels at winter and summer solstices which are 23.45 degrees for summer and - 23.45 degrees for winter (Leonard Bachman [no history]).

$$\cos\gamma = \frac{\cos\phi \sin\delta - \sin\phi \cos\delta \cos w}{\cos\theta} \quad \textbf{(3.2)}$$

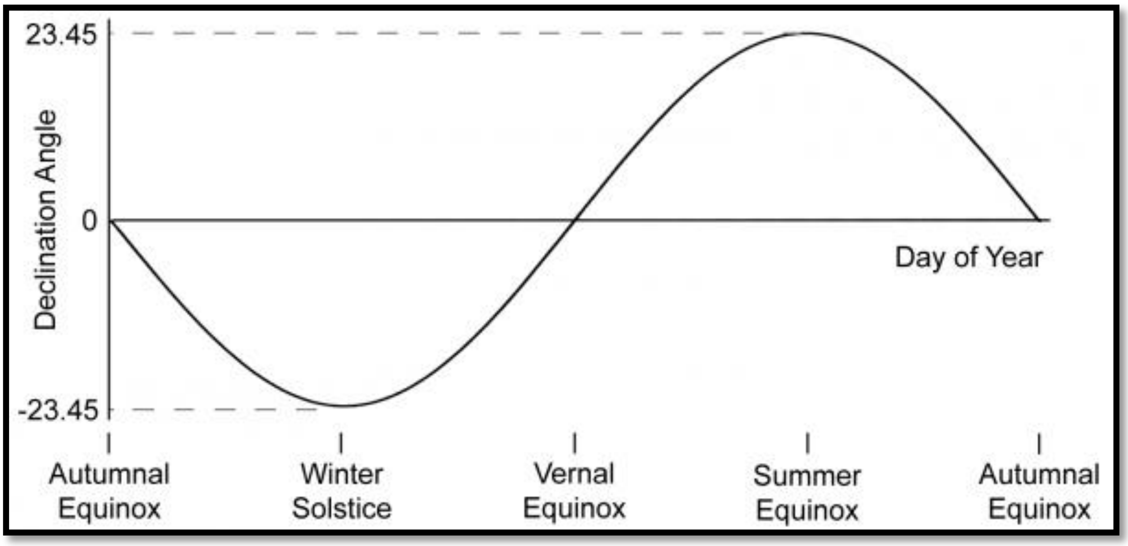
The formula 3.2 represents the azimuth angle γ of the sun. ϕ is the geographical latitude angle of the area on the Earth's surface, δ is the solar declination angle and w is the solar hour angle.

[5] *Air Masses and Fronts.* http://cimss.ssec.wisc.edu/wxwise/class/frntmass.html

The declination δ of the sun can be found by the empirical Cooper's formula (3.3). The parameter n represents the number of the day of the year which means that n = 1 for January 1 and n= 365 for December 31.  The variation of declination angle is shown in Figure 3.4.

$$\delta = 23.45 \sin(360x \frac{(284+n)}{365}) \quad \textbf{(3.3)}$$

**Figure 3.4: The yearly variation of declination angle**



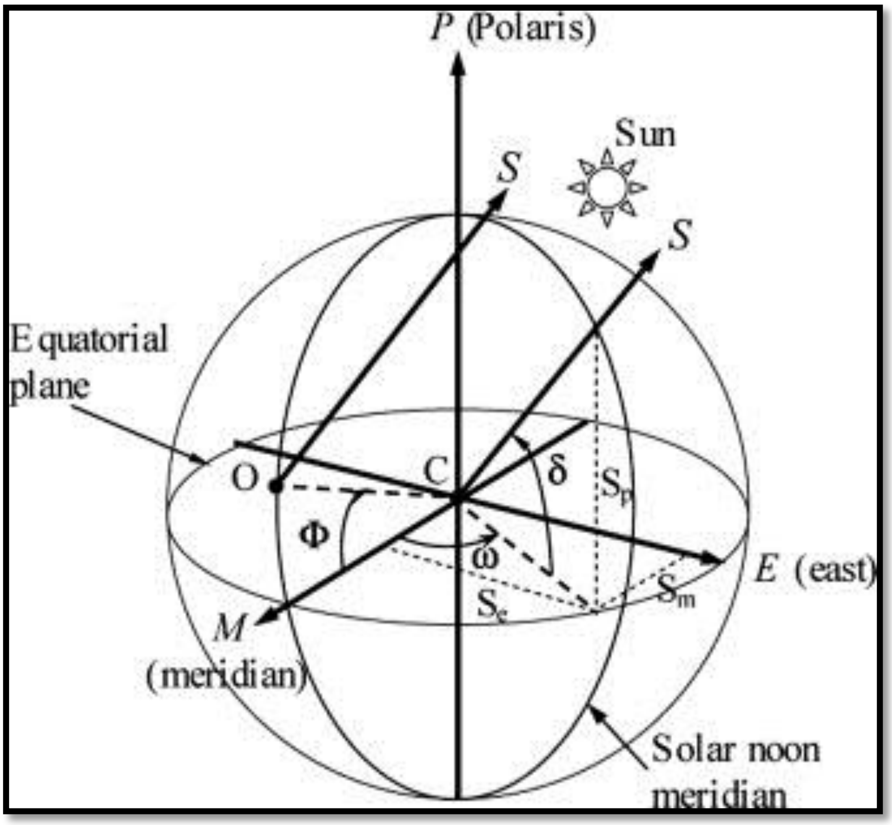

*Source:* www.itacanet.org

Another solar angle is the elevation also called altitude angle which is the angle between the horizon and direction of the center of the sun. The elevation angle can also be described as the altitude of the sun in the air from the horizontal. The altitude is 90 degrees when the sun is at the peak and zero at sunrise. The design of photovoltaic technologies necessitates the maximum elevation angle which occurs at the solar noon and it is also associated with the solar declination angle and the latitude of the geographical site. A similar angle to the elevation angle is the zenith angle which is measured from the vertical instead of horizontal. [6]

$$\sin\theta = \sin\phi\sin\delta + \cos\phi\cos\delta\cos w \quad \textbf{(3.4)}$$

The formula (3.4) represents the calculation of elevation angle θ of the sun where ϕ is the latitude of the site, δ is the solar declination angle and w is the solar hour angle. Figure 3.5 and Figure 3.6 represents the position of sun relative to Earth and solar angles on the Earth's surface respectively.

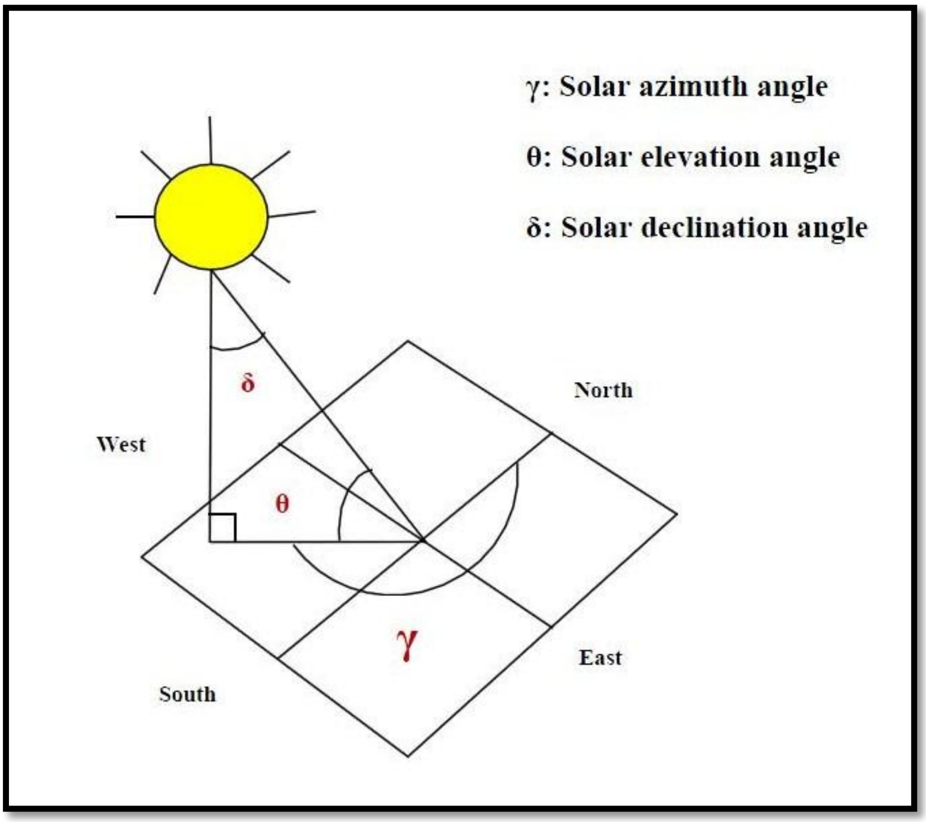
**Figure 3.5: Sun's position relative to the centre of the Earth**




*Source:* Chong, K. K., Wong, C.W., 2009. General formula for on-axis sun-tracking system and its application in improving tracking accuracy of solar collector. *Elsevier.* **83**(3), pp. 298–305.

[6]Honsberg, C. ,Bowden, S. , Elevation Angle. http://www.pveducation.org/properties-of-sunlight/elevation-angle .

**Figure 3.6: Solar angles on the Earth's surface**




## 3.4 PHOTOVOLTAIC ENERGY SYSTEMS AND DESIGN CONSIDERATIONS

It is important to compare the energy alternatives to decide the most suitable system for the intended projects. The photovoltaic energy systems are designed on the purpose of converting solar energy to electrical energy. There are many simple and complicated systems that photovoltaic energy is applied such as calculators, watches, water pumps, lights and various household appliances all around the world.

Photovoltaic energy systems are environmental friendly because the greenhouse gases don't come out, fossil fuel reserves aren't used and any kind of pollution doesn't occur during the process. Some regions of the world are not suitable to apply photovoltaic energy because of some factors such as lack of sun, climate and pollution but there are lots of areas that can benefit from the sun through their locations and region characteristics.

According to the U.S department of energy predictions of photovoltaic systems' energy payback period, if three or four year's investment period is provided, photovoltaic energy will meet the energy demand of thirty or more years.[7] However, high initial costs of this technology make the countries to think twice for applying solar photovoltaic energy. For that purpose, the solar energy incentive mechanisms of the countries should be considered and developed.

The PV system requirements, technology types, internal and external factors that affect the energy output are fundamental for renewable energy investors to comprehend.

### 3.4.1 Grid-Interactive Systems

The photovoltaic technology comprise of two systems which are on-grid PV and off-grid PV applications. The photovoltaic solar panels are connected to the grid and the power which is required to operate the system is provided by the electricity grid at the on-grid applications. On the other hand, off-grid applications are the systems that are operated without the electricity grid.[8] The utilization of photovoltaic energy based on off-grid applications is an important area to be developed. The population of the rural areas lives in distance from the electricity grid and photovoltaic energy is an advantage to meet the energy demands by powering the batteries with the electricity which is produced by the photovoltaic modules in the daytimes.

### 3.4.2 System Components

The main components of PV systems are photovoltaic cells or semiconductors which are used at the conversion process of sunlight to electricity. There are also supplementary components also called balance of systems which are commonly batteries, inverters, controllers, wires and cables, trackers, fuses and structure.

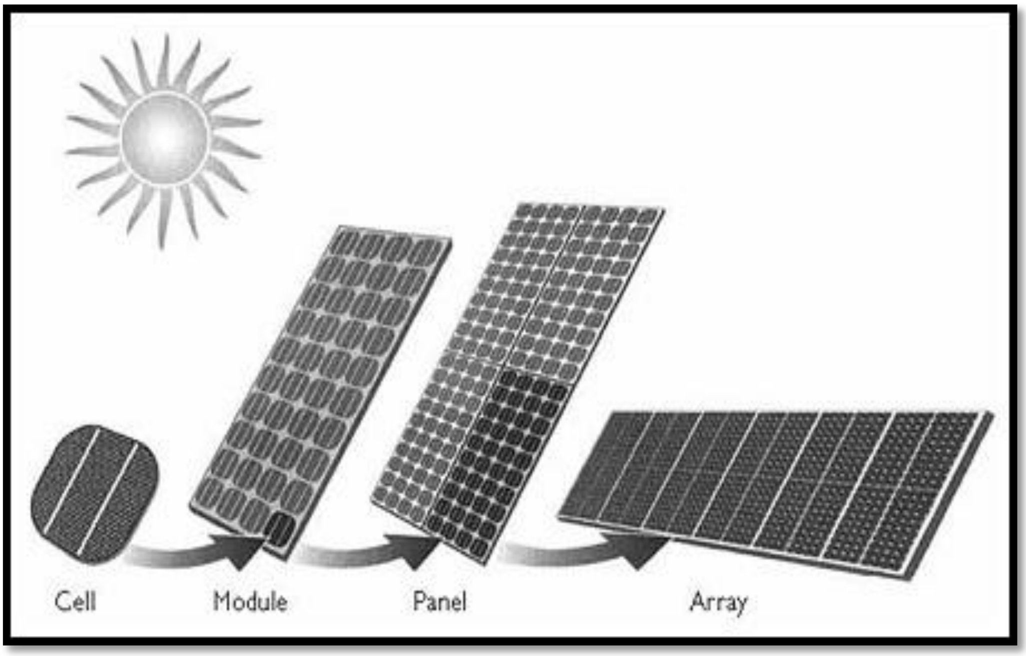
---

[7] Ardani, K. & Margolis, R., 2011. *Solar Technologies Market Report.* U.S Department of Energy: USA.
[8] European Communities, 2009. Photovoltaic Solar Energy Development and Current Research. *Solar Energy Report.* Luxembourg : EU.

#### 3.4.2.1 PV array

A PV array is the composition of a group of PV modules .The integration of PV cells constitutes PV modules. A module is commonly consists of 36 cells and the energy output is dependent on the size of the photovoltaic arrays.[9] A standard house generally uses approximately 10 or 20 PV modules to meet the electric needs of the house whereas a large facility uses hundreds of PV arrays. Figure 3.7 shows cell, module, panel and array relationship.

**Figure 3.7: Formation of PV Arrays**




*Source: http://www.cmhc-schl.gc.ca*

#### 3.4.2.2 DC-AC inverters

The inverters are used for converting the DC power which is generated by photovoltaic modules to AC power. The inverters are always necessary for on-grid PV applications because AC power is the power type that is used by electricity grids.

[9] National Renewable Energy Laboratory, 2012. http://www.nrel.gov .

### 3.4.3 Estimating System Energy Output

A true estimation of solar energy return is crucial before the implementation. It can be achieved by considering various environmental and technical factors that affects the system's performance that were explained below.

#### 3.4.3.1 Standard test conditions

The modules' performances are quite effective on the qualification of PV projects. The PV modules are rated under standard test conditions that generally vary between 100 to 300 watt DC ratings. The STC procedure includes 1000 W/m² solar irradiance, standard solar spectrum and 25 °C solar cell temperature. The PV producers can rate modules owing these quantities. [10]

#### 3.4.3.2 Temperature

When the modules were warmed up overmuch in sunny days, the productivities starts to decline. Therefore, a standard temperature reduction factor of 0.89 is suggested by PV specialists.

#### 3.4.3.3 Dirt and dust

PV modules' performance is affected by dirt that occurs in time. The standard dirt reduction coefficient is accepted as 0.93.

#### 3.4.3.4 Mismatch and wiring losses

A single module's maximum power production is more than the maximum power production of a PV array. This is because of discrepancies that may be occurred between the modules that are called mismatch losses. The power that is diminished due to resistance is the wiring losses. The standard reduction factor for mismatch and wiring losses is 0.95 (Papadopoulou 2011).

---

[10] *Background on PV Systems for Builders and Developers*. 2008. http://www.consol.ws/.

#### 3.4.3.5 DC to AC conversion losses

When DC power was turned to AC power by inverters, some power is lost in the process. The standard conversion loss is stated as 0.90 (Papadopoulou 2011).

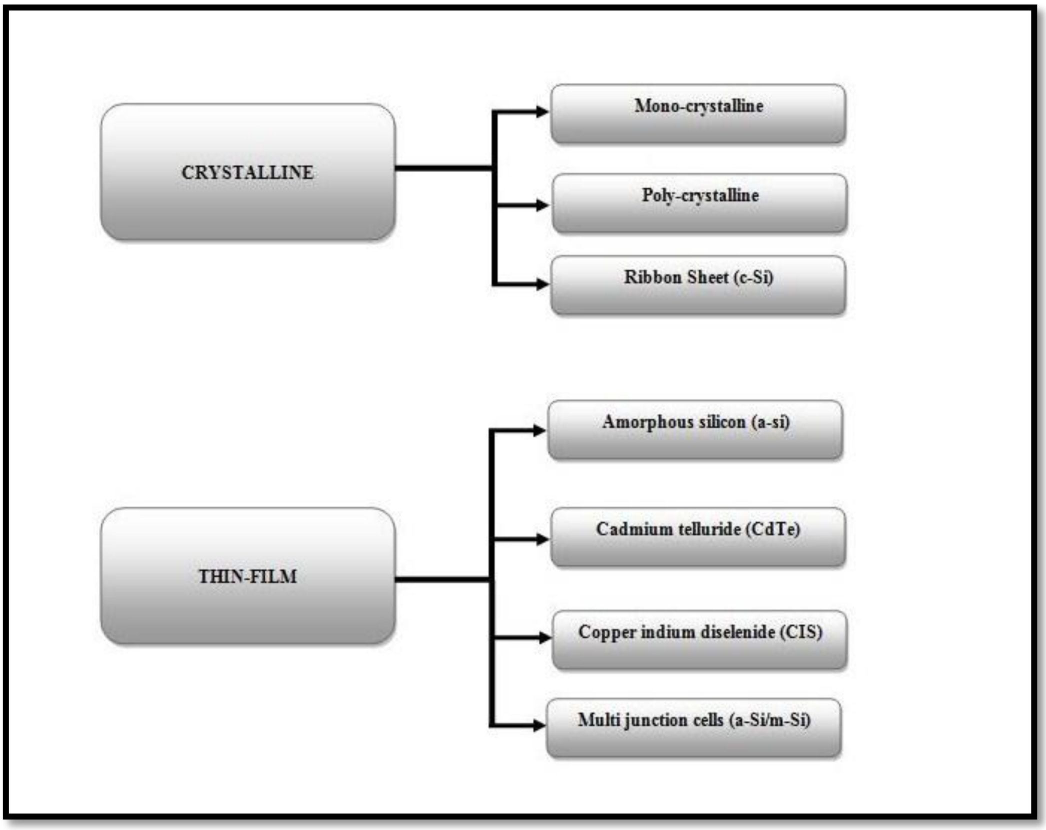
#### 3.4.3.6 Solar angle and field orientation

The angles of the sun continuously changes during the day and the generated power amount varies simultaneously. Therefore, it is required to adjust PV panels with regard to optimum angles to absorb the maximum amount of energy. The calculation techniques of optimum angles to obtain maximum irradiation were explained in detailed in subsequent phases.

## 3.5 PV TECHNOLOGIES

The photovoltaic system types are crystalline silicon and thin film technologies as shown in Figure 3.8. The specialties and manufacturing processes of these technologies are described below.

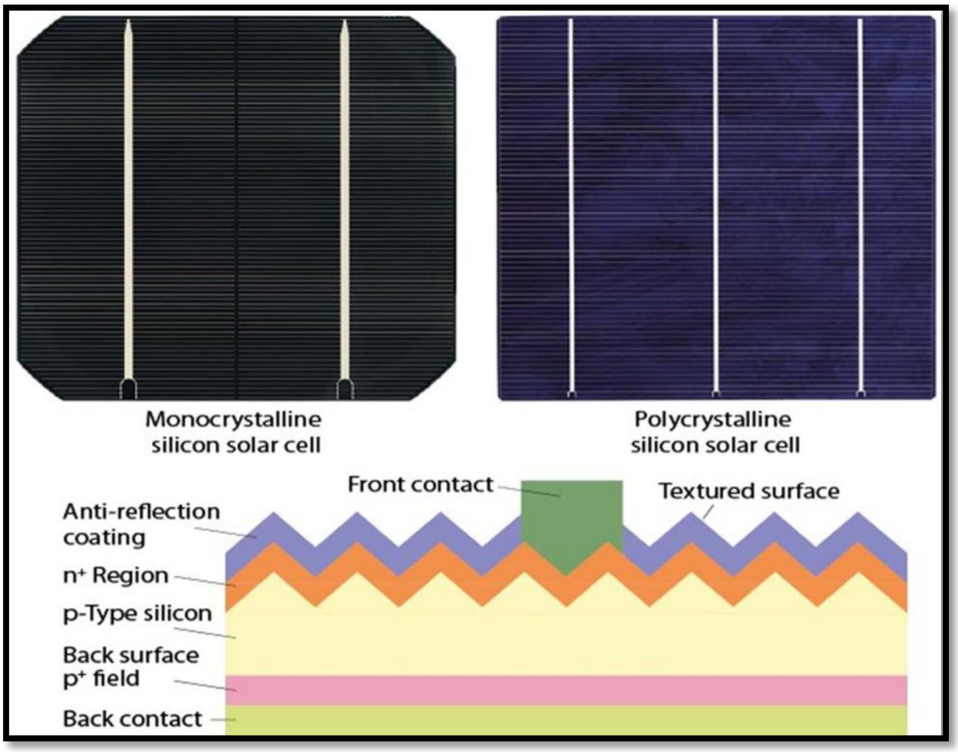
**Figure 3.8: PV cell types**



### 3.5.1 Crystalline Silicon Technology

The solar photovoltaic systems with crystalline silicone cells are the most common technology which is preferred by 90 percent of the PV market in the world. The prevalence of crystalline silicon cells arises from efficiency and decreasing prices of this technology. There are three types of crystalline cells which are mono-crystalline, multi-crystalline and ribbon sheets. [11] Figure 3.9 represents mono-crystalline and multi-crystalline silicon cells.

**Figure 3.9: Mono-crystalline and poly-crystalline silicon solar cells**




*Source:* T. Saga, NPG Asia Mater. 2(3) 96–102 (2010).

#### 3.5.1.1 Mono-crystalline

The mono-crystalline silicone cells are produced by thin sliced parts of a mono crystalline which is a single silicon crystal. The mono-crystalline silicon cells are more efficient than multi-crystalline cells but the production process of the multi-crystalline cells is more easy and cheap. The efficiency of mono-crystalline solar cells is between 18-24 percent.

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[11] Tobias,I. ,Canizo , C.,Alonso,J.2003. *Crystalline Silicon Solar Cells and Modules* .Luque,A.,Hegedus,S.(ED), Spain: John Wiley & Sons, Ltd.

The crystalline silicon technology is the most widespread type of photovoltaic energy due to its high efficiency and reliability that is standardized as 25 years period of time. The silicon material that is used at the production process of the crystalline silicon photovoltaic cells is a prevalent material on the world but to produce crystalline silicon solar cells, silicon should be purified and this operation is quite costly. The silicon requirement is tried to be reduced due to high amounts of usage. Therefore, until recently, the system was considerably expensive so that the undesired effects to the solar energy utilization and expansion were occurred. Because of the excess supply of the cheap photovoltaic panels at China, the prices fell down and the market position of the crystalline silicon solar energy is kept.

#### 3.5.1.2 Multi-crystalline

The multi-crystalline silicon cells are manufactured by segmented parts of a poly crystalline which is a silicon crystal block as distinct from mono-crystalline silicon. The productivity of multi-crystalline cells is approximately between 14-17 percent which is lower than mono-crystalline silicon.[12]

#### 3.5.1.3 Ribbon Silicon Cells

The ribbon silicon cells are produced by integrating a wire to the silicon and combining it with a ribbon sheet. The silicon quantity is less than the other crystalline photovoltaic cells.

### 3.5.2 Crystalline Module Manufacturing

There is a seven step process to be followed to produce a crystalline based PV system. First of all, mono-crystalline silicon ingots are produced. The silicon raw materials are melted at a high temperature which is approximately 1420 °C and a seed crystal is dipped into the molten silicon and then pulled back to form mono-crystalline ingots by rotating the seed crystal. After generating the ingots, ingot squaring is made to form the silicon as quadrilateral by slicing the ingots in fits to the size of the wafers with the aim of making the ingots suitable for producing wafers. This process is made through grinding and ingots are shaped conveniently for solar panel production. The next phase

[12] Fraile,D.,Latour,M.,Gammal, A. E.,Annet, M., 2010. Photovoltaic Energy: Electricity from the Sun. Belgium: European Photovoltaic Industry Association.

is the wafer slicing. The squared ingots are sliced into wafers which are the cores of the solar cells, all of the finished wafers are cleaned, tested and the ones that accomplish the test are used to generate the cells. The solar cells are made with the integration of the wafers and the cells are used to generate solar modules. To obtain a photoelectric effect, various impurities are mixed with silicon wafers. As the last phase of the process, to produce a module, the cells are soldered with a ribbon wire and the connections between the electrodes are made. The connected cells are assembled and laminated by using the tempered glasses. Then, the cells are covered with aluminum, positive and negative terminal boxes are integrated to the cells, so that, a module is produced. [13]

The production steps of a crystalline silicon PV system are given in Figure 3.10.

**Figure 3.10: The production process of crystalline silicon solar system**


*Source:* www.epia.org

[13] *Production Process of PV Panels. 2012.* http://www.europesolar.de/catalog/index.php?main_page=page&id=32

### 3.5.3 Thin Film Technology

Thin film is a relatively new technology on the photovoltaic energy system's field. In the recent years, the solar energy industry started to pay importance to this technology due to its low cost and short supply chains, yet the market share of the thin film technology is approximately 8 to 13 percent.

Thin film photovoltaic modules are generated by integrating several thin layers of photovoltaic materials to a backing material. The thin film solar modules are more economic in proportion to crystalline silicon technology due to the low production costs and the preference of low cost PV back sheet materials. The thin-film modules are effective at cloudy days with low irradiation angles. Therefore, they are actively used on the building facades due to the efficiency and aesthetic appearance.[14]

There are four types of thin film modules which are amorphous silicon, cadmium telluride, copper indium diselenide and multi junction cells. The CIS and CIGS thin film modules are light weighted and usually preferred for building integrated photovoltaic systems whereas cadmium telluride thin film solar cells are the most commonly used in the industry. The efficiencies of the thin film module types are approximately 6 to 9 percent for a-Si, 8 to 19 percent for CIGS and 9 to 20 percent for CdTe. [15]

#### 3.5.3.1 Thin-film module manufacturing

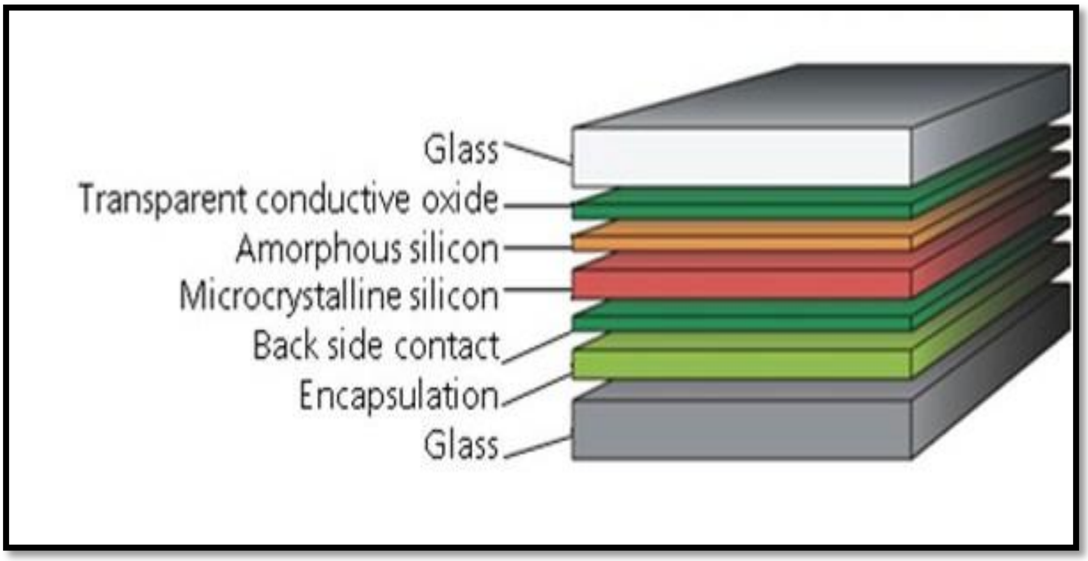
The thin film photovoltaic cells have fewer processes in proportion to the crystalline photovoltaic cells. The system is flexible and the layers of the thin film solar cells are approximately one micron thick whereas crystalline silicon wafer cells are three hundred fifty microns thick.

To produce thin film photovoltaic cells, there are three layers to be considered to integrate onto a back sheet material which are presented in Figure 3.11. The layers are generally a transparent conductive oxide layer, a middle semiconductor photovoltaic layer and a thin metal layer. Furthermore, some of the rare materials can be used to produce the thin film technologies which are tellurium, cadmium and indium that

[14] *Thin-Film PV.* 2011. http://www.pvthin.org/ .
[15] Gross, H., CIGS Turnkey Solutions, *Thin Film Module.* Centrotherm Photovoltaics.

corresponds to platinum on the earth. Because of the rarity of these materials, the researches are made to generate alternatives to cadmium, telluride and indium.[16]

**Figure 3.11: The layers of thin film photovoltaic cells**




*Source: www.ikts.fraunhofer.de*

The production process of the thin film solar cells are faster than manufacturing of the crystalline solar cells owing to the layers that constitutes the thin film module are sprayed or printed immediately to the backing material.

As a drawback of this technology, the cell conversion efficiency of the thin film cells is weak. The reason of this disadvantage is the non-single crystal characters of the thin films. Therefore more land is necessary for installation of the modules than crystalline silicon technology and produce energy as well. Furthermore, the rarity of the materials that are used at the thin-film production process effects the outlook of the products and some of the materials such as cadmium are quite toxic and can be harmful for the environment.[17]

[16] Bogue, R. , 2012. Thin-Film PV, Solar Novus Today UK., www.solarnovus.com.
[17] Photovoltaic Solar Cell Types and Technologies, 2012. http://www.alternative-energy-tutorials.com/solar-power/photovoltaic-types.html .

# 4. IRRADIATION AND POWER CALCULATIONS

## 4.1 INTRODUCTION

Four different areas in Turkey that are suitable to implement the photovoltaic energy systems were selected and system's size was assumed as 10 MW for each installation. The areas were chosen with regard to the monthly average daily global solar irradiation rates that were obtained from Ministry of Energy and Natural Resources of Turkey. The annual energy production capacity of each implementation was calculated and required number of panels to provide desired quantity of energy was determined. The optimum angles of photovoltaic panels with regard to months of a year were calculated through a formulation mechanism that uses the monthly average daily global irradiation rates to obtain irradiation on inclined surfaces.

In order to evaluate the photovoltaic systems' performance, a feasibility study was presented. The acknowledged financial analysis procedures were expressed and required mathematical calculations were given. The calculations were made based on fundamental capital budgeting techniques in the field of finance. The integration of solar energy systems and the investment mechanisms were practiced.

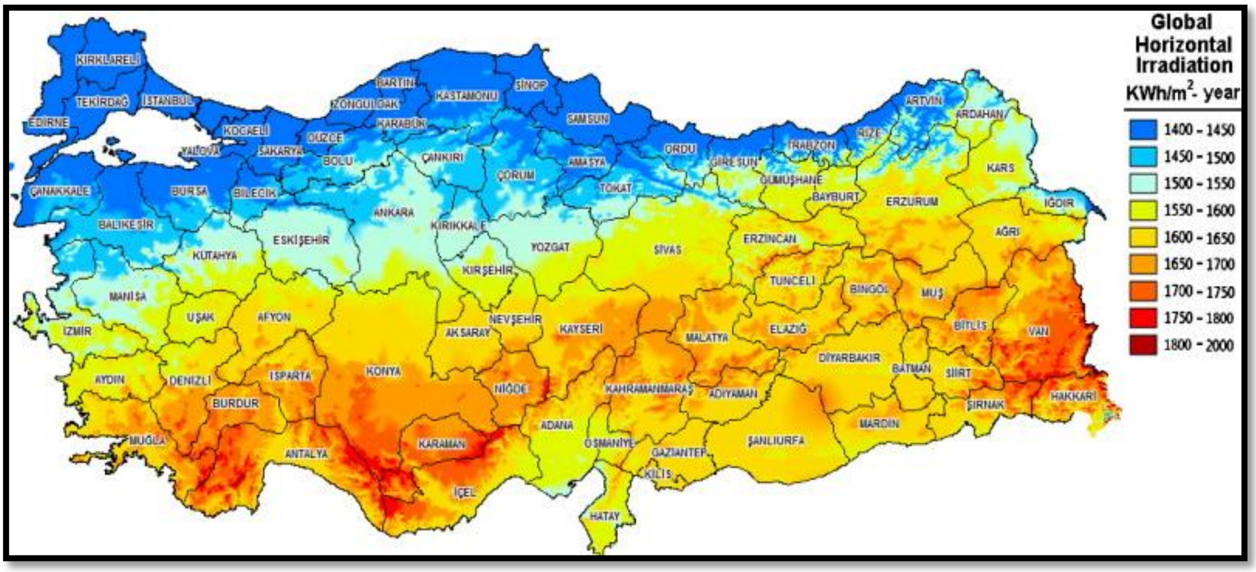
## 4.2 CALCULATION OF IRRADIATION ON INCLINED SURFACES

The solar radiation rates of the regions are usually obtained as monthly average daily global irradiation on a horizontal surface. If photovoltaic panels are positioned towards the sun with the detected optimum inclination angles considering each month of a year, the solar energy flux reaches its maximum rates. The global irradiation values which are denoted by G can be used to calculate the irradiation on a tilted array.

The global irradiation data of the areas are used to assign the direct also called beam and diffuse solar radiation values. The extraterrestrial solar radiation $B_0$ on horizontal plane which is the incoming radiation from out of the Earth's atmosphere is used as a reference to determine the clearness index, afterwards, diffuse and direct radiation on the horizontal. The sunrise hour angle of the sun which is denoted by $w_s$ states the position of the sun depending on solar declination angle $\delta$ and the geographical latitude of the chosen site. The sunrise hour angle should be calculated to determine the extraterrestrial solar radiation. The clearness index $K_T$ specifies the ratio of global solar radiation on the Earth's surface to the extraterrestrial solar radiation. The diffuse radiation on horizontal was determined depending on clearness index and global solar radiation data. When the diffuse solar radiation on horizontal was obtained, the subtraction of diffuse radiation from global radiation gives the beam radiation on horizontal plane (Markvart 2000).

As a second phase of the calculation procedure, the beam irradiation $B_\beta$ and diffuse irradiation $D_\beta$ on a tilted array were determined by considering required angles. Furthermore, the albedo radiation $R_\beta$ was calculated based on the common reflectivity values for ground types. Finally, the summation of beam, diffuse and albedo radiation on an inclined surface gives the total irradiation on a tilted array.

**Figure 4.1: Global radiation rates in Turkey**




*Source:* http://www.yegm.gov.tr/MyCalculator/Default.aspx

**Table 4.1: Reflectivity values for various ground types**

| Ground Cover | Reflectivity(p) |
|---|---|
| Dry bare ground | 0.2 |
| Dry grassland | 0.3 |
| Desert Sand | 0.4 |
| Snow | 0.5-0.8 |

*Source:* Markvart, T., 2000. *Solar electricity*.2nd edition. E.U: Wiley.

The notations of the formula to calculate the total solar radiation on a tilted array is as follows (Markvart 2000):

**Nomenclature:**

**G:** Monthly average daily global irradiation on a horizontal surface.

**B:** Monthly average daily beam irradiation on a horizontal surface.

**D:** Monthly average daily diffuse irradiation on a horizontal surface.

$G_\beta$**:** Monthly average daily global irradiation on an inclined surface.

$B_\beta$**:** Monthly average daily beam irradiation on an inclined surface.

$D_\beta$**:** Monthly average daily diffuse irradiation on an inclined surface.

$R_\beta$**:** Albedo irradiation reflected from the ground to the inclined surface.

$B_0$**:** Daily extraterrestrial irradiation on a horizontal surface.

**S:** Solar constant.

$K_T$**:** Clearness index.

$\beta$**:** Inclination angle of the panel to the horizontal surface.

$\boldsymbol{\delta}$**:** Solar declination angle.

$\boldsymbol{\phi}$**:** Geographical latitude of the site.

$\boldsymbol{p}$: Reflectivity value of the ground.

$\boldsymbol{w_s}$**:** Sunrise hour angle.

$\boldsymbol{w_s'}$ **:** Sunrise hour angle on the tilted array.

$\boldsymbol{w_0}$**:** Minimum of $\boldsymbol{w_s}$ and $\boldsymbol{w_s'}$**.**

The overall formula mechanism to calculate the total solar flux on a tilted array is as follows:

$$\boldsymbol{\delta} = 23.45 \times \sin(360 \times \frac{(284+n)}{365}) \qquad \textbf{(4.1)}$$

Formula (4.1) gives the solar declination angle in degrees which is used for determination of sunrise hour angle and n is the day of the year that can be chosen as the middle of each month.

$$\boldsymbol{\omega_s} = \cos^{-1}(-\tan\varphi \times \tan\delta) \qquad \textbf{(4.2)}$$

Sunrise hour angle can be found by using formula (4.2) where ϕ is the latitude of the chosen area and δ is the solar declination angle which is obtained by formula (4.1) above.

$$\boldsymbol{\omega_s}' = \cos^{-1}(-\tan(\varphi - \beta) \times \tan\delta) \qquad \textbf{(4.3)}$$

Formula (4.3) calculates the sunrise hour angle on the tilted array.

$$\boldsymbol{\omega_0} = \min\{\omega_s, \omega'_s\} \quad \textbf{(4.4)}$$

The minimum of $\omega_s$ and $\omega'_s$ is determined by (4.4). This value should be obtained to calculate the beam radiation on inclined surfaces properly.

$$\boldsymbol{B_0} = \frac{24}{\pi} \times S \times \left\{1 + 0.033 \cos\left(\frac{2\pi d_n}{365}\right)\right\} \{\cos\varphi \cos\delta \sin\omega_s + (\omega_s \frac{\pi}{180}) \sin\varphi \sin\delta\} \quad \textbf{(4.5)}$$

Formula (4.5) represents the extraterrestrial solar radiation on the horizontal surface which is used as a reference value for clearness index calculation and $d_n$ is the day of the year which starts from 1 on first day of January to 365 on last day of December. S is the solar constant which is 1367 W/m$^2$.

$$\boldsymbol{K_T} = \frac{G}{B_0} \quad \textbf{(4.6)}$$

Formula (4.6) gives the clearness index ratio which is used to obtain the condition of the sky after the alleviation of the incoming radiation due to clouds and atmosphere.

$$\boldsymbol{D} = G \times (1 - 1.13K_T) \quad \textbf{(4.7)}$$

Diffuse irradiation on horizontal surface is obtained by formula (4.7) which is the scattered light while arriving the Earth’s surface.

$$\boldsymbol{B} = G - D \tag{4.8}$$

Formula (4.8) represents the beam irradiation on a horizontal surface which is the light that reaches to the Earth without scattering.

$$\boldsymbol{B_\beta} = B \times \frac{\cos(\varphi - \beta)\cos\delta\sin\omega_0 + (\omega_0 \frac{\pi}{180})\sin(\varphi - \beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_s + (\omega_s \frac{\pi}{180})\sin\varphi\sin\delta} \tag{4.9}$$

Formula (4.9) calculates the beam irradiation on an inclined surface with an angle $\beta$.

$$\boldsymbol{D_\beta} = \frac{1}{2} \times (1 + \cos\beta) \times D \tag{4.10}$$

Diffuse radiation on a tilted array can be calculated by formula (4.10).

$$\boldsymbol{R_\beta} = \frac{1}{2} \times (1 - \cos\beta) \times p \times G \tag{4.11}$$

Formula (4.11) represents albedo irradiation on an inclined surface with an angle β which is the radiation that occurs because of the reflectivity of the Earth's surface.

$$\boldsymbol{G_\beta} = B_\beta + D_\beta + R_\beta \tag{4.12}$$

The summation of beam, diffuse and albedo irradiation on an inclined surface gives the total global irradiation on the tilted array with an angle β as represented in formula (4.12).

## 4.3 CALCULATION OF ANNUAL ENERGY PRODUCTION

It is required to determine the annual energy production of photovoltaic energy systems to specify size of 10 MW PV installation's energy output with respect to characteristics of the regions for our case. Energy output of a PV system is dependent on the annual irradiation rate, size of the system and peak sun value of the area.

The term peak sun is an approximate measure valued at 1000 W/m² that is expected to be produced by solar panels in ideal conditions which is at solar noon on equator (Boxwell 2012). It means that peak sun varies from region to region on the world and a lower value should be expected.

The calculation of average peak sun hours for a year is necessary to attain annual energy production. Peak sun hours are number of hours that the sun beams to an area with its highest rate. It is associated with total irradiation and peak sun value of the area.

Formula to calculate the peak sun hours is as follows:

$$Peak\ Sun\ Hours = Total\ Irradiation[Wh/m^2]\ /\ Peak\ Sun[W/m^2] \quad \textbf{(4.13)}$$

Formula to determine annual energy production is shown in (4.14).

$$Annual\ Energy\ Production = Average\ peak\ sun\ hours \times 365 \times system\ size \quad \textbf{(4.14)}$$

### 4.3.1 Number of Panels Required

It is essential to designate the required number of panels to produce the necessary energy amount in the implementation of a photovoltaic system. The determination of how many photovoltaic panels are needed to generate foregoing energy production is contingent on the size of the PV system which was previously mentioned in the annual energy production calculation. It is also an entailment to obtain the DC watt ratings of solar panels which will be used in the system to reach the results properly.

The specified watt ratings of PV panels are affected by various factors and a certain amount of energy loss occurs. Therefore, the required number of panels should be calculated in a yearly basis by considering the system losses which are commonly temperature losses, mismatch and wiring losses, inverter losses and the loss dependent on dust and dirt that were explained in detailed before. After the net watt rating of a PV panel was determined, number of panels can be calculated by the ratio of obtained annual energy production to the annual energy production of a single PV panel which is represented in formula (4.15).

$$Number\ of\ panels = \frac{Annual\ Energy\ Production}{Annual\ Energy\ Production\ of\ one\ PV\ panel} \quad \textbf{(4.15)}$$

The required area to locate the PV panels is generally considered as approximately between 17 and 20 square foot for each panel.[18] It means that after the optimum number of panels was determined, the area to position the panels can be found by a simple multiplication of number of panels and required space for each panel.

**4.3.2 PV Power Example**

In this example, it is aimed to represent the calculation methods of annual energy production and required number of panels for a power plant in a particular region.

Assume that a photovoltaic energy power plant with a size of 1 MW is desired to be established to a city with 3700 Wh/m² annual average irradiation rate. The required data to calculate annual energy production is as follows:

Total irradiation of the area: 3700 Wh/m²

Peak sun value of the region: 480 W/m²

Average insolation hours of the area: 7 hours

[18] http://sroeco.com/solar/

System size: 1 MW

Panel wattage: 150 watt

**Step 1:** Calculating Peak Sun Hours

The peak sun hours of an area should be obtained to calculate the annual energy production. In our case, peak sun hours can be calculated by dividing total yearly irradiation rate of the area to the irradiance value of the region.

$$Peak\ sun\ hours = \frac{3700Wh/m^2}{480W/m^2} = 7.70 \text{ hours}$$

**Step 2:** Calculating Annual Energy Production

After the peak sun hours were calculated, annual energy production of a PV system can be determined by multiplying peak sun hours, system size in kW and number of days in a year as follows:

$$Annual\ energy\ production = 7.70 \times 1000 \times 365 = 2{,}810{,}500 \text{ kWh/year}$$

**Step 3:** Calculating Number of Panels

It is necessary to determine the required number of panels to meet the annual energy production capacity. In this example, PV panels' wattage is assumed as 150 watt. But power losses should be considered to obtain a more accurate result. The industry standards for losses are as follows:

Temperature loss: 0.89

Dust/dirt loss: 0.93

Mismatch/wiring loss: 0.95

DC/AC inverter loss: 0.90

When considering these losses, a 150 watt panel will act as an approximately 106 watt PV panel. The result is shown below:

$$Considering\ loss\ factors = 150 \times 0.93 \times 0.89 \times 0.95 \times 0.90 = 106.15\ Wh$$

The average insolation hours was assumed as 7 hours in a day. It means that the area is exposed to sun 2555 hours in a year. A panel produces 106 watt power in an hour. It also means that, a PV panel will produce 270,830 watt power in a year. Based on the power of one PV panel in a year, the panel numbers to match the 2,810,500 kWh annual energy production can be calculated.

$$Number\ of\ panels = \frac{2810500000\ Wh}{270830\ Wh} = 10{,}377\ panels$$

The results show that 10,377 PV panels are required to produce 2,810 MWh energy in a year.

# 5. INVESTMENT ANALYSIS TECHNIQUES IN SOLAR ENERGY

## 5.1 INTRODUCTION

The total life cycle cost of the solar energy projects based on four selected area to build a photovoltaic energy system was obtained on the purpose of calculating the payback periods of the investments. The annual energy production amount of per site was considered to determine required number of panels which also affect the cost of the system. After the return on investment for each project was revealed, the payback period of the investments were calculated. The capital budgeting techniques that were used to analyze the photovoltaic energy investments were explained below.

## 5.2 TOTAL LIFE CYCLE COST METHOD

The life cycle cost method is a technique that obtains the total cost of operating and owning goods, services, structures or systems in a period of time and helps to find the lowest cost and the best way to achieve a project. The comparison between associated alternatives can be made through this technique. The total cost of a system can be calculated by considering the life cycle period of that system. This method is usually used by the professional environment and provides the decision maker with significant inputs which are relevant to the design of the system, development and utilization. The life cycle cost method considers the initial costs which are design and development cost, equipment cost, the cost of installation, operation and maintenance costs which are raw material cost, labor cost, maintenance cost and energy cost.

The formula to calculate the life cycle cost is as follows[19]:

$$\mathrm{TLCC} = \sum_{n=0}^{N} \frac{C_n}{(1+d)^n} \qquad \textbf{(5.1)}$$

[19] Short,W.,Packey , D.J. and Holt,T., 1995. *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies.* U.S. Department of Energy: National Renewable Energy Laboratory.

where:

$C_n$: cost in period n

N: analysis period

d: annual discount rate

It can be seen that various parameters are important to be taken into consideration which are the rate of discounts, subsidies, taxes, costs of component, financing, replacement and renovation, costs of installation, the evaluation of costs of exploitation and maintenance to achieve the life cycle cost analysis. The discount rate is a measure when the time value of money was considered and it is used to evaluate the present value of a future investment. The calculation of discount rate requires considering nominal interest rate and expected inflation rate of the country.

Formula (5.2) shows the discount rate calculation.

$$Discount\ rate = Nominal\ interest\ rate - Inflation\ rate \quad \textbf{(5.2)}$$

### 5.2.1 Government Incentives for Renewable Energy Systems

The government’s incentives of the countries are designed on the purpose of supporting various potential fields that can contribute to the economy. The renewable energy systems are in the need of these support policies due to recent expansion of the technology and high initial costs. Therefore, many countries constitute incentive mechanisms to encourage the implementation of renewable energy technologies.

It is important to consider the incentive rate of the country in the calculation of total life cycle cost of a project. After the total cost of the project was determined, the incentives should be simply subtracted from the obtained costs to approach a more realistic result.

According to law No. 6094: “ The Utilization of Renewable Energy Sources for Electrical Energy Production “ in Turkey, the incentive given for solar energy systems is 13,3 dollar/cent for 1 kWh energy production and the investment is limited with the size of 600 MW. [20]

**5.3 RETURN ON INVESTMENT METHOD**

The return on investment method is an economic evaluation method to determine if a project is profitable or not. The benefits of a project with respect to cost can be assessed by return on investment analysis. After the analysis, the project’s adequacy is detected and in the case of ineffectiveness, new approaches are searched. The return on investment method can be generally expressed as net operating income divided by average operating assets. Net operating income is the income before the interest and taxes. The denominators of the formula which is operating assets are consists of inventory, equipment and cash, accounts receivable and some other assets that are important for the foundation.

Formula to calculate the return on investment is as follows:

$$\mathrm{ROI} = \frac{\text{Net operating income}}{\text{Average operating assets}} \tag{5.3}$$

After the PV technologies was realized and accepted by the countries, the estimation of return on investment became possible by investigating the real life applications that are operative. The industry standard of annual return on investment for PV applications is between 10-20 percent with positive cash flow (Black 2009). The results of PV investment calculations changes with regard to some factors such as the weather conditions of the regions, irradiation values, average insolation hours of the area and incentive rates.

[20] Icli, S., Colak, M., Cubukcu, M., 2011. PV Technology Status and Prospects. *PVPS Annual Report.* IEA Photovoltaic Power Systems Programme: Switzerland.

## 5.4 SIMPLE PAYBACK PERIOD METHOD

The payback period method is an investment analysis technique which is broadly used in the areas of energy efficiency technologies. The method is defined as the period of time required for the return on an investment to repay the sum of the original investment with ignoring the time value of money, risk and financing measurements, cash flows and any benefits after the payback period, the opportunity cost and various considerations. This method is preferred because of its ease of use by the individuals and organizations especially in capital budgeting and it doesn’t measure profitability (Williams 2012).

The formula to calculate the payback period is as follows:

$$\text{Payback Period} = \frac{\text{Total cost of the project}}{\text{Annual cash flow}} \tag{5.4}$$

This formula assumes that the annual cash inflow which means the amount of cash that your project generates doesn’t change year to year and helps with cash flow analysis for short term budgeting. According to the obtained results, it is stated at the literature that a project would be accepted if its payback period is less than the maximum or standard payback period set by management.

# 6. APPLICATIONS OF SOLAR INVESTMENT ANALYSIS

## 6.1 INTRODUCTION

The selected sites with regard to abundant average irradiation rates to implement photovoltaic energy systems are Van, Karaman, Niğde and Denizli cities of Turkey. The obtained results of calculation of irradiations on tilted array, life cycle costs of the projects, estimated return on investments and therefore estimated payback periods were clarified for each city. The irradiation on different inclination angles for Karaman city was presented in detailed whereas irradiation values of other cities were given in appendix.

## 6.2 EVALUATION OF KARAMAN

The calculated monthly average daily irradiation values on different inclination angles from 0 to 90 degrees are as follows:

**Table 6.1: Irradiation on different inclination angles for Karaman city**

| Inclination Angle | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Average Year (Wh/$m^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0° | 2150 | 2620 | 4380 | 5330 | **6400** | **6950** | **6850** | 6130 | 5220 | 3860 | 2510 | 1890 | 4524 |
| 10° | 2546 | 2925 | 4745 | 5489 | 6394 | 6842 | 6783 | **6231** | 5558 | 4344 | 2950 | 2258 | 4755 |
| 20° | 2904 | 3189 | 5004 | **5536** | 6269 | 6615 | 6594 | 6206 | 5771 | 4730 | 3326 | 2593 | 4894 |
| **30°** | 3212 | 3405 | 5147 | 5466 | 6023 | 6271 | 6283 | 6052 | **5851** | 5006 | 3624 | 2883 | **4935** |
| 40° | 3460 | 3566 | **5180** | 5274 | 5665 | 5816 | 5858 | 5775 | 5798 | 5161 | 3836 | 3120 | 4876 |
| 50° | 3642 | 3667 | 5091 | 4991 | 5202 | 5264 | 5329 | 5382 | 5599 | **5194** | 3957 | 3296 | 4718 |
| 60° | 3751 | **3705** | 4887 | 4601 | 4652 | 4995 | 4717 | 4885 | 5298 | 5101 | **3982** | 3407 | 4498 |
| 70° | **3786** | 3679 | 4573 | 4123 | 4033 | 3970 | 4041 | 4302 | 4866 | 4886 | 3910 | **3449** | 4135 |
| 80° | 3743 | 3590 | 4160 | 3574 | 3369 | 3264 | 3332 | 3652 | 4331 | 4556 | 3743 | 3420 | 3728 |
| 90° | 3626 | 3440 | 3659 | 2974 | 2693 | 2573 | 2628 | 2963 | 3707 | 4121 | 3487 | 3322 | 3266 |

It can be seen from the Table 6.1 that average maximum irradiation of twelve months is at 30 degrees of inclination angle. The average global irradiation is 4524 Wh/m² whereas the irradiation on a tilted array with an angle of 30° is 4935 Wh/m². In case of PV arrays are set to 30 degrees fixed tilt angle over a year, a better efficiency will be acquired.

**Table 6.2: Maximum irradiation and monthly optimum angles for Karaman city**

| Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Average Year (Wh/m²) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3786 | 3706 | 5184 | 5536 | 6412 | 6950 | 6850 | 6237 | 5851 | 5198 | 3985 | 3449 | 5262 |
| 69° | 61° | 38° | 19° | 4° | 0° | 0° | 13° | 31° | 48° | 58° | 71° | **Optimum Angles** |

If the array tilt is changed with respect to optimum angles of every month of a year instead of a fixed inclination angle, the productivity will be increased as shown in Table 6.2. When array tilt is adjusted as optimum angles, the average irradiation value of a year becomes 5262 Wh/m² that is a considerably high value relative to 4935 Wh/m² which is aforementioned average maximum irradiation rate of one year.

It was assumed that PV panels will be adjusted with 30° inclination angle which is yearly optimum fixed tilt for each studied area. The angular decisions of PV panels are required on the calculation of annual energy production due to affect of irradiation rates. The irradiation rates on 30° inclination angle for Karaman is represented in Table 6.3. The annual energy productions of the selected cities were calculated based on average peak sun hours and system’s size. The average annual irradiance intensity data of the regions in Turkey is required to calculate peak sun hours which are shown in Table 6.4.

**Table 6.3: Irradiation rates of Karaman on 30° tilted PV panel**

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Average (Wh/m²) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **30°** | 3211 | 3405 | 5147 | 5466 | 6023 | 6271 | 6283 | 6052 | 5850 | 5005 | 3624 | 2883 | **4935** |

**Table 6.4: Average annual intensity of irradiance in Turkey (W/m²)**

| **Geographical Regions of Turkey** | **Average Annual Irradiance Intensity(W/m²)** |
|---|---|
| Southern Anatolia Region | 477 |
| Mediterranean Region | 463 |
| Central Anatolia Region | 457 |
| Aegean Region | 450 |
| Eastern Anatolia Region | 447 |
| Marmara Region | 363 |
| Black  Sea Region | 343 |

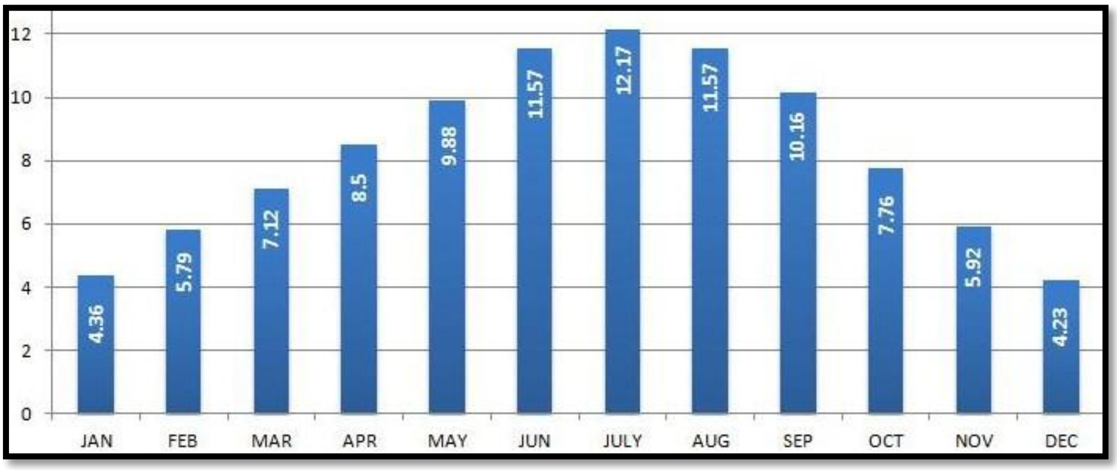
The peak sun hours for Karaman was calculated as 10.66 hours by dividing average irradiation rates on 30 ° tilt angle to the peak sun which is 463 W/m² for Mediterranean region and used in the determination of annual energy production.

The average insolation hour of an area is a deterministic factor to comprehend how many hours in a year the sun is abundant for an area and accordingly to obtain required number of panels. Annual energy productions of a 10 MW PV system, average solar hours and number of panels for Karaman are represented in Table 6.5 and insolation hour data for Karaman is shown in Figure 6.1.

**Table 6.5:  Annual energy production and number of panels for Karaman city**

| **Average Insolation Hours** | **Annual Energy Production (kWh/year)** | **Number of Panels** |
|---|---|---|
| 8.25 | 38,908,000 | 71,765 |

**Figure 6.1: Insolation hours of Karaman city**




*Source: [http://www.yegm.gov.tr/MyCalculator/Default.aspx](http://www.yegm.gov.tr/MyCalculator/Default.aspx)*

It was assumed that 250 watt/h PV panels are used in the implementation. The loss factors were considered and it was found that a PV panel with 250 watt rating operates approximately as a PV panel with 180 watt power.

The results for Karaman shows that 38,908 MWh energy can be produced in a year and 71,765 PV panels with 250 watt energy rating are required to generate this power.

On the basis of these calculations, the life cycle cost of a photovoltaic energy project, by this means estimated return on investment and payback periods can be determined. The life cycle cost of the project for a year was studied for three different module technologies which are mono-crystalline silicon, poly-crystalline silicon and thin-film solar panels. The total cost of the project was calculated by considering various cost factors including price distinction of PV module types, inverters, monitoring, design and installation, land acquisition, contingency and operation and maintenance. The energy lines and high voltage cables were also considered. It was assumed that the nearest regulator is in 3 kilometers. Based on this assumption, it was estimated that, a high voltage pole will be constructed for each 300 meters which means 10 poles are required. Furthermore, the high voltage cable costs were determined by considering 8 lines exists on the way of 3000 meters regulator distance. The replacement costs were ignored because PV projects are assumed as durable for 25 years. In this case, it was aimed to evaluate the status of the system after one year.

The government's incentive policy for photovoltaic energy systems was also considered in the calculations. According to renewable energy sources legislation in Turkey, $ 0.13 incentive is given for per kilowatt electricity that was produced from the sun. This incentive rate is valid in ideal conditions which is being monopoly in the solar energy sector. Therefore, it was also assumed an incentive rate of $ 0.1 by considering the competitors and cost calculations were made based on both cases.

The discount rate is a significant factor for a realistic calculation of total life cycle cost. The required inputs are nominal interest rate and inflation rate of the country in question. The nominal interest rate of Turkey is between 5-10 percent and inflation rate is 8.06 percent. The system characteristics and calculation inputs are shown in Table 6.6. The total cost of the project in Karaman is given in Table 6.7.

**Table 6.6: PV system characteristics and inputs for calculations**

| | |
|---|---|
| **System Size** | 10 MW |
| **Land** | 20,000 m² |
| **Interest rate of land acquisition** | 5.75 % |
| **Incentive rate for ideal condition** | $ 0.133 for 1 kWh energy production |
| **Incentive rate for non-ideal condition** | $ 0.1 for 1 kWh energy production |
| **Nominal Interest Rate** | 5-10 % |
| **Inflation Rate** | 8.06 % |

**Table 6.7: TLCC for Karaman project**

| | $ Unit Price | $ Cost | PV( Poly) | PV(Thin) |
|---|---|---|---|---|
| **PV Modules(Mono)** | 1.95 | 34,985,336 | 49,517,707 | |
| **PV Modules(Poly)** | 2.76 | - | | |
| **PV modules(Thin)** | 1.67 | - | | 29,961,801 |
| **Inverter** | 0.95 | 9,500,000 | 9,500,000 | 9,500,000 |
| **Monitoring** | 0.50 | 5,000,000 | 5,000,000 | 5,000,000 |
| **Design&Installation** | 0.45 | 4,500,000 | 4,500,000 | 4,500,000 |
| **Land Acquisition + Interest Rate** | 0.5 | 10,000 + 10,575 | 20,575 | 20,575 |
| **Energy Lines** | 0.0056 | 56,200 | 56,200 | 56,200 |
| **High Voltage Cables** | 0.56 | 13,440 | 13,440 | 13,440 |
| **Contingency** | 0.70 | 7,000,000 | 7,000,000 | 7,000,000 |
| **O&M costs (for one year)** | 0.015 | 150,000 | 150,000 | 150,000 |
| **TOTAL** | 5.63 | 61,225,551 | 75,757,922 | 56,202,016 |
| **Ideal Incentives ($ 0.133 for 1 kWh)** | -5174790 | -5174790 | -5174790 | -5174790 |
| **Total after ideal incentives** | - | 56,050,762 | 70,583,132 | 51,027,226 |
| **Estimated Incentives ($ 0.1 for 1 kWh)** | -3890819 | -3890819 | -3890819 | -3890819 |
| **Total after estimated incentives** | - | 57,334,732 | 71,867,103 | 52,311,197 |

The total life cycle costs were calculated based on both cases which are incentive rates on ideal conditions and estimated incentive rate for non-ideal conditions. The total life cycle costs are given in Table 6.8.

**Table 6.8: Total life cycle costs for PV technologies for Karaman**

| **$ 0.133 INCENTIVE RATE** | | | **$ 0.1 INCENTIVE RATE** | | |
|---|---|---|---|---|---|
| **Mono Crystalline** | **Poly Crystalline** | **Thin-Film** | **Mono Crystalline** | **Poly Crystalline** | **Thin-Film** |
| $ 54,984,071 | $ 69,239,879 | $ 50,056,137 | $ 56,243,606 | $ 70,499,414 | $ 51,315,673 |

The industry standards of annual returns on investment of photovoltaic projects are approximately between 10-20 percent according to real life applications. The return on investment percentages of the projects were estimated based on average insolation hours of the sites, irradiation rates of the adjusted angles and the productivity rates of PV technology types. It was assumed that return on investment for monocrystalline technology will be 19 percent, for polycrystalline 17 percent and 15 percent for thin-film technology in Karaman project. The payback periods were calculated by dividing total cost of the project to the estimated annual cash inflow. The payback period calculations for Karaman based on these assumptions are as follows:

$$Payback\ period\ for\ monocrystalline = \frac{54{,}984{,}071}{54{,}984{,}071 \times 0.19} = 5.26\ years$$

$$Payback\ period\ for\ polycrystalline = \frac{69{,}239{,}879}{69{,}239{,}879 \times 0.17} = 5.88\ years$$

$$Payback\ period\ for\ thin\ film = \frac{50{,}056{,}137}{50{,}056{,}137 \times 0.15} = 6.67\ years$$

The estimated payback periods based on total life cycle costs of the project that were calculated with $ 0.133 incentive rate are shown in Table 6.9.

**Table 6.9: Estimated payback periods for Karaman project**

| | Mono-crystalline | Poly-crystalline | Thin-Film |
|---|---|---|---|
| **Total Life Cycle Cost** | $ 54,984,071 | $ 69,239,879 | $ 50,056,137 |
| **Payback Period** | **5.26 years** | 5.88 years | 6.67 years |

It can be seen from the results that mono-crystalline technology is the best option with almost 5 years payback period time for Karaman project.

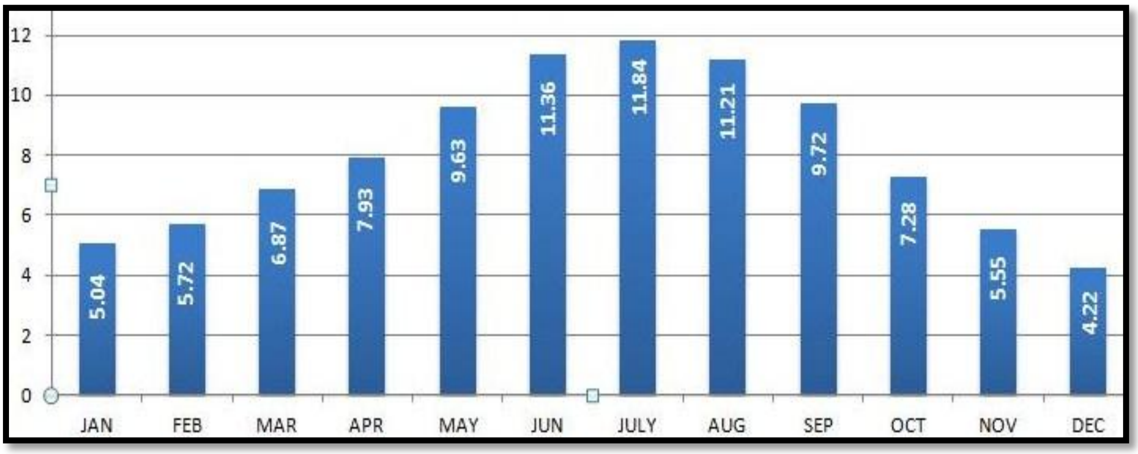
## 6.3 EVALUATION OF DENİZLİ

The optimum angles and maximum irradiation values for Denizli project is shown in Table 6.10 and Figure 6.2 represents solar hours for Denizli. The calculated irradiation values of different inclination angles for Denizli is given in Appendix 3.

**Table 6.10: Maximum irradiation and monthly optimum angles for Denizli**

| Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Average Year (Wh/m²) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3357 | 3231 | 4742 | 5395 | 6123 | 6650 | 6500 | 6058 | 5495 | 5012 | 3697 | 3239 | 4958 |
| 70° | 60° | 38° | 19° | 5° | 0° | 0° | 14° | 31° | 48° | 57° | 71° | **Optimum Angles** |

**Figure 6.2: Insolation hours of Denizli**




*Source: http://www.yegm.gov.tr/MyCalculator/Default.aspx*

The best angle is 30 degrees for a fixed array adjustment and if array angle is changed with regard to optimum angles, irradiation value will increase from 4665 Wh/m² to 4958 Wh/m². The irradiation values on optimum 30° fixed tilt that were used in the calculation of peak sun hours are shown in Table 6.11.

**Table 6.11: Irradiation rates of Denizli on 30° tilted PV panel**

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Average (Wh/m²) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **30°** | 2864 | 2987 | 4709 | 5331 | 5769 | 6029 | 5989 | 5887 | 5518 | 4823 | 3369 | 2706 | **4665** |

The peak sun hours for Denizli are 10.37 hours that were obtained by dividing average irradiation rates on 30 ° tilt angle to the peak sun which is 450 W/m² for Aegean region and used in the determination of annual energy production.

The annual energy production capacity of Denizli area and the required number of panels to match 10 MW systems energy production in is given in Table 6.12.

**Table 6.12: Annual energy production and number of panels for Denizli city**

| Average Solar Hours | Annual Energy Production (kWh/year) | Number of Panels |
|---|---|---|
| 8.03 | 37,842,000 | 71,728 |

Total cost of Denizli project and costs after incentive rates are shown in Table 6.13 and Table 6.14 respectively.

## Table 6.13: TLCC for Denizli project

| | $ Unit Price | $ Cost | PV( Poly) | PV(Thin) |
|---|---|---|---|---|
| **PV Modules(Mono)** | 1.95 | 34,967,161 | 49,491,982 | 29,946,236 |
| **PV Modules(Poly)** | 2.76 | - | | |
| **PV modules(Thin)** | 1.67 | - | | |
| **Inverter** | 0.95 | 9,500,000 | 9,500,000 | 9,500,000 |
| **Monitoring** | 0.50 | 5,000,000 | 5,000,000 | 5,000,000 |
| **Design&Installation** | 0.45 | 4,500,000 | 4,500,000 | 4,500,000 |
| **Land Acquisition + Interest Rate** | 0.5 | 10,000 + 10,575 | 20,575 | 20,575 |
| **Energy Lines** | 0.0056 | 56,200 | 56,200 | 56,200 |
| **High Voltage Cables** | 0.56 | 13,440 | 13,440 | 13,440 |
| **Contingency** | 0.70 | 7,000,000 | 7,000,000 | 7,000,000 |
| **O&M costs (for one year)** | 0.015 | 150,000 | 150,000 | 150,000 |
| **TOTAL** | 5.63 | 61,207,376 | 75,732,197 | 56,186,451 |
| **Ideal Incentives ($ 0.133 for 1 kWh)** | - 5033049 | - 5033049 | - 5033049 | - 5033049 |
| **Total after ideal incentives** | - | 56,174,327 | 70,699,148 | 51,153,401 |
| **Estimated Incentives ($ 0.1 for 1 kWh)** | -3784248 | -3784248 | -3784248 | -3784248 |
| **Total after estimated incentives** | - | 57,423,129 | 71,947,950 | 52,402,203 |

**Table 6.14: Total life cycle costs for PV technologies for Denizli**

| $ 0.133 INCENTIVE RATE | | | $ 0.1 INCENTIVE RATE | | |
|---|---|---|---|---|---|
| **Mono Crystalline** | **Poly Crystalline** | **Thin-Film** | **Mono Crystalline** | **Poly Crystalline** | **Thin-Film** |
| $ 55,105,284 | $ 69,353,686 | $ 50,179,911 | $ 56,330,320 | $ 70,578,722 | $ 51,404,947 |

It was assumed that the return on investments for mono-crystalline technology will be 16 percent, for poly-crystalline 14 percent and for thin-film technology 12 percent in Denizli. The same calculation method was used as shown in Karaman project. The estimated payback periods based on total life cycle costs of the project that were calculated with $ 0.133 incentive rate are given in Table 6.15.

**Table 6.15: Estimated payback periods for Denizli project**

| | **Mono-crystalline** | **Poly-crystalline** | **Thin-Film** |
|---|---|---|---|
| **Total Life Cycle Cost** | $ 55,105,284 | $ 69,353,686 | $ 50,179,911 |
| **Payback Period** | **6.25 years** | 7.14 years | 8.33 years |

The results indicate that best technology to use in Denizli is mono-crystalline silicon with approximately 6.25 years payback period.

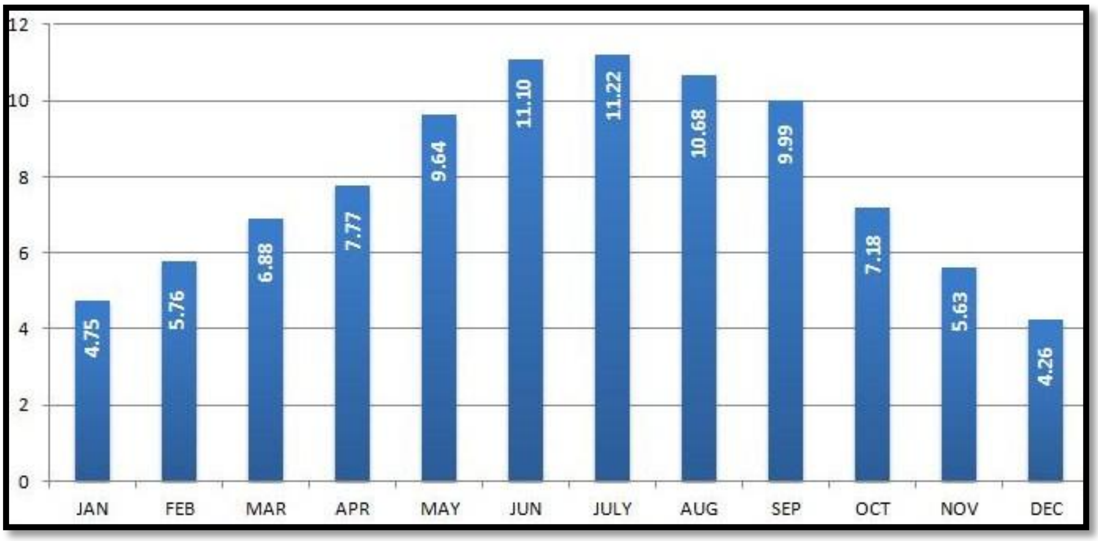
## 6.4 EVALUATION OF VAN

The maximum irradiation rates and optimum angles for Van are presented in Table 6.16 and Figure 6.3 shows insolation hours of Van. The obtained irradiation values on different inclination angles for Van is given in Appendix 1.

**Table 6.16: Maximum irradiation and monthly optimum angles for Van**

| Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Average Year (Wh/m²) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3433 | 5328 | 4941 | 5365 | 6649 | 6990 | 7300 | 6203 | 6037 | 5037 | 3774 | 3322 | 5365 |
| 70° | 63° | 39° | 20° | 5° | 0° | 0° | 14° | 32° | 48° | 58° | 72° | **Optimum Angles** |

**Figure 6.3: Insolation hours of Van**




*Source: http://www.yegm.gov.tr/MyCalculator/Default.aspx*

30 degrees is the best angle for a fixed array adjustment and if optimum angles are considered when array angle is set, irradiation rate will rise from 5020 Wh/m² to 5365 Wh/m². The irradiation values on optimum 30° fixed tilt that were used in the calculation of peak sun hours are represented in Table 6.17.

**Table 6.17: Irradiation rates of Van on 30° tilted PV panel**

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Average (Wh/m²) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **30°** | 2906 | 4711 | 4900 | 5308 | 6276 | 6341 | 6723 | 6040 | 6032 | 4833 | 3416 | 2752 | **5020** |

The peak sun hours for Van are 10.52 hours that were calculated by dividing average irradiation rates on 30° tilt angle to the peak sun which is 477 W/m² for Southern Anatolia region and used in the determination of annual energy production.

The annual energy production amount of Van and the required number of panels to meet systems energy production is shown in Table 6.18.

**Table 6.18: Annual energy production and number of panels for Van city**

| Average Solar Hours | Annual Energy Production (kWh/year) | Number of Panels |
|---|---|---|
| 7.90 | 38,415,000 | 73,975 |

Total cost of Van project and costs after incentive rates are given in Table 6.19 and Table 6.20.

**Table 6.19: TLCC for Van project**

<table>
<tr><th></th><th>$ Unit Price</th><th>$ Cost</th><th>PV( Poly)</th><th>PV(Thin)</th></tr>
<tr><td>PV Modules(Mono)</td><td>1.95</td><td>36,062,608</td><td rowspan="3">51,042,461</td><td rowspan="3">30,884,388</td></tr>
<tr><td>PV Modules(Poly)</td><td>2.76</td><td>-</td></tr>
<tr><td>PV modules(Thin)</td><td>1.67</td><td>-</td></tr>
<tr><td>Inverter</td><td>0.95</td><td>9,500,000</td><td>9,500,000</td><td>9,500,000</td></tr>
<tr><td>Monitoring</td><td>0.50</td><td>5,000,000</td><td>5,000,000</td><td>5,000,000</td></tr>
</table>

| | | | | |
|---|---|---|---|---|
| **Design&Installation** | 0.45 | 4,500,000 | 4,500,000 | 4,500,000 |
| **Land Acquisition**<br>**+**<br>**Interest Rate** | 0.5 | 10,000<br>+<br>10,575 | 20,575 | 20,575 |
| **Energy Lines** | 0.0056 | 56,200 | 56,200 | 56,200 |
| **High Voltage Cables** | 0.56 | 13,440 | 13,440 | 13,440 |
| **Contingency** | 0.70 | 7,000,000 | 7,000,000 | 7,000,000 |
| **O&M costs**<br>**(for one year)** | 0.015 | 150,000 | 150,000 | 150,000 |
| **TOTAL** | 5.63 | 62,302,823 | 77,282,676 | 57,124,603 |
| **Ideal Incentives**<br>**($ 0.133 for 1 kWh)** | -5109217 | -5109217 | -5109217 | -5109217 |
| **Total after**<br>**ideal incentives** | - | 57,193,606 | 72,173,459 | 52,015,386 |
| **Estimated Incentives**<br>**($ 0.1 for 1 kWh)** | -3841517 | -3841517 | -3841517 | -3841517 |
| **Total after**<br>**estimated incentives** | - | 58,461,307 | 73,441,159 | 53,283,086 |

**Table 6.20: Total life cycle costs for PV technologies for Van**

| **$ 0.133 INCENTIVE RATE** | | | **$ 0.1 INCENTIVE RATE** | | |
|---|---|---|---|---|---|
| **Mono Crystalline** | **Poly Crystalline** | **Thin-Film** | **Mono Crystalline** | **Poly Crystalline** | **Thin-Film** |
| $ 56,105,166 | $ 70,799,940 | $ 51,025,491 | $ 57,348,741 | $ 72,043,515 | $ 52,269,066 |

It was assumed that the return on investments for mono-crystalline technology will be 18 percent, for poly-crystalline 16 percent and for thin-film technology 14 percent in Van. The same calculation method was used as shown in Karaman project. The estimated payback periods based on total life cycle costs of the project that were calculated with $ 0.133 incentive rate are given in Table 6.21.

**Table 6.21: Estimated payback periods for Van project**

| | **Mono-crystalline** | **Poly-crystalline** | **Thin-Film** |
|---|---|---|---|
| **Total Life Cycle Cost** | $ 56,105,166 | $ 70,799,940 | $ 51,025,491 |
| **Payback Period** | **5.5 years** | 6.25 years | 7.14 years |

According to results, best product to use in Van project is mono-crystalline silicon with 5.5 years estimated payback period time.

## 6.5 EVALUATION OF NİĞDE

Table 6.22 shows maximum irradiation values and optimum angles for Niğde. Figure 6.4 gives average solar hours of Niğde. The calculated irradiation rates on different inclination angles for Niğde is given in Appendix 2.

**Table 6.22: Maximum irradiation and monthly optimum angles for Niğde**

| **Jan** | **Feb** | **Mar** | **Apr** | **May** | **June** | **July** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Average Year (Wh/m²)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3537 | 3777 | 4991 | 5299 | 6385 | 6810 | 6940 | 6165 | 5725 | 5032 | 3746 | 3293 | 5142 |
| 70° | 62° | 38° | 19° | 5° | 0° | 0° | 14° | 31° | 48° | 58° | 71° | **Optimum Angles** |

**Figure 6.4: Insolation hours of Niğde**


*Source: http://www.yegm.gov.tr/MyCalculator/Default.aspx*

The optimum angle for a fixed array is 30 degrees for Niğde and if arrays are adjusted with respect to optimum angles every month, the irradiation will be 5142 Wh/m² instead of 4826 Wh/m². The irradiation values on optimum 30° fixed tilt are given in Table 6.23.

**Table 6.23: Irradiation rates of Niğde on 30° tilted PV panel**

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Average (Wh/m²) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **30°** | 2997 | 3448 | 4951 | 5237 | 6018 | 6173 | 6386 | 5996 | 5723 | 4837 | 3404 | 2742 | **4826** |

The peak sun hours for Niğde are 10.56 hours that were calculated by dividing average irradiation rates on 30° tilt angle to the peak sun which is 457 W/m² for Central Anatolia region and used in the determination of annual energy production.

The annual energy production of Niğde site and the required number of panels to match systems energy production capacity is represented in Table 6.24.

**Table 6.24: Annual energy production and number of panels for Niğde city**

| Average Solar Hours | Annual Energy Production (kWh/year) | Number of Panels |
|---|---|---|
| 7.99 | 38,548,000 | 73,416 |

Table 6.25 and 6.26 indicates total cost of Niğde project and costs after incentive rates.

**Table 6.25: TLCC for Niğde project**

| | $ Unit Price | $ Cost | PV( Poly) | PV(Thin) |
|---|---|---|---|---|
| **PV Modules(Mono)** | 1.95 | 35,790,481 | 50,657,296 | 30,651,335 |
| **PV Modules(Poly)** | 2.76 | - | | |
| **PV modules(Thin)** | 1.67 | - | | |
| **Inverter** | 0.95 | 9,500,000 | 9,500,000 | 9,500,000 |
| **Monitoring** | 0.50 | 5,000,000 | 5,000,000 | 5,000,000 |
| **Design&Installation** | 0.45 | 4,500,000 | 4,500,000 | 4,500,000 |
| **Land Acquisition + Interest Rate** | 0.5 | 10,000 + 10,575 | 20,575 | 20,575 |
| **Energy Lines** | 0.0056 | 56,200 | 56,200 | 56,200 |
| **High Voltage Cables** | 0.56 | 13,440 | 13,440 | 13,440 |
| **Contingency** | 0.70 | 7,000,000 | 7,000,000 | 7,000,000 |
| **O&M costs (for one year)** | 0.015 | 150,000 | 150,000 | 150,000 |
| **TOTAL** | 5,63 | 62,030,696 | 76,897,511 | 56,891,550 |
| **Ideal Incentives ($ 0.133 for 1 kWh)** | -5126930 | -5126930 | -5126930 | -5126930 |

| | | | | |
|---|---|---|---|---|
| **Total after ideal incentives** | - | 56,903.766 | 71,770.581 | 51,764.620 |
| **Estimated Incentives ($ 0.1 for 1 kWh)** | -3854835 | -3854835 | -3854835 | -3854835 |
| **Total after estimated incentives** | - | 58,175,861 | 73,042,677 | 53,036,715 |

**Table 6.26: Total life cycle costs for PV technologies for Niğde**

| **$ 0.133 INCENTIVE RATE** | | | **$ 0.1 INCENTIVE RATE** | | |
|---|---|---|---|---|---|
| **Mono Crystalline** | **Poly Crystalline** | **Thin-Film** | **Mono Crystalline** | **Poly Crystalline** | **Thin-Film** |
| $ 55,820,842 | $ 70,404,729 | $ 50,779,498 | $ 57,068,728 | $ 71,652,616 | $ 52,027,384 |

It was assumed that the return on investments for mono-crystalline technology will be 17 percent, for poly-crystalline 15 percent and for thin-film technology 13 percent in Niğde. The same calculation method was used as shown in Karaman project. The estimated payback periods based on total life cycle costs of the project that were calculated with $ 0.133 incentive rate are given in Table 6.27.

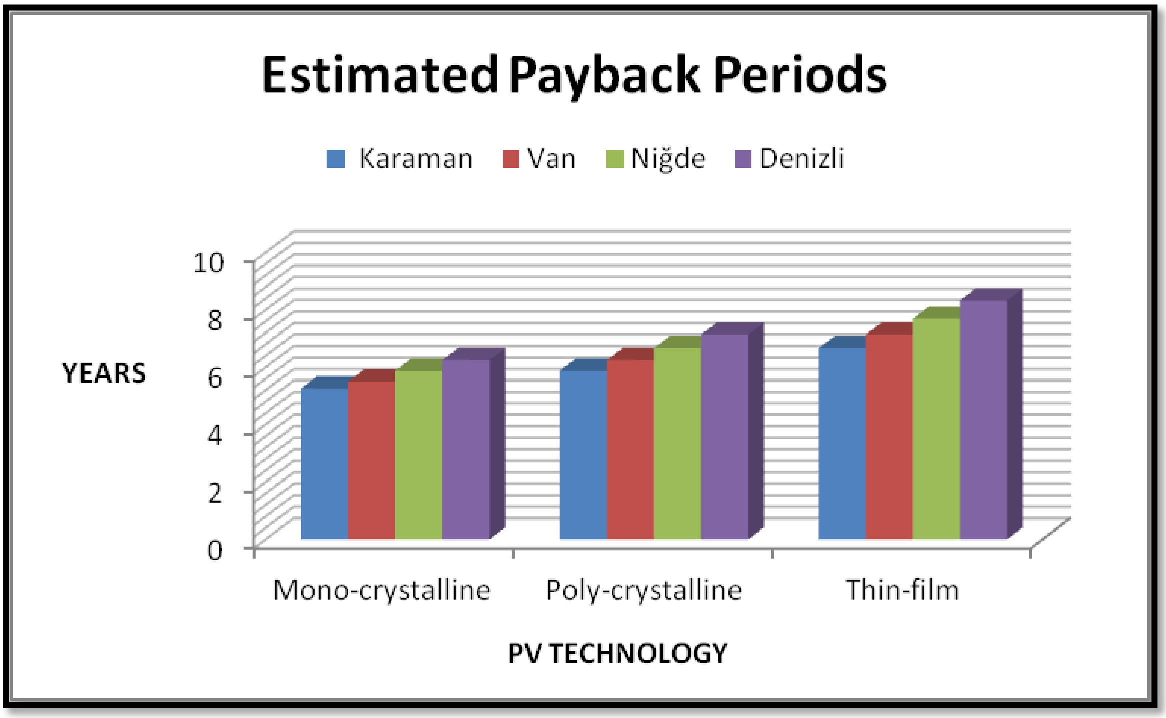
**Table 6.27: Estimated payback periods for Niğde project**

| | **Mono-crystalline** | **Poly-crystalline** | **Thin-Film** |
|---|---|---|---|
| **Total Life Cycle Cost** | $ 55,820,842 | $ 70,404,729 | $ 50,779,498 |
| **Payback Period** | **5.88 years** | 6.67 years | 7.69 years |

Results show that mono-crystalline silicon is the best option with approximately 6 years payback period time for Niğde.

When four different investment projects were compared, the results indicates that Karaman project with mono-crystalline technology utilization is the best alternative to be considered with approximately 5 years payback period in ideal conditions. If a photovoltaic project is built to Karaman, it can be a profitable investment. The overall estimated payback periods of each selected area are given in Figure 6.5.

**Figure 6.5: Estimated Payback Periods of Selected Cities**



# 7. CONCLUDING DISCUSSION

The energy consumption increases rapidly due to the growth on population, economical advancement concerns of countries and technological improvements. The inadequate reserves of conventional energy types and harmful effects to the environment had led countries to search for alternative energy systems to meet the world’s demand. In this respect, the photovoltaic energy is a sufficient option for growing energy needs.

The investments on solar energy systems were advanced after the benefits of these technologies were realized. In spite of the advantages of these systems, the energy investments require large amount of capital and the investors wish to get their investment paybacks as soon as possible. Therefore, accurate steps should be taken during the investment, management and operation period to obtain satisfactory results.

The economies are performed with regard to particular rules and the returns on investments of the projects are interconnected with the status of the economy. The world average for the return on investment of solar energy projects is approximately nine years. However, the payback periods can be minimized if the required conditions for solar energy applications are provided.

The return on investment period of a photovoltaic energy system is affected by various parameters which are productivity, technological developments, operations ability, incentive mechanism of the countries and feed-in tariffs. A solar energy power plant should be established by considering irradiation rates, annual average insolation hours, the incidence angle of the sun, optimum productivity temperature and weather conditions of a region. The productivity can be enhanced through the preference of an abundant region. It is also essential to decide the technology that will constitute the main components of the entire system. The efficiencies of the considered photovoltaic systems should be investigated and the most suitable technology that is convenient for the region should be preferred. The role of executives on the solar energy investments is important as well. If the management consists of qualified and informed members on the subject of photovoltaic energy, the system would be performed better.

When considering the substantial studies on the subject of photovoltaic energy systems which were expressed in depth previously, the most common drawback of the system is high initial costs. Even though, the price reduction of PV components stimulates countries to consider solar energy, the tendency towards solar power is not at desired extent. Therefore, the policies on solar energy, incentives and feed-in tariffs are required to be encouraged by governments to support photovoltaic energy implementations.

In conclusion, it would be clearly stated that the solar investments are heavily depended on geographical conditions, weather conditions, the PV technology used, DC/AC inverter quality, cabling quality, power transmission capacity as well as the distance to nearest power regulator centre, tracking ability, minimizing the causes of losses, governmental incentives, the last but not the least is operational capability and ability. The right combination of all the affecting factors in solar power generation and transmission would considerably affect the payback period length and in this study it is presented that how different the solar investments and the payback periods could be with four different geographical places with different PV technologies.

# 8. CONCLUSION

The importance of photovoltaic energy systems was started to be comprehended owing to harmful effects of fossil fuels to the environment and also price reduction of PV technologies. Turkey has a great potential for PV applications. An analysis of solar radiation concept and financial investment techniques was made to evaluate feasibility of photovoltaic energy systems in four different regions in Turkey. It was aimed to generate a guideline to calculate the true level of irradiation as well as investment analysis for solar energy systems.

The comparison between Van, Niğde, Karaman and Denizli cities of Turkey shows that 30 degrees of fixed array tilt is optimum for each area. The very same result is derived from similar global irradiation rates of the sites. However, in case of array adjustment for every month of a year based on obtained monthly optimum angles, the best average irradiation on an inclined surface is in Van city.

In the financial analysis side of the project, total cost of implementing a photovoltaic power plant was determined and payback periods of the projects were estimated based on applied systems in the literature. According to results, the most suitable area between four cities to establish a photovoltaic energy power plant is Karaman with a total cost of $ 54,984,071, for a 10 MW system with annual energy production of 38,908 MWh and with approximately 5 years of payback period. This result generates from the areas' average solar hour's value and yearly irradiation rates on optimum inclination angle. Various factors such as government incentives were also considered to attain these results that were discussed in detailed previously. Furthermore, mono-crystalline technology is the best alternative for all the sites. The productivity of mono-crystalline technology and payback periods are cited in the literature, so that, the results are convenient with surveyed studies.

In order to acquire better results corresponding with solar energy investments, the methods to shorten the return on investment period should be considered. The quality of the sun, the characteristics of the PV technology based on efficiency rates and compatibility to the system, proficiency of the management and personnel and support policies of the government are recommended to be taken into account by the investors before investing the PV systems. It can also be suggested that the innovative technologies can be used for taking advantage of undesirable conditions. The solar energy technologies are quite progressed and there exist high capacity batteries and PV modules on the market. When the energy demand is high and the production capability is low which occurs during the winter due to low irradiation rates and solar hours, the batteries that have high storage capacities can be utilized to meet the energy demand by storing the solar power in advance. Thus, the productivity can be augmented. Furthermore, the solar trackers that follow the sun's movements and change the angle of the PV panels through the incoming sunlight each day in a year can be used on the PV systems. When adjusting PV panels with respect to the yearly optimum inclination angle, it was seen that the energy output was increased. If the tracking mechanism is operated, a better result will be attained in proportion to annual optimum inclination angle because the array tilt will be set depending on optimum angles of every day of a year in this case. It can be useful to see the calculated values of maximum irradiation on monthly optimum angles to be able to comprehend the increment on the productivity.

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# APPENDICES

## APPENDIX 1: Irradiation on Different Inclination Angles for Van City

| Inclination Angle | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Average Year (Wh/m²) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0° | 1950 | 2900 | 4160 | 5250 | 6630 | **6990** | **7300** | 6080 | 5310 | 3700 | 2350 | 1780 | 4533 |
| 10° | 2306 | 3808 | 4509 | 5312 | **6638** | 6892 | 7240 | **6193** | 5684 | 4176 | 2770 | 2140 | 4806 |
| 20° | 2628 | 4302 | 4760 | **5365** | 6520 | 6676 | 7048 | 6180 | 5928 | 4558 | 3129 | 2467 | 4964 |
| **30°** | 2906 | 4711 | 4900 | 5308 | 6276 | 6341 | 6723 | 6040 | **6032** | 4833 | 3416 | 2752 | **5020** |
| 40° | 3131 | 5023 | **4939** | 5138 | 5896 | 5894 | 6271 | 5769 | 5999 | 4994 | 3623 | 2987 | 4972 |
| 50° | 3297 | 5229 | 4861 | 4869 | 5436 | 5347 | 5705 | 5396 | 5813 | **5035** | 3743 | 3163 | 4825 |
| 60° | 3399 | **5322** | 4675 | 4502 | 4866 | 4720 | 5045 | 4912 | 5515 | 4956 | **3773** | 3275 | 4580 |
| 70° | **3432** | 5300 | 4384 | 4049 | 4222 | 4034 | 4314 | 4339 | 5081 | 4758 | 3711 | **3321** | 4246 |
| 80° | 3398 | 5163 | 3999 | 3528 | 3527 | 3321 | 3543 | 3699 | 4535 | 4448 | 3560 | 3298 | 3835 |
| 90° | 3295 | 4916 | 3531 | 2954 | 2816 | 2620 | 2773 | 3016 | 3894 | 4035 | 3324 | 3208 | 3365 |

# APPENDIX 2: Irradiation on Different Inclination Angles for Niğde City

| Inclination Angle | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Average Year (Wh/m$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0° | 2010 | 2620 | 4210 | 5100 | 6370 | **6810** | **6940** | 6050 | 5090 | 3720 | 2360 | 1790 | 4422 |
| 10° | 2378 | 2939 | 4560 | 5253 | **6372** | 6713 | 6878 | **6157** | 5425 | 4191 | 2772 | 2142 | 4648 |
| 20° | 2710 | 3218 | 4812 | **5299** | 6255 | 6501 | 6694 | 6140 | 5639 | 4567 | 3123 | 2463 | 4785 |
| **30°** | 2997 | 3448 | 4951 | 5237 | 6018 | 6173 | 6386 | 5996 | **5723** | 4837 | 3404 | 2742 | **4826** |
| 40° | 3229 | 3620 | **4987** | 5062 | 5728 | 5739 | 5961 | 5719 | 5679 | 4993 | 3604 | 2970 | 4774 |
| 50° | 3399 | 3731 | 4906 | 4794 | 5216 | 5209 | 5430 | 5350 | 5493 | **5029** | 3718 | 3141 | 4618 |
| 60° | 3503 | **3776** | 4714 | 4428 | 4673 | 4576 | 4812 | 4866 | 5205 | 4946 | **3743** | 3250 | 4374 |
| 70° | **3537** | 3755 | 4418 | 3978 | 4061 | 3938 | 4128 | 4296 | 4790 | 4744 | 3678 | **3293** | 4051 |
| 80° | 3500 | 3668 | 4026 | 3463 | 3402 | 3248 | 3407 | 3659 | 4274 | 4430 | 3525 | 3268 | 3656 |
| 90° | 3393 | 3517 | 3551 | 2898 | 2729 | 2573 | 2689 | 2981 | 3671 | 4015 | 3288 | 3177 | 3207 |

## APPENDIX 3: Irradiation on Different Inclination Angles for Denizli City

| **Inclination Angle** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **June** | **July** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** | **Average Year (Wh/m²)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0° | 1950 | 2340 | 4040 | 5190 | **6110** | **6650** | **6500** | 5950 | 4920 | 3720 | 2350 | 1780 | 4291 |
| 10° | 2291 | 2592 | 4359 | 5347 | 6109 | 6555 | 6443 | **6051** | 5221 | 4186 | 2753 | 2123 | 4502 |
| 20° | 2599 | 2810 | 4584 | **5395** | 5995 | 6348 | 6273 | 6031 | 5423 | 4558 | 3096 | 2436 | 4629 |
| **30°** | 2864 | 2987 | 4709 | 5331 | 5769 | 6029 | 5989 | 5887 | **5518** | 4823 | 3369 | 2706 | **4665** |
| 40° | 3077 | 3119 | **4729** | 5152 | 5435 | 5608 | 5597 | 5611 | 5444 | 4975 | 3563 | 2928 | 4603 |
| 50° | 3234 | 3201 | 4644 | 4878 | 5005 | 5093 | 5110 | 5250 | 5260 | **5009** | 3672 | 3094 | 4454 |
| 60° | 3328 | **3230** | 4457 | 4503 | 4490 | 4504 | 4543 | 4776 | 4980 | 4923 | **3694** | 3198 | 4219 |
| 70° | **3357** | 3207 | 4173 | 4044 | 3973 | 3861 | 3916 | 4217 | 4591 | 4720 | 3627 | **3238** | 3910 |
| 80° | 3319 | 3130 | 3801 | 3515 | 3288 | 3192 | 3255 | 3594 | 4088 | 4405 | 3473 | 3213 | 3523 |
| 90° | 3217 | 3004 | 3352 | 2936 | 2651 | 2538 | 2597 | 2932 | 3513 | 3990 | 3238 | 3123 | 3091 |