# ANALYSIS OF PHOTOVOLTAIC SOLAR PANELS WITH TRACKING SYSTEM

by
Muaaz Jnani

Submitted to the Institute of Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science
in
Electrical and Electronics Engineering

**Istanbul Bilgi University**
**2020**

**ANALYSIS OF PHOTOVOLTAIC SOLAR PANELS WITH TRACKING SYSTEM**

**TAKİP SİSTEMLİ FOTOVOLTAİK GÜNEŞ PANELLERİNİN ANALİZİ**

Muaaz Jnanı

117815001

**Tez Danışmanı :** Doç. Dr. Mehmet Erdem Günay (İmza) ..............................

İstanbul Bilgi................................................ Üniversitesi

**Jüri Üyeleri** Prof. Dr. Kerim Mehmet Murat Tunç (İmza) ..............................

İstanbul Bilgi................................................ Üniversitesi

**Juri Üyesi:** Prof. Dr. İsmail Cem Parmaksızoğlu

İstanbul Gedik................................................ Üniversitesi (İmza) ..............................

Tezin Onaylandığı Tarih : ....16/01/2020..........

Toplam Sayfa Sayısı: 93..........................

Anahtar Kelimeler (Türkçe)

1) Güneş Paneli
2) Yenilenebilir Enerji
3) Takip Sistemi
4) Güneş Enerjisinin Hesaplanması
5) Işınım ve Işıma

Anahtar Kelimeler (İngilizce)

1) Solar Panel
2) Renewable Energy
3) Tracking System
4) Calculating Solar Energy
5) Irradiance and Irradiation

# ACKNOWLEDGEMENTS


To the most precious thing in existence to the light of the eyes and the care of the hearts
To the light that lit up my future and charted my way of success
My dear father
To the rose that adorns every place where it is
To that who spreads fragrant aroma, warmth and tenderness
To who I kiss her hands every morning and evening
Moreover, ask God Almighty to extend in her lifetime
My dear mother

To those shining suns and illuminated candlesticks
To those who share my joy, my sadness, my love and my happiness
To those who grew up with them in the confines of my parents and ask God Almighty not to differentiate us after we gathered and ask Almighty to achieve each of their goals and aspirations.
My brothers and sisters

To whom I found by my side of the classroom.
To those who were my brothers.
My colleagues
To whom I spent and lived with them memorable days in memory.
My friends
I extend my sincere thanks and appreciation to the person who has made an unforgettable effort with me.
Prof. **Dr. Mehmet Erdem Günay** For the constant assistance and guidance that he provided to me

Big thanks to assistant prof. **Zafer Yavuz Aksoz** who helped me very well in order to make this thesis better.

And all those who helped me in this modest study
Finally, I extend my sincere thanks and respect to all our distinguished professors.

# ABSTRACT


## ANALYSIS OF PHOTOVOLTAIC SOLAR PANELS WITH TRACKING SYSTEM

Year by year our demands for energy have been increasing and one day we may not have a good source for energy so we would need to concern some solutions for that. Actually, in my humble thesis, I am going to show the population and energy demands, the interesting in the manufacture and development of solar panels with the cost of PV modules, absorption of solar radiation, the benefits of the solar panels with the tracking solar system and how much this technology effect to our performance. Considering the primary source of energy is solar energy, which is sustainable, free and reachable from anywhere. Today, the usage of photovoltaic technology has increased. Because photovoltaic could be settled in any place to take to solar radiation, it is clean energy that means environmentally friendly, maintenance easy and installation of panels cheaper rather than all the other kind of energy. In this thesis, the types of solar panels and differences between them are analyzed, and the effects of orbit and the rotation of the earth to the efficiency of the panels were studied. Then, for a case power plant, a detailed feasibility analysis was made by observing the solar irradiation and sunshine duration data for a variety of regions. After finding the optimum location, the performances of different solar panels were compared and the maximum power output with the minimum cost was estimated. It is my greatest hope that the readers of this thesis will devote themselves to building a world in which kids and grandkids could be been with both pure water and air could be breathed, in which individuals and the remainder of nature will nurture themselves.

# ÖZET


## TAKİP SİSTEMLİ FOTOVOLTAİK GÜNEŞ PANELLERİNİN ANALİZİ

Yıllar geçtikçe enerji talebi hızla artmakta olmasıyla beraber gelecekte bir gün bu talebi karşılayacak yeterli kaynaklar bulamayabiliriz. Bundan dolayı bu talebi karşılayabilecek alternatif çözümler bulmalıyız. Bu tezde nüfus ile beraber enerji talebinin nasıl arttığını, fotovoltaik güneş panellerine karşı ilginin ve bu panellerin üretiminin nasıl geliştiğini, takip sistemli güneş panellerinin kullanımımın avantajlarını ve bu teknolojinin performansı nasıl etkilediğini göstereceğim. Temel bir kaynak olan güneş enerjisi sürdürülebilir olmakla beraber, herkesin kullanımına açık durumdadır. Günümüzde fotovoltaik güneş teknolojisi hızla gelişmektedir. Fotovoltaik sistemler herhangi bir bölgeye kurulabilir, temiz bir enerji üretim şeklidir, çevre dostudur, bakımı kolaydır, panellerin kurulumu ucuzdur. Bu tezde değişik güneş panelleri ve bunlar arasındaki farklar ile beraber dünyanın dönme eksenin bu panellerin performansına etkisi analiz edilmiştir. Ardından, olası bir güç santrali için çeşitli bölgelerde güneşlenme süresi ve güneş radyasyonu verilerini incelenmiş ve detaylı bir fizibilite analizi yapılmıştır. Optimum bölge bulunduktan sonra farklı güneş panellerinin performansları kıyaslanmış ve minimum masraf olacak şekilde maksimum güç için tahmin yapılmıştır. Ümit ediyorum ki bu tezi okuyan okuyucular kendilerini, çocuklarımızın ve torunlarımızın dilediğince nefes alabileceği temiz bir atmosfer ve dilediğince içebileceği temiz suları bulabileceği, insanların ve doğanın birbiriyle büyük bir uyum içinde yaşayabileceği bir dünya yaratmaya adayacaktır.

# TABLE OF CONTENTS

# LIST OF FIGURES

## LIST OF TABLES

## LIST OF SYMPOLS

(EHP): Electron-Hole Plasma

(AU): astronomical unit

(ISC): short circuit current

(VOC): open circuit voltage

(IMPP): the maximum power point current

(VMPP): the maximum power point voltage

($PSH_s$): peak sun hours

(AM): air mass

P.power: Power of the solar panel (Wp).

(BTU): British thermal unit

(MSRI): Million Solar Roofs Initiative

(PV): photovoltaic

(VR): voltage regulation

(RPSs): renewable portfolio standards

(CNN): Cable Network News

(GDP): gross domestic product

$E_{ph}$: energy of a photon

$E_G$: threshold energy

(L1): one longitude

($\alpha$): The solar altitude

($\psi$): azimuth angle

(DH): number of hours of daylight

($\omega_s$): sunrise angle

($\omega$): hour angle

(TMY): Typical Meteorological Year

($\theta_Z$): position of the Sun at solar noon

(ETA): extremely thin absorber

(EVA): ethylene vinyl acetate

(CIGS): Copper indium gallium selenide

(a-Si): Amorphous silicon

(CdTe): Cadmium telluride

(CIGS): Copper indium gallium selenide

(TFSC): Thin-Film Solar Cells

($V_{OC}$): Open Circuit Voltage

($I_{SC}$): Short Circuit Current

($P_{MPP}$): Maximum power output

(FF): Fill factor

(η or PCE): Power conversion efficiency

(FF): fill factor

(AST): active solar tracking system

(PCM): Phase Change Material

(NREL): National Renewable Energy Laboratory

(MPPT): Maximum Power Point Tracker

(PSCs): Perovskite Solar Cells

(ETLs): Electron Transporting Layer

# 1. INTRODUCTION

## 1.1. RENEWABLE ENERGY

Energy is undoubtedly a resource that has made humanity dependent on it. Our society will not function without energy. Without energy, we cannot find or administer disease cure medicines, prepare food, purify water, operate computers, etc. Current energy needs are approximately 15 TW ($15 \cdot 10^{12}$ W) and are projected to increase further in the future. Fossil fuels (coal, petroleum, and natural gas) have enabled our energy consumption for the last century and continue to dominate our energy production. Today, approximately 81 percent of our energy comes from fossil fuels, 2.7 percent from nuclear energy, and only the remaining part from renewable sources (biomass is considered the largest source of energy at around 12 percent). The total energy consumption is given in Figure 1.1 [1, 2].

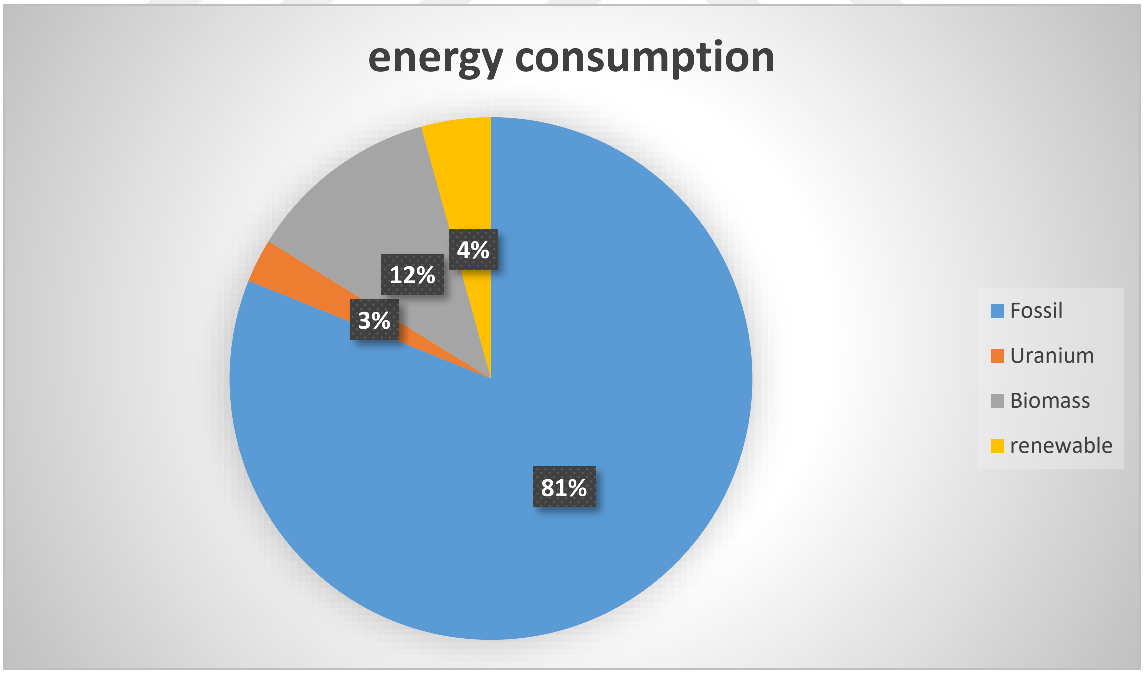


**Figure 1.1** Current energy mix. The total energy consumption is almost 15 TW.

Through natural processes such as anaerobic decomposition of buried dead organisms fueled by photosynthesis, fossil fuels are constantly produced. These are non-renewable resources, because they require millions of years to develop, and existing applicable reserves are being depleted faster than new reserves. Even if fossil fuels can be used for many years to come, there are many other reasons to look for alternatives [1, 3].

The $CO_2$ emission is possibly the strongest excuse against fossil fuels, but the burning of fossil fuels also creates other air pollutants, such as nitrogen oxides, sulfur dioxide, flown organic components and heavy metals. Moreover, harvesting, processing, and distributing fossil fuels create their own environmental concerns. Moreover, fossil fuels have harmful effects on people's health, especially in rural areas, which leads to the deaths of more than 7,500 women and children each year due to dirtiness in indoor air [1-4].

While searching for newly available energy sources that can replace fossil fuels, it is useful to consider how much energy each process can deliver. Estimated available power for each energy process is given below:

- Tide: 0.3 TW
- Earth heat: 2 TW
- Hydropower: 4 TW
- Wind: 75 TW
- Biomass: 6 TW
- Direct radiation: 26,000 TW
- Coal: 900 TWy
- Petroleum: 240 TWy
- Natural gas: 215 TWy
- Uranium: 300 TWy

It should be noted that the numbers for fossil fuel and uranium are based on total energy while the remaining numbers are given as resources available per year. Although the specific numbers may vary from source to source, the magnitude of the numbers is reasonably accurate [1, 5].

Renewable energy is an expression that refers to types of energy, which are derived from natural sources that can be naturalistically regenerated forever; these involve solar, wind, geothermal, hydroelectric and biomass. The concept of renewable energy must not be discomfited with alternative energy, which defines energy sources outside of conventional forms such as petrol, considered more environmentally friendly or less hurtful [6].

The benefits of using renewable sources of energy are lower repair costs as most sources involve few or no moving parts and therefore less mechanical harm. They are economical and can reduce the costs paid to coal. They deploy little or no loss into the environment; for example, Photovoltaic (PV) power generation on a small scale can save 335,9 kg per MWh of $CO_2$ [3]. There is no depletion of renewable energy sources; therefore, they have a better future prospect [4, 6].

The tiny pieces called photons; the Photons hit atoms and generate energy. Therefore, when we stand under sunlight, our skin feels warm. Because they produce electricity from light, photovoltaic cells are also called solar cells ("photo" is Greek for light and "volt" is an electricity unit) [5, 7, 8].

A photovoltaic cell uses special metals called semiconductors to capture a photon from the sun. When photons strike semiconductors, instead of heat, they may generate electricity. Electricity can be produced from sunlight; the popular semiconductor that is used for building solar cells is silicon. Electron is sometimes released when a photon hits silicon. The solar cell catches and moves all the electrons emitted by the silicon in one direction and generates an electrical current [7, 9].

Solar cells are also used in spacecraft such as the International Space Station but are also used on Earth in places where there is plenty of sunlight during the year. The more sunlight is obtained, the more electricity is generated so that regions with little sunlight are not good places to use solar cells [7, 9].

## 1.2. THE SUN

The Sun supplies the necessary energy from our solar system to sustain life. The Earth receives ample energy from the Sun in just one hour to fulfill its energy requirements for nearly a year. In other words, this is about 7,500 times the assistance of all other sources to the Earth's energy budget [10].

The Sun is made up of a mixture of hydrogen-dominated gases. Accordingly, the Sun transforms hydrogen into helium in a major thermonuclear fusion reaction, mass is converted to energy by the famous theorem of Einstein, $E = mc^2$. The Sun's surface is held at a temperature of around 5800 K as a result of this reaction [10, 11]. When sunlight enters the atmosphere of the Earth, some are absorbed, some are dispersed, And some pass through atmospheric molecules without effected and are either absorbed or reflected by ground-level objects [10, 12].

One more evident observation is that rainy areas get less sunshine than sunny regions. It might be less obvious, though, that the hours of the sunshine during the year are the same for every point, given only hours are counted between sunrise and sunset, irrespective of the cloud lid. Some parts of the planet closest to the poles, which have long hours of winter, also have long days of summer. Nevertheless, since the Sun is, on average, lower in the polar regions than in the tropics, so in the polar regions, sunlight should across more air mass than in the orbit places [10].

## 1.3. SOLAR ENERGY

Solar energy is sunlight and thermal that is employed using a collection of including applied science such as photovoltaics [13]. Technology has offered several ways of using this plenty of resources. It can be called as Green technology because it does not diffuse greenhouse gases. Solar energy is plentiful and used both as an energy source and as a heat source [6, 14].

The technology of solar can be commonly categorized as active solar and passive solar technology. The use of photovoltaic devices is a successful solar application; solar power and solar water heating are optimized to harvest energy. In operations like air heating and drying clothes, active solar is consumed directly [14, 15]. The passive solar mechanism includes the alignment of a building towards the Sun, the use of materials with desirable thermal mass or light-dispersing properties, and the construction of natural air circulation areas [6, 14, 15].

The conversion of solar energy by obtaining electricity from sunlight is referred to as the Photovoltaic method, which is achieved using a semiconductor material. The process requires the absorption of particles carrying energy in the rays of the Sun called photons [6, 16]. The other way to obtain solar energy is by using thermal technologies, which provide two types of energy-tapping manners. The first is the absorption of solar energy to power calorific turbines while the second manner is for cooling and heating applications used in solar air conditioning and water heating [6, 14, 15].

## 1.4. FROM A SOLAR CELL TO A PV SYSTEM

PV systems are designed around the PV cell. Since a typical PV cell produces less than 5 W at approximately 0.5 $V_{DC}$, cells must be connected in series-parallel configurations to produce enough power for high-power applications. Modules may have peak output powers ranging from a few watts, depending upon the intended application, to more than 400 W.

The typical output power of the PV arrays is in the range of 100 W-to-kW, while megawatts and gigawatts are becoming more common now [1, 10]. Because PV arrays only generate power when illuminated, PV systems use an energy storage mechanism such as batteries so the captured electrical energy can be useful later [1, 10].

Over the past two decades, the use of photovoltaics has grown rapidly due to the belief that it could make a fundamental contribution to the transition from conventional fossil fuels to renewable energy economies. Nevertheless, the long-term sustainability of photovoltaics will depend largely on the efficiency of the process that will be implemented to recycle the enormous amount of end-of-life panels expected to be generated soon [17].

## 1.5. THE PV CELLS

The PV cell is a P-N junction or Schottky partition unit that is specially designed. The well-known diode equation explains how the PV cell functions. When the cell receives light, EHPs are formed by the incident photons acting with the cell's atoms [10, 16]. The electrical field produced by the cell junction divides the photon-generated EHPs, with the electrons migrating into the cell's n-region and the holes drifting into the p-region, providing that the

EHPs are induced sufficiently close to the PN junction [10, 16]. According to the materials that are used in the manufacturing of solar cells, solar cells can be divided into 3 main groups: organic, inorganic and organic-inorganic, in Figure 1.2 [18].

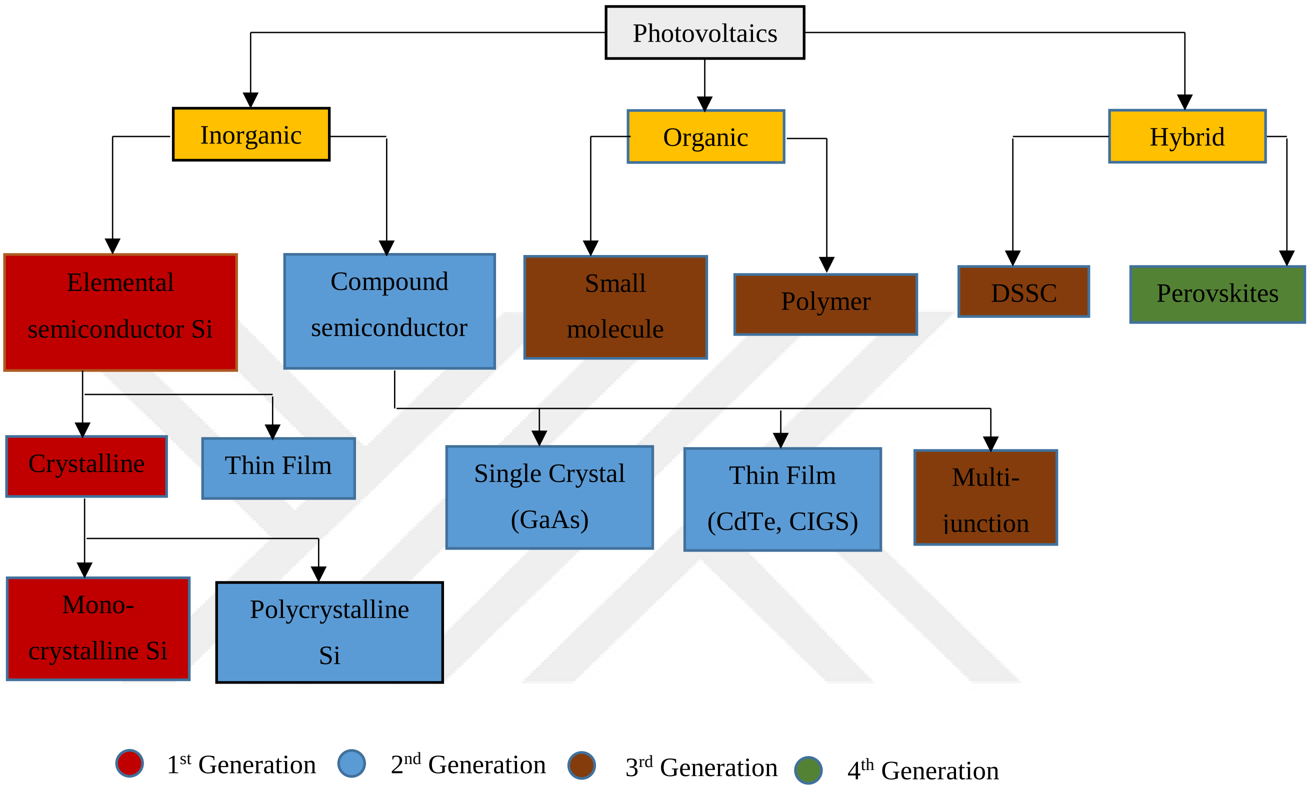


**Figure 1.2** Classification of solar cells

The goal of this thesis is to analyze the feasibility of constructing a photovoltaic solar power plant on a case location. First, the improvement of solar cells through history is reviewed in Chapters 2.1 to 2.6. Second, the theoretical background on how light energy is converted to electricity is given in Chapter 2.7. Moreover, the effect of the position of the sun and the orbit of the earth on solar power is discussed in Chapters 2.8 and 2.9. Then, the energy of the sun and the role of irradiance of sunlight were mentioned in Chapters 2.11 to 2.13. Next, the manufacturing and development of most kinds of solar panels with their efficiency and the shading effect on the solar cells are written in Chapters 2.14 to 2.16. Finally, in Chapter 3, all the results and calculations related to the case system such as the shadow effect, implementation of a solar tracking system and employment cooling systems are given.

# 2. THESIS BACKGROUND AND LITERATURE SURVEY

## 2.1. HISTORY OF SOLAR PANELS

The first milestone is 1839 Alexander Edmond Becquerel, who discovered the PV effect as a 19-year-old and thus created the first solar photovoltaic cell, he used liquid electrolyte, and for that reason, his cell was not that practical it was also not that efficient [1, 19-21]. The next one is William Grylls Adams and Richard Evans Day 1877, they did the observation of the photovoltaic effect in solidified selenium, this was the first all-solid-state photovoltaic device.

After this, just a few years later, 1884 Charles Fritz installed the first solar panel in New York [1, 19-21]. It had an efficiency of almost 1%, and this was actually a major achievement at that time, and it’s important to know the electricity was still quite new, and this meant there is a huge optimism about solar cells because it seemed we could produce the energy we would demand using this. However, after this development got really slow and within a few years, electricity became much more common, power generators sprung up everywhere, And suddenly, 1% efficiency from a solar cell was not impressive at all, it was a too expensive way to produce electricity [10, 21].

Until the 1950s, not a lot happened we got the next big development, this was the invention of the silicon solar cell this was pioneered at the laboratories by Calvin Fuller, Gerard Pierson, and Daryl-Chapin, and they created the first truly useable solar cell with great efficiency and this lead to the modern silicon solar cells of today [1, 20].

On June 26, 1997, it was proclaimed by (MSRI) “Now we will work with businesses and communities to use the sun’s energy to reduce our reliance on fossil fuels by installing solar panels on 1 million more roofs around our nation by 2010. Capturing the sun’s warmth can help us to turn down the Earth’s temperature” [10, 22]. In 1997, little concern was being expressed in the public sector about energy problems and perhaps even less discussion related to global warming, so this statement by President Clinton carries special significance from nowadays perspective [10, 21].

By the end of 2007, it was estimated that more than 600,000 solar systems had been installed around the United States. In the 12 months of 2013, over 145,000 residential PV systems were installed in the United States, in addition to over 1 GW of PV installed by U.S. utilities [10].

In 2013, China and Japan were the largest markets for PV and the United States was falling behind. In the United States, more and more states are now adopting renewable portfolio standards (RPSs), which set goals for the percentage of the electrical energy mix to be provided by renewable sources by a certain date. Implementation of these goals will require engineers who understand the how and why of PV system design [10].

### 2.1.1. Solar cells in Space

It's really a big topic because of the space race really fueled the development of modern silicon solar cells, it's really expensive to carry batteries into space and since we can generate electricity using solar cells directly in space. This becomes much more cost-efficient, even though the solar cells themselves may be quite expensive the first use of solar cells in space was the Vanguard 1 in 1958 [10, 20, 21]. So as you may know this is just the year after invent Vanguard 1, four satellites are launched, and this really lead the use of solar cells in space.

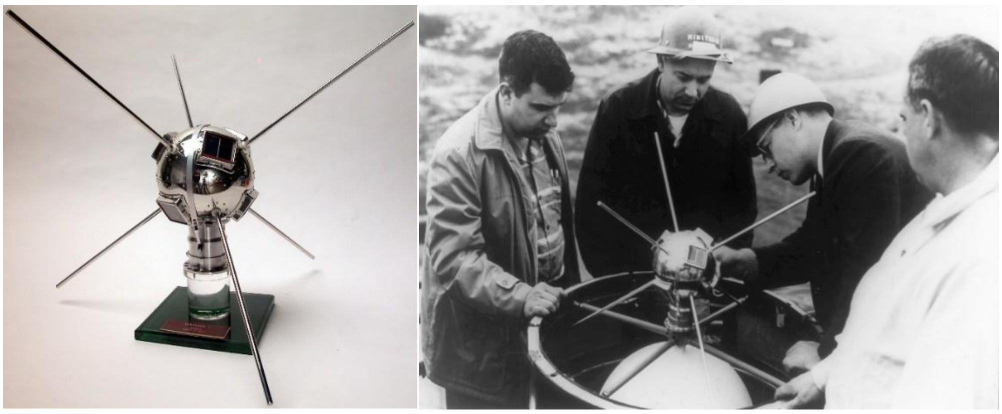

**Figure 2.1** Vanguard1 [1, 20, 21]

After Vanguard 1 there's a lot of developments. Moreover, many new satellites started using solar cells. So, for example, the Explorer One, the Telstar satellite, and of course also the space stations. So here, we can see Skylab with its solar cells. In space applications, it is important to notice that the price of the solar cell is really not that important, it is the efficiency that matters. And for this reason, we've seen a move away from silicon-based solar cells and a move towards gallium arsenide based solar cell technologies instead [1, 19].

## 2.2. POPULATION AND ENERGY DEMAND

Earth's human population has now gone over 7.3 billion, and all these people need to get the energy needed to sustain their lives. The exact amount of energy needed to meet these requirements and exactly what sources of energy will meet these demands will be issued for current and future years to address [23]. So, developing countries will, therefore, increase their per capita energy use such as China (1997) they built power stations at a level of 300 MW a week [10].

Global demand for primary energy is expected to increase from 2009 to 2035 by an average of 1.3 percent per year. 1.7% of the annual rate increase in energy density. $CO_2$ releasing from the combustion of fuel rise by 0.9% a year to attain a long-term level straightforward with an average global temperature increase of more than 3.5°C [4].

## 2.3. CURRENT WORLD ENERGY USE PATTERNS

The expiration of coal and the warming stemming from the use of these existing energy sources show the desire to rely on clean energy. Photovoltaics are now gaining more attention as renewable and clean energy, making it one of the most successful alternatives and clean energy. Since the development by Bell laboratories of modern photovoltaics in 1954, several kinds of photovoltaic panels have been produced. Solar panel techniques are generally referred to as light-absorbing contents. For this reason, tremendous efforts have been made in recent decades to develop new photovoltaic items to create high-quality solar panels with low electricity costs [18].

Figure 2.2 shows the rise in source-by-source global energy output from 1989 to 2014. In 2000, there were about 397.40 quads of primary energy consumption worldwide.

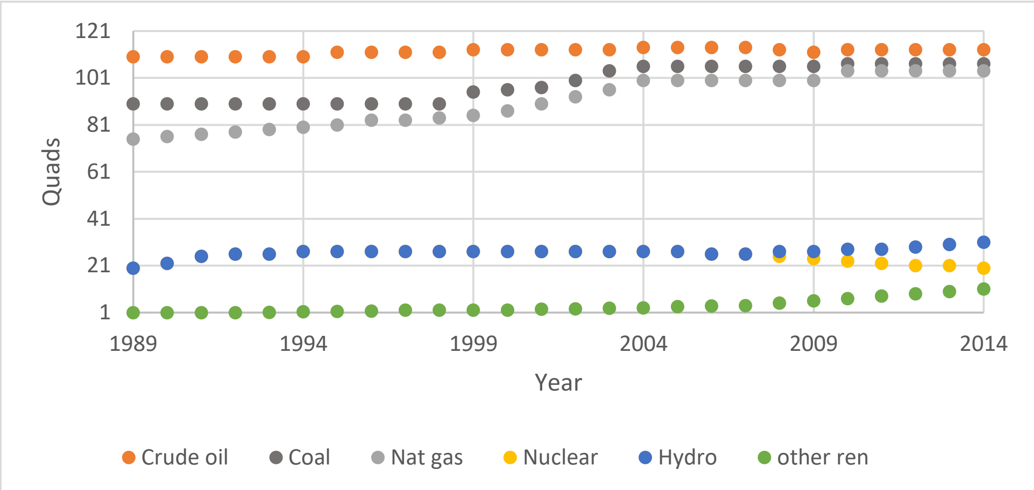


**Figure 2.2** Source-based global energy production

The world's developed countries expended about 75% of energy, whereas approximately 2 billion people stayed without energy in developing countries, mostly in the tropical regions where are very good for setting up solar panels. In 2005, primary energy use worldwide rose to 462 quads and 2 billion people were still living lacking power [10, 24]. Remember that crude oil production continued to rise after the oil crisis of 1973, followed by significant growth in crude oil prices in the 1970s and the beginning of the 1980s. Among this time, high oil prices prompted the implementation of regulations on efficiency of energy, like the National Energy Conservation and Policy Act, codes for the efficiency of energy in constructing and raised standards for vehicle fleet miles [10, 24]. Consumers have contributed by reducing power usage by reducing thermostats and installing isolation and other steps to conserve energy.

In the mid-1980s, the outcome was lower oil production, as a request was lower. In the same period, the more efficient use of electricity led to the termination of the building of nuclear power stations, turn results in a substantial reduction in the rate of growth of nuclear power. Finally, the issue about the control of oil prices and economic sanctions led to a shift from oil to coal and natural gas for carbon-fired energy production [10, 24]. Figure 2.3 illustrates the global energy mix in 2013.

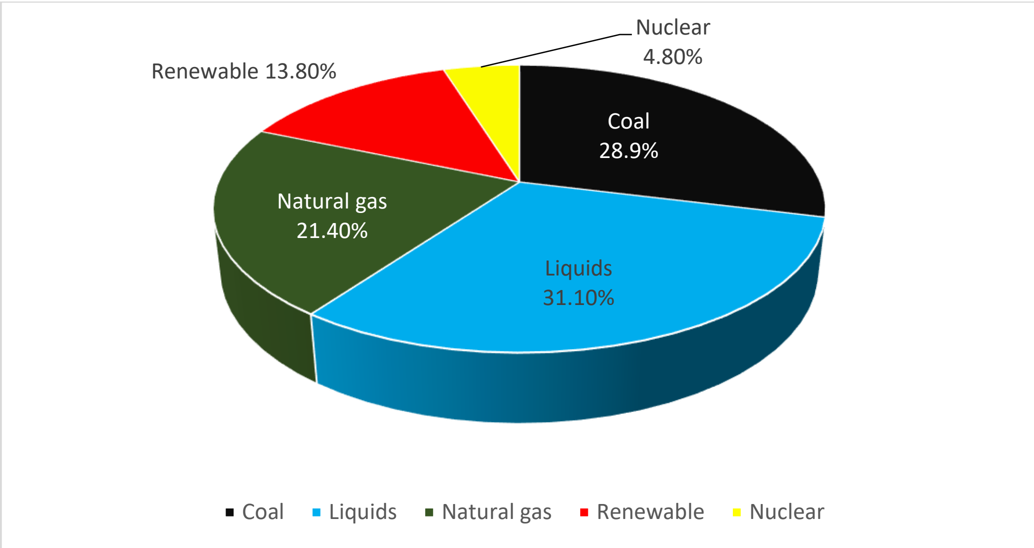


**Figure 2.3** 2013 global energy sources

Figures 2.3 and 2.4 illustrate that the world is facing a huge challenge as developing countries seek to achieve parity in energy with advanced nations. Consider that power equity is just another word for trying to achieve equivalent living standards. And although reaching a higher living standard will bring a cost with it [10, 24]. The cost includes not only financial commitments but also the opportunity for substantial deterioration of the environment if electricity equity is followed through the cheapest alternatives at first cost [10, 24].

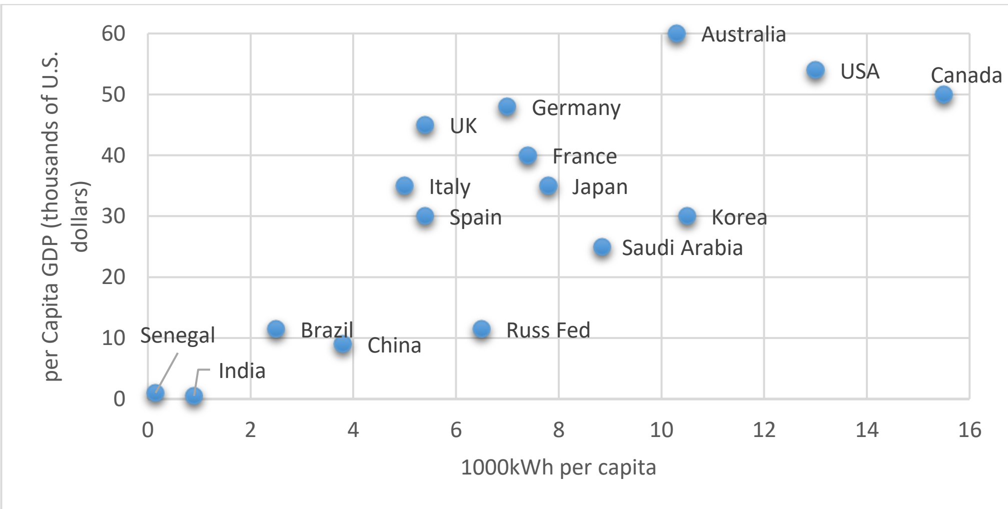


**Figure 2.4** 2013 worldwide per capita GDP versus per capita kW

Sadly, this is the most likely result, as it is already taking place in countries such as Eastern Europe and Asia. In reality, the use of low-cost energy choices may lead to similar energy consumption per capita, but at the same time can reduce living standards by generating air that is not appropriate for breathing and water that is not desirable for drinking [10, 24]. When developed nations raise their production capacity by using cheap yet polluting local power supplies, the pressure might be exerted to rest standards of pollution control in the industrialized world to retain the competitiveness with developing nations' production [10, 24].

Objection to international trade conventions was partially based on environmental issues, such as agreements prohibiting any country from placing tariffs on goods manufactured in countries with low environmental laws [10, 24]. So, advanced nations are forced to send products to advancing nations. Nonetheless, the status has changed since 2016, with both the United States and China actively supporting the November-December 2015 Paris Climate Agreement [10, 24].

Both countries, along with nearly 200 others, appear to have concluded that energy efficiency is good for business and the economy as well as for the environment. But what has this debate to do with the development of PV power? PV power sources are renewable, but existing photovoltaic installation prices have only recently become combative with the premier direct costs of coal and oil generation [10].

This means the user must be familiar with the cost of the cycle of life and the engineer should be willing to make the most price-effective PV option. It also ensures that a large amount of work and improvement must be carried out to ensure that the price of PV generation continues to fall [10]. It also implies that action must proceed to put a monetary value on the deterioration of the environment generated by sources of energy, so this cost can be taken into account in the actual cost to society of any power source [10, 24]. The fact of the matter is that there is still a considerable amount of research to be done in the field of energy research, growth and public schooling, and especially in the sector of PV. [10].

## 2.4. EXPONENTIAL GROWTH

The electrical engineer who knows the diode equation, in which (I) and (V) are the diode current and voltage, is possibly most familiar with exponential growth, respectively, $I_o$ is the reverse saturation current and KT/q is 26 mV at T = 300 K, or, specifically, $I = I_o(e^{qv/KT} - 1)$.

Exponential growth is a particular way of increasing a quantity over time. It occurs when the instantaneous rate of change (that is, the derivative) of a quantity concerning time is proportional to the quantity itself [25]. Although this formula is central to the quality of PV cells, exponential growth also describes many other natural processes. Exponential growth is generally called compounded interest. Most have heard of it, but few understand the consequences of a continuous annual growth rate in amount, whether that be money, population, or supply of energy or request. [10]. Malthus was among the first to warn about the dangers of exponential growth in 1798. He informed that growth in population will reduce the capacity to make more people be fed. The Malthusian theory is frequently the topic of growth enthusiasts' mockery [26].

The aim of this argument is not to affirm or dismiss Malthus ' predictions, but simply to highlight an important mathematical concept frequently ignored by engineers. The implementation of unsustainable growth concepts is common in society, so the theories of continuous growth must be as essential with a well-informed engineer as the second thermodynamic law. Thermodynamics is a theory that less energy comes out of each cycle than is placed into it. In other words, no free lunch is available [10, 26].

## 2.5. ECONOMICS OF BTU AND SUSTAINABILITY TEST:

The net energy correlated with a source of energy is essentially the difference between the energy needed to gain and transform the source into usable energy and the factual power from the source. For example, to be able to burn a vat of petroleum, it is important to locate the petroleum, extract the petroleum, transit the petroleum, duplicate it and build the petroleum-burning facility [10, 27]. The reduplicate petroleum should then be shipped to the burning location and, hopefully, any damage to the environment resulting from the extraction, shipment, processing, and burning should be fixed after the oil is burned. The fact of the matter is if more than one vat of petroleum is required to extract and turn the available power into an oil barrel, One should seriously ask if it makes reasonable to burn the petroleum [10, 27].

In some cases, expending the energy to obtain the source of energy may make sense. Suppose, for example, that an else use for petroleum has been found, such as the supply of an important chemical for cancer cure. Then that will make reasonable to use energy from sources other than petroleum, even if the power surpassed the oil's energy worth, to make the petroleum accessible for greater use.

Another case is to use the shape of the energy of lower performance to make a higher quality form of energy. Such activity may make energy sense. For example, burning coal for production electricity requires about three coal units to generate one unit of electrical power. Before television sets running directly from coal are invented, this inefficient method of turning the energy of coal into electrical, given the established environmental issues with coal, will probably continue. In 1976, Odum and Odum published the net energy concept [10].

They integrated the concept of net energy into a new economic standard that they did make more reasonable than the gold standard. It was called the BTU standard. The BTU standard simply describes that everything has a content of power. The concept of BTU has been widely written by Henderson (BTU) British Thermal Unit is the volume of heat required to raise the temperature of 1 pound of fluid water by 1 degree Fahrenheit at the temperature at which water has the highest density (about 39 degrees Fahrenheit). Technical information: 3413 BTU = 1 kWh. Burning a wooden matchstick makes one BTU available [10, 28, 29].

Having analyzed the effect of total energy production on economic expansion, we are now disaggregating overall energy generating into renewable and non-renewable generation and analyzing its effects on growth. Global renewable electricity generation has been on the rise over the past three decades, especially in developed economies, but non-renewable electricity retains the primary source of electricity for most nations. This would be interesting to study if the positive effect of energy production is guided by development in non-renewable energy, renewable energy or both since the results could have major political consequences [30].

Nevertheless, if energy is allowed to be transferred by the source from a very large reservoir, the source becomes almost limitless [10]. For example, if a photovoltaic cell can produce more electric power over its working life than was spent on manufacturing and operation and eventually on disposal, including the cost of environmental power, then the cell would be labeled net positive energy.

## 2.6. THE DIRECT TRANSFORMATION OF ELECTRICITY FROM THE SUNLIGHT

The sunlight could be converted directly into electricity is discovered by Becquerel in 1839, when he observed the photo galvanic effect. Adams and Day discovered in 1876 the selenium had PV functions. As Planck observed the quantity existence of light in 1900, other scientists were opened the door to expand on this concept [10, 16, 19]. Wilson presented the quantity theory of solids in 1930, establishing a theoretical connection between the photon and the behaviors of solids. Ten years later, Mott and Schottky introduced the solid-state diode theory, and Bardeen, Brattain, and Shockley fabricated the bipolar transistor in 1949 [10, 16, 19, 20].

Naturally, this development rampaged the solid-state devices world. It had a 6 percent efficiency. The first solar cells on the Vanguard 1 were used 4 years later. One might wonder why designing the PV cell took so long [10, 16, 19, 20]. The answer lies in the challenge of manufacturing materials that are clear enough to achieve a decent level of cell efficiency. There was little impetus for the preparation of strongly clear semiconductor materials before the invention of the beginning of the space program and bipolar transistor. [10, 31].

Coal and oil served the globe's energy requirements, and transistors met the electronics industry's needs. However, as transistors and traditional power sources were not practical for use in space, solid-state took hold. PV cells are made of elements with semiconductors and assembled into 36 or more cells. Traditional homogeneous semiconductor PV cells or photoelectric inverters (PCs) consisting of one p-n junction produce voltages whose qualities are decided by the height of the possible junction barrier [10, 16, 32].

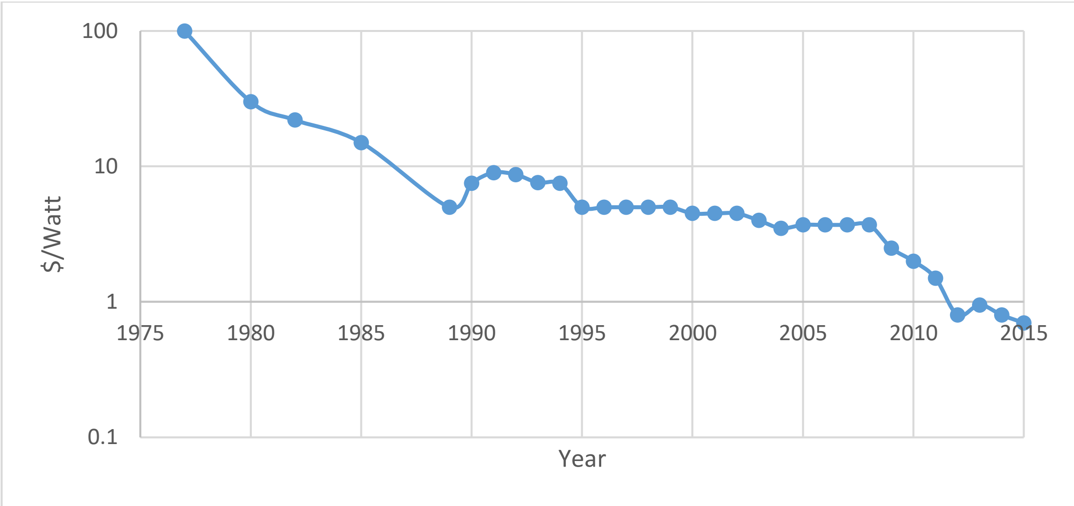


**Figure 2.5** Decline in cost per watt for PV modules

This understanding is considerable because this means that the same industry that has developed from the growth of the bipolar transistor to computer chips involving millions of transistors over the past 60 years is also included in the production of PV cells. Figure 2.5 illustrates the decrease since 1977 in the price of PV systems [10, 20].

Most of the actual cost decrease was due to improved processes in cell processing. The critical factor at this level is the energy cost of the cells. For a few years following 2005, refined silicon prices increased significantly due to a worldwide shortage, but then fell again in 2008 as supply caught up with demand [10, 20]. Therefore, the task for the future will decrease the density of energy in the cell development processes while preserving or increasing cell size, quality, and accuracy. Figure 2.6 illustrates worldwide PV exports from 1975 to 2014 [10, 20].

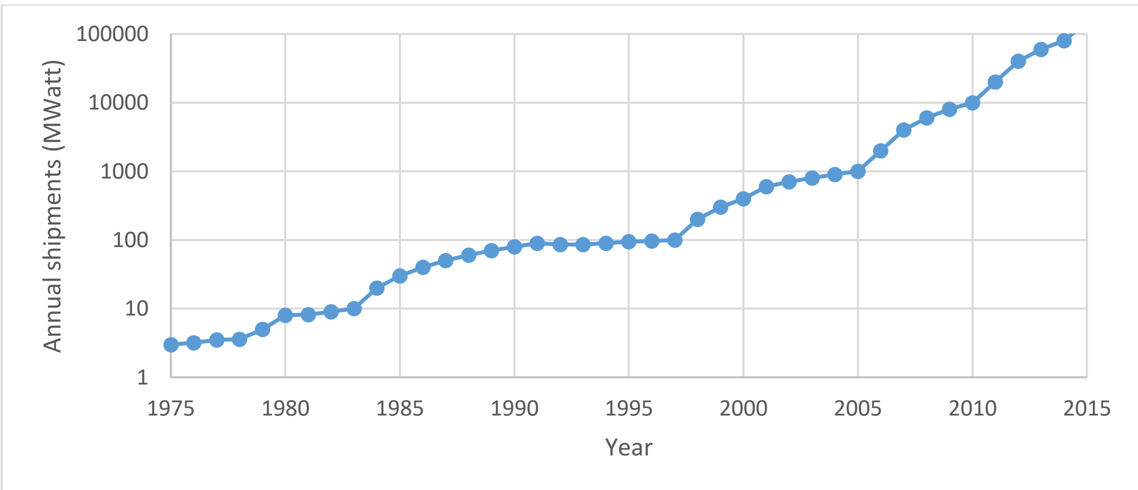


**Figure 2.6** Worldwide PV exports from 1975 to 2014

An important finding is that 45% of the world's PV modules were produced in the United States in 1995, while 80% of the world's PV modules were produced in Europe, Japan and the rest of the world in 2002 and 93% of the world's PV cells in 2007. Just like the United States has enabled consumer technology products to be moved to other nations, it seems that the United States still allows the same to occur with the photovoltaic industries [10, 20]. Therefore, it seems essential for studying this development in more detail. To explore different sources of energy, it is useful to compare the units with which the available energy is measured in these sources [10].

## 2.7. THE PHOTOVOLTAIC MANNER OF TRANSFORMATION SOLAR POWER INTO ELECTRICITY

Before moving on to learning the principle of photovoltaic effect, it is important to have a fundamental understanding of PN junctions. Russell of Bell's laboratories in the USA invented the PN Junction [1, 6, 16]. It relates to a section of two semiconductors, i.e. P-type and N-type. Russell found the two semiconductors at the junction have an unusual activity that induces only one direction of conduction [1, 6]. [16, 33].

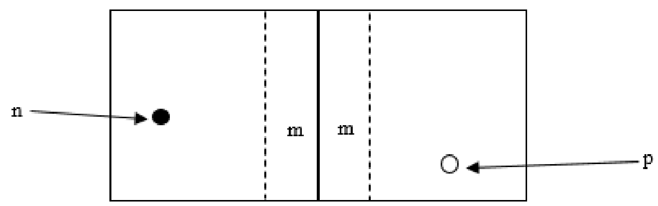


**Figure 2.7** Russell's two semiconductors [6]

Around the intersection in the diagram above: Additional charges spread out to the counter junctions so the positive on the p-side absorbs and neutralizes negative charges. Likewise, the negatives on the N-side are charged positively and neutralized [6, 16]. It creates a gap (m) on either side where additional charges are minimized to make it area stable and balanced. This zone is called a depletion layer and there is no charge from either side. The depletion layer provides a possible barrier and therefore needs exterior tension to beat it [6].

This operation is known as inequality. The applied voltage will inject electrons (negative) from the n-junction to the p-side of the junction in the forward biasing. Constant current ensures that the electrons are constantly moving to fill the holes, thus leading the conduction through the depletion layer [6]. The reversal of the applied voltage allows holes and electrons to move apart in a process called reverse biasing, raising the depletion layer. The exterior charge is applied to a solar cell with a positive terminal linked to the wafers on the N side and the negative one to the wafers on the P side [6].

The photovoltaic impact produces a voltage differential. The current gained by photon-displaced electrons is not enough to make a significant potential difference. Therefore, the current is included to give rise to further collisions and release more electrons [6].

### 2.7.1. Photovoltaic Effect

In capturing solar energy, a solar cell uses the concept of a p-n junction. This figure shows a semiconductor's fermi level.

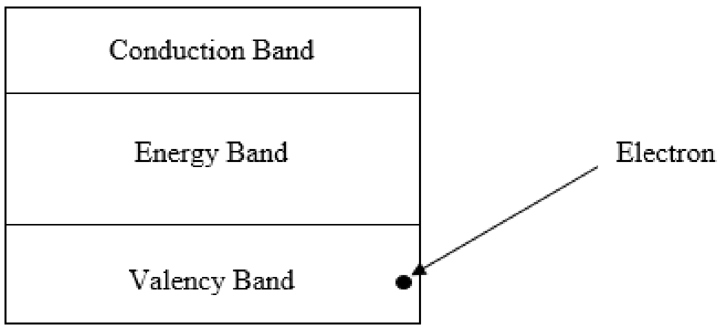


**Figure 2.8** A semiconductor's fermi level

Electrons must cross the energy gap between the valence band and the conductive band for a semiconductor to conduct. These electrons need some power to displace and pass through the valence gap. The emitted photons from the Sun in solar cells supply the energy needed to beat the hole.

A photon event may be absorbed, mirrored or transferred on the surface of the panel. It does not help to displace an electron if it is mirrored or transferred and is lost. A photon should therefore be soaked up to supply the power needed to displace and shift electrons through the parity gap [6].

If $E_{ph}$ is a photon's power and $E_G$ is the power of threshold to cut across the gap of energy the possible results will be when photons hit a semiconductor's surface:
$E_{ph} < E_G$ − In this sıtuatıon, the photon does not reach the threshold and will only flow through.
$E_{ph} = E_G$ − the photon has the same threshold for dislodging an electron and producing a pair of hole electron.
$E_{ph} > E_G$ − The energy of photons exceeds the threshold. It produces a hole-electron pair, although it is a mistake because the electron is moving towards the gap of energy [6].

### 2.7.2. Solar radiation absorption:

In many situations, the semiconductor absorption coefficient is used to define the efficiency of Sun energy absorption. Low factor means a low absorption. Consequently, the extent to which a photon goes is an operator of both the absorption coefficient (α) and the radiation wavelength (λ) [6].

## 2.8. THE EARTH ORBIT AND ROTATION:

The Earth orbits around the sun one time per year in an elliptic orb with the Sun, in a focal point the range between the Sun to the Earth can be given:

$$d = 1.5 \times 10^{11} \left\{1 + 0.017\, sin \left[\frac{360(n-93)}{365}\right]\right\} m \qquad (2.1)$$

Which (n) reflects the day of the year for example 5 of January as day 5. Since the deviation of the orbit is so small from the circular, this distance should normally be expressed from its average value. The Earth spins once a day around its own polar axis [10].

The Earth's polar axis is inclined to the Earth's orbit around the Sun by an angle of 23.45°. This phenomenon makes the Sun in the summer higher in the sky than in the winter. It is also responsible for longer hours of summer sunshine and shorter hours of winter sunlight.

In this Figure, we can see the orbit of the Earth with the inclined polar axis around the Sun [10, 34].

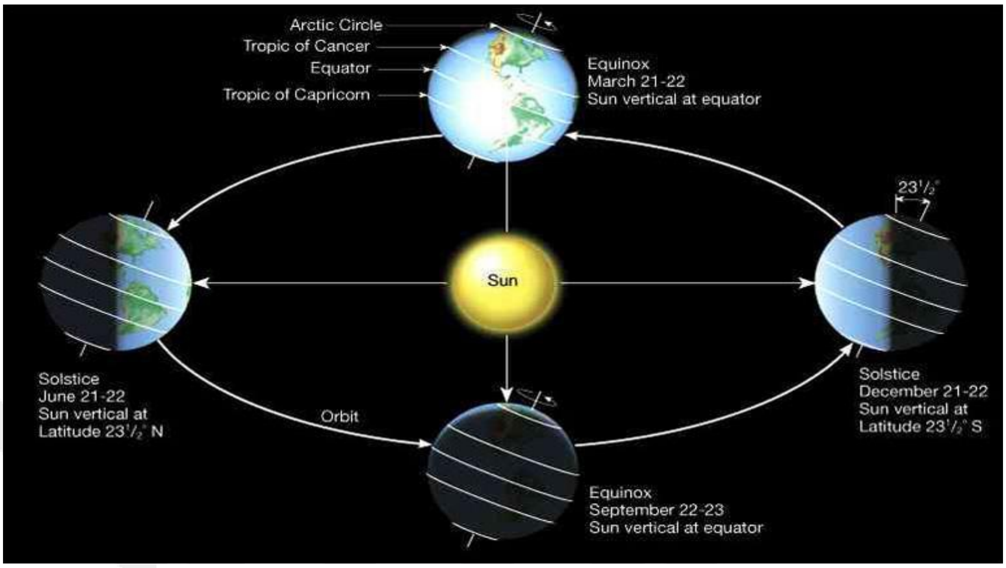


**Figure 2.9** orbit of the Earth with the inclined polar axis around the Sun [35]

Note that the Sun appears vertically above the tropic of Cancer on the first day of summer in the Northern Hemisphere, which is 23.45 ° N latitude of the equator. The Sun appears vertically above the tropic of Capricorn on the first day of winter, which is 23.45 ° S latitude of the equator [10, 34].

The Sun is directly above the equator on the first day of spring and fall. The Sun is south of the equator from fall to spring, and the Sun is north of the equator from spring to fall. The angle of the Sun's deviation from the equator is called the declination, δ. When angles to the north of the equator are considered positive and angle to the south of the equator are considered negative, then the aberration can be observed on any given day of the year from:

$$\delta = 23.45° sin\,[\frac{360(n-80)}{365}] \quad (2.2)$$

This equation will be approximately good because the year is not perfectly 365 days and the first day of summer is not always the 172nd day of the year [10]. Under any situation, the declination is an essential factor to decide the position of the Sun in the sky at any time of the day at any time of the year at any place on the earth. It is also significant to be able to define the time when solar noon happens. Solar noon happens in just one longitude, L1, in any time zone at noon. Solar noon will happen at longitudes east of L1 before noon and at longitudes west of L1 afternoon [10, 36]. When a shadow points directly north or directly south on a sunny day, depending on the latitude, solar noon can be defined. Remember that, the shadow will point north for part of the year in the tropics and will point south for the rest of the year [10, 36].

Luckily, if the longitude is known, the estimated relationship between clock noon and solar noon is easy to determine. Since the day is 24 hours and during this period, the Earth rotates 360 °, so the Earth spins at a rate of 15 ° / h. It is also useful that the zero longitude matches to the noon at solar noon. The outcome is that solar noon happens at midday at multiples of 15° longitude west or east [10, 36].

Moreover, since it requires 60 minutes to rotate the Earth 15 °, it is direct to inset to locate solar noon at average lengths. For example, solar noon can be found at a length of 90 ° W by noting that 90 ° is between 85 ° and 100 °, where solar noon happens at the standard time of the clock at noon [10]. Because 90 ° is west of 85 °, the Sun will be at 90 ° east of south when the Sun is directly south at 85°. Therefore, interpolation (t) determines the clock time at which the Sun will be south at 90 ° (solar noon at 90 °):

$$t = 12 + \frac{90-85}{15} \times 60 = 12 + 20 \text{ Minutes= 12:20 p.m} \qquad (2.3)$$

Remember that this time is the standard time zone for the 85 ° W solar noon. When 100 ° W is used as the guide for the solar noon, then at 100 ° solar noon will happen 40 minutes after the 90 ° solar noon. Notice the answer remains the same [10, 36].

## 2.9. SUN TRACKING

To fully determine the position of the Sun, three coordinates must be defined. If the range between the Earth and the Sun is assumed to be fixed, so the position of the Sun can be located using two angles, the solar altitude and the azimuth [10, 37].

The solar altitude, α, is the angle in a plane determined by the zenith and the Sun between the horizon and the incident solar beam as shown in Figure 2.10. The angular perversion of the Sun from the south can be represented by the azimuth angle ψ, which calculates the angular position of the Sun to the east or west of the south [10, 38].

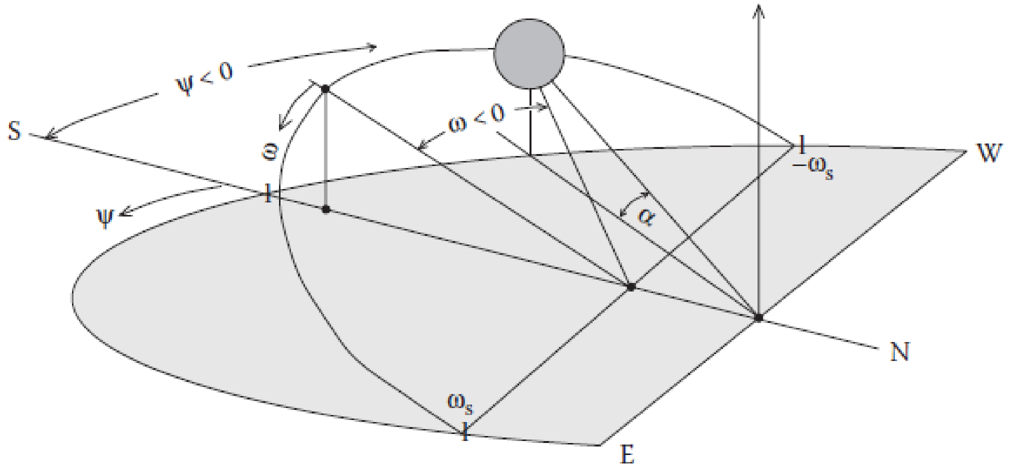


**Figure 2.10** Corners of the sky, height, azimuth, and angle of the hour [10, 37]

At solar noon, the angle of azimuth is zero and increases to the east. It is the angle between the observer's vertical plane intersection and the horizontal of the Sun [10].

It should note that the azimuth angle is referred to as the north in many publications so that the solar noon occurs at ψ= 180°. In fact, Compass angles are azimuth angles indicated to the magnetic north. Another important, though repetitive, angle in the definition of the Sun's location is the angular displacement of the Sun from the solar noon on the Sun's apparent travel plane. The angle of the hour is the distinction between midday and the preferred time of day in a 24-hour rotation of 360°. [10, 37] In other words,

$$\omega = \frac{12-T}{24} \times 360° = 15(12-T)° \quad (2.4)$$

Where T is the moment of the day for solar mid of the day, a 24-hour clock. For example, T=10 am, ω = 30 °. By making ω reference to the other angles mentioned above, it can be shown the angle of sunrise by [10, 38]:

$$\omega_s = \cos^{-1}(-tan\ \phi\ tan\ \delta) \quad (2.5)$$

In addition, this means that the angle of sunset is given by $-\omega_s$. This calculation is helpful because it helps to estimate the number of hours that the Sun is over the horizon on a given day. to involve the hours from solar noon to sunset, thus the number of daylight hours (DH) by converting the angle of sunrise to hours from sunrise to solar noon, and then multiplying by two [10, 37]:

$$DH = \frac{48}{360} \times \omega_s = \frac{\cos^{-1}(-tan\,\phi\; tan\,\delta)}{7.5}\, hour \tag{2.6}$$

The reader who loves trigonometry will evaluate two very important relationships between α and ψ. If δ, ϕ, and ω are known, then the location of the Sun at this location from this date and time, in terms of α and ψ, can be determined from

$$sin\,\alpha\; = sin\,\delta\; sin\,\phi + cos\,\delta\; cos\,\phi\; cos\,\omega \tag{2.7}$$

And

$$cos\,\psi\; = \frac{sin\,\alpha\; sin\,\phi - sin\,\delta}{cos\alpha\; cos\,\phi} \tag{2.8}$$

Note that angles are measured in degrees in all of the above expressions. Throughout the year, the highest spot of the Sun will be at $\theta_z = \phi - 23.45°$ and the lowest point of the solar noon Sun in the sky will be at $\theta_z = \phi + 23.45°$, provided that $\phi > 23.45°$ [10].

It is especially motivating to note that if $\phi > (90° - 23.45° = 66.55°)$, then under the horizon is the lowest point of the Sun in the sky, indicating that the Sun will not come or fall in that day. This is, of course, the case in the polar places, which are subject to 24-hour darkness. If $\phi < 23.45°$, θz will be negative at some point in the summer. This purely means that the Sun will show north at solar noon. The relationships between θz, ϕ, and δ at solar noon are shown in Figure 2.11 [10, 37].

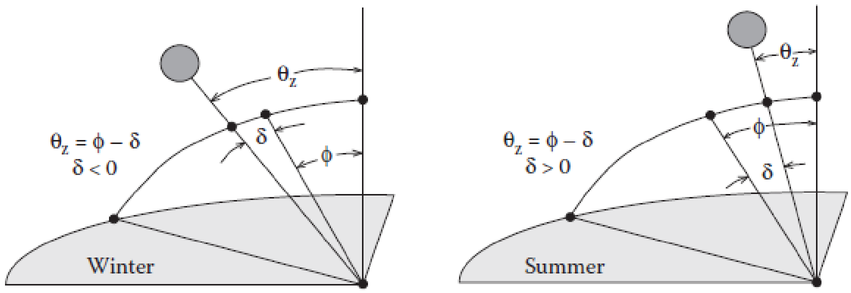


**Figure 2.11** Relationships among zenith angle, latitude, and declination at solar noon in winter and summer [10]

As the last two equations are rather hard to visualize, for particular latitudes and days of the year it is easy to plot α versus ψ. Figure 2.12 displays a collection of altitude and azimuth plots at 40° N latitude. The curves indicate how high the Sun will be in the sky during a given month at a certain time of day, with the angle of azimuth calculated by the moment of the day [10, 39].

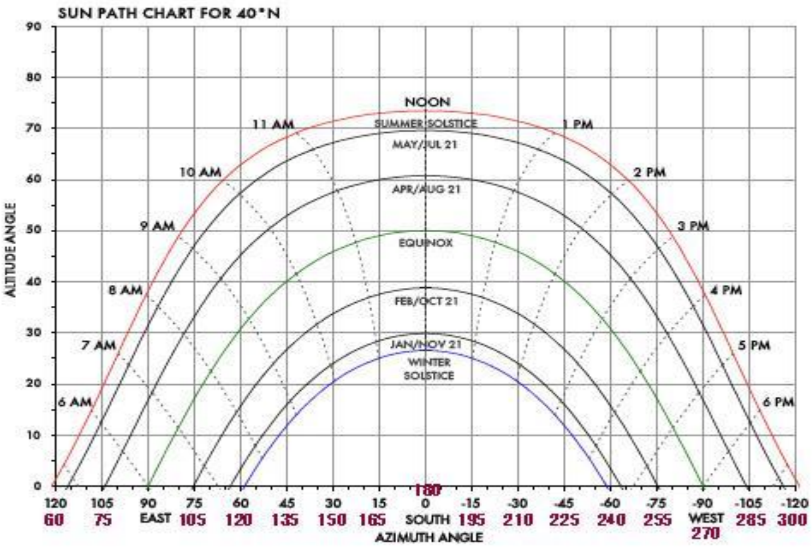


**Figure 2.12** Solar altitude versus azimuth at 40 ° N latitude for different months of the year [39].

Surprisingly enough, when all the numerical work is done, it ends up with a response that does not account for the cloudiness. The most accurate method of cloud cover accounting is to make long-term calculations to define average figures [10]. Indeed, the precise prediction of PV systems' performance also relies on temperature. Thus, if sunlight data are included as a result of measured meteorological data, which include irradiance and temperature over an hourly basis for a given location for the 8760 hours per year, reasonably reliable estimates can be made of PV system performance [10].

Of course, measuring hourly data for a given year, say 2019, will not necessarily be a good predictor for other years. To achieve a better predictor for annual performance, experts have defined the typical meteorological year (TMY) by selecting data for each month from a different year [10].

## 2.10. WHAT IS A METEOROLOGICAL TYPICAL YEAR (TMY)?

Exemplary weather year is a set of chosen weather data for a particular place, showing hourly values of solar radiation and meteorological factors for a period of one year. The numbers are created from a database over a period of more than one year. It is specifically chosen to show the spectrum of weather events for the region in question, while still presenting annual averages associated with the long-term averages for the location in question [40].

TMY data is often used in construction modeling to determine the potential heating and cooling costs for building design. This is also used by developers of solar energy systems including solar hot water systems and solar thermal power plants on a large scale. Because they are normal rather than difficult conditions, they are not ideal for developing structures to withstand the worst conditions at a location. The reference data can be downloaded from the National Laboratory for Renewable Energy.

## 2.11. IRRADIANCE & IRRADIATION

Irradiance is the calculation of sunlight's power intensity and is expressed in $W/m^2$. Irradiance is, therefore, an immediate amount and is often specified as sunlight intensity. The Earth's solar constant is that irradiance is received from the Sun at the earth's surface, for example, at AM 0, irradiance is equal to 1367 $W/m^2$. The irradiance is reduced to about 1000 $W/m^2$ after crossing the atmosphere with a path length of AM 1 [1, 10, 41]. For AM 1.5 the irradiance is admitted as the standard spectrum for PV cells.

Irradiation is a measure of sunlight's power density and is measured in kWh / m2. Since the energy is power combined over time, irradiation is the total of irradiance. The integration time frame is usually 1 day, which of course means during daylight hours [1, 10, 41].

Peak Sun Hours ($PSH_s$) is often defined for Irradiation. The ($PSH_s$) is simply the period in hours at 1 kW/m$^2$ of irradiance required to product the daily irradiation gained from the total of irradiance throughout the hours of daylight. Figure 2.13 illustrates the result of this integration for an example day of sunshine with a few cloudy moments [10, 41].

Note that Figure 2.13 plots irradiance versus time in order to determine irradiation. All sunlight components are applied to irradiance and irradiation. The irradiation will rely on weather conditions, the location, and time of year at a given time, or for a given day. They will also rely on whether trees or buildings shade the panels and whether the panels are horizontal or angled. The daily irradiation is equivalent to the daily (PSHs) [10, 41].

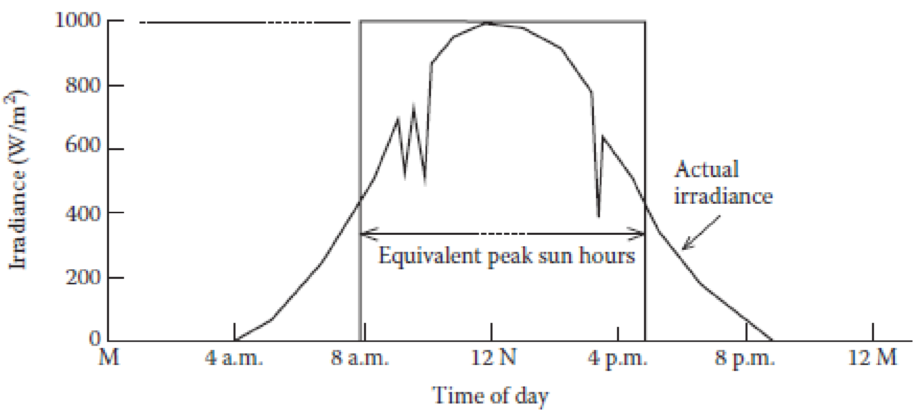


**Figure 2.13** Determination of ($PSH_s$) or (irradiation) through the integration of irradiance[10]

In order to assess the volume of appropriate irradiation for conversion to electricity at a given location, it is useful to establish multiple terms for panels irradiance, depending on the angle between the surface of panels and the light. It is also motivating to be able to calculate at a given location the hours of sunlight on a given day [10].

## 2.12. MAXIMIZING OF IRRADIATION

The developer of any device that absorbs sunlight will determine how the system can be installed. Maybe most systems can be easily installed horizontally. This approach does not optimize the working of panels, where the collected beam radiation component is symmetrical to the angle cosine between the incident beam and the panel's surface, as shown in Figure 2.14 [10].

Based on the ratio of diffuse to beam irradiance elements, there will be a proportion of the available energy obtained between cos $\gamma$ and unity. Of course, the beam irradiance will only be a small fraction of the global irradiance in a highly diffuse environment. There are several options for horizontal mounting.

Since $\theta_Z = \phi - \delta$ determines the position of the Sun at solar noon, if this angle is adjacent to the panel, it will be vertical to the Sun. Where the Sun is in the highest point in the sky leading in its minimum atmospheric path and the corresponding lowest air mass for the day. As the Sun travels over an angle of 15 ° per hour, it will be close to the panel for about 2 hours. After this time, due to the increase in air mass and the angle between the sunlight incident and the panel the density of the sunlight will decrease [10].

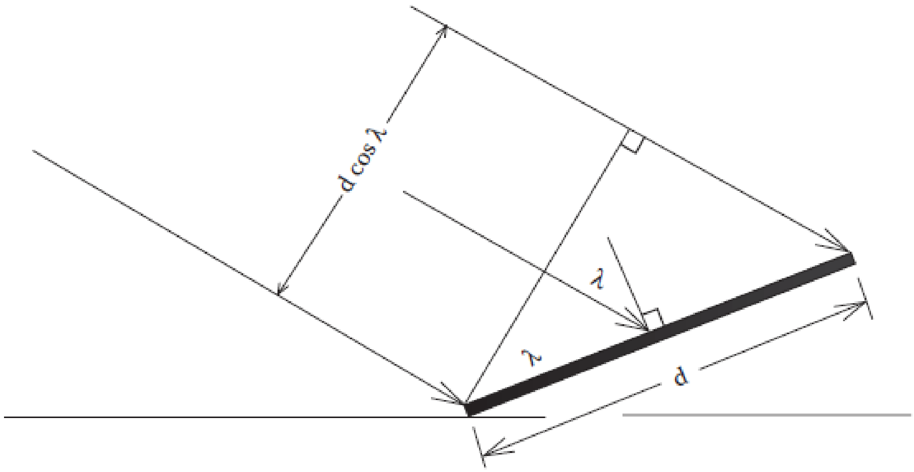


**Figure 2.14** Two-dimensional of the collector [10]

Those two factors lead to a relatively rapid decrease in the energy produced by the collector among the hours before 10 am and after 2 pm. Figure 2.15 shows the approximate cumulative irradiation received by a south-facing panel tilted at the latitude angle in a place where the beam radiation element is significantly stronger than either the diffuse or the albedo elements [10].

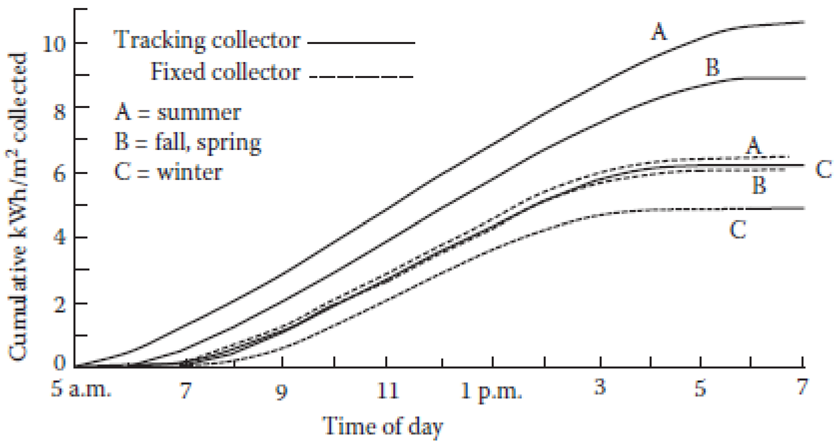


**Figure 2.15** Cumulative daily irradiation [10]

If the collector is positioned to track the Sun, then the irradiance will only be influenced by the air mass as the Sun reaches the horizon. Figure 2.15 indicates also the added accumulated irradiation provided by a tracker under direct beam conditions. During summer, 50 percent more energy can be approximately stored in dry weather using a tracker [10]. However, only about 20 percent more energy is collected through a tracker during the winter months [10].

It becomes an important economic decision for the engineer to use a two-axis tracker since a tracking mode is more expensive than a fixed one. To make the range of setting even more reasonable, a single-axis tracker can be considered which rotates perpendicular to θz around an axis. It is also possible to consider mountings that can be adjusted manually many times per day or perhaps several times per year [10].

Each of these choices will allow the complete set of energy between the optimal results of the fixed panel and the results of the two-axis tracker. The direction of the collector may also depend on the season. For example, a remote cabin, which is only used during the summer months, will need its collector oriented for ideal summer collection [10].

For optimum working on a given day, a fixed collector should be placed at a degree of $\phi - \delta$ concerning the horizontal angle, as shown in Figure 2.16. This will induce the collector's plane to be perpendicular to the Sun at midday. For maximum seasonal efficiency, the average value of $\delta$ for the season is simply selected [10].

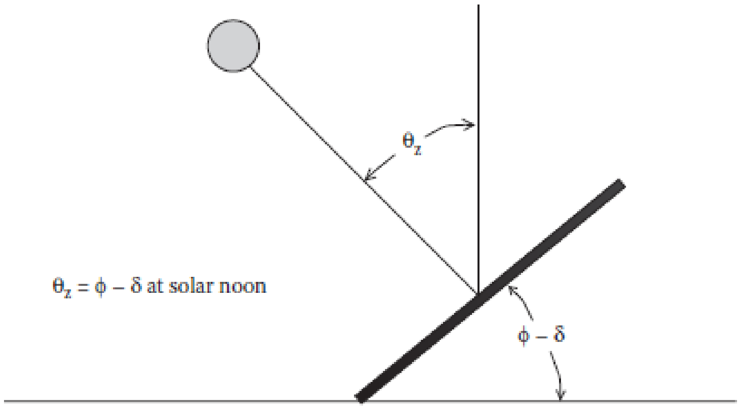


**Figure 2.16** Optimizing the panel's angle [10]

## 2.13. THE ENERGY OF THE SUN

In concord with Planck's black body radiation formula, this power is irradiated from the Sun regularly in all paths. The energy intensity per unit area, $w_\lambda$ , as a function of wavelength, $\lambda$, is given by [42]:

$$w_\lambda = \frac{2\pi hc^2\lambda^{-5}}{e^{(\frac{hc}{\lambda kT})}-1} \text{ (w/m}^2\text{/unit wavelength in meters)} \tag{2.9}$$

where h = 6.63 × $10^{-34}$ W $s^2$ (Planck’s constant), c = 3.00 × $10^8$ m/s (speed of light in a vacuum), k = 1.38 × $10^{-23}$ J/K (Boltzmann’s constant), and T = absolute temperature of blackbody in K (Kelvin, where 0 K = −273.16°C) [10, 42]. This equation yields the energy intensity on the Sun's surface in W/$m^2$/unit wavelength in meters. By the time this energy journeyed 150 million km to the Earth, the total density of extraterrestrial energy falls to 1367 W/$m^2$ and is often called the solar constant [10].

## 2.14. DEVELOPMENT OF SOLAR PANELS

First, we have to mention the production of silicon solar cells. The production of crystalline silicon solar cells is a process we can split into several discrete steps, see figure 2.17.

At the first step is silica ($SiO_2$ or sand) goes over a reduction process and takes shape metallurgical grade silicon at a pureness level of approximately 98%. Polysilicon raw materials are refined to become at a purity level of around 99.999 % (5N) by the metallurgical grade silicon [1, 10, 31, 43].

Then two paths are possible for growing the silicon crystals resulting in either mono-crystalline silicon or multi-crystalline silicon. Once the crystals are grown, wafers are made. The difference between these two types of silicon solar cell modules in cell conversion efficiency is typically 1.5-2% [1, 10, 31, 43].

Nevertheless, multi-crystalline silicon can be produced at a lower cost than mono-crystalline silicon. After the wafers are made, several steps are taken to fabricate the final cells including the doping and wiring. Lastly, the cells are assembled into solar modules [1, 10, 31, 43]. The remainder of this section will deal with each step in Figure 2.17.

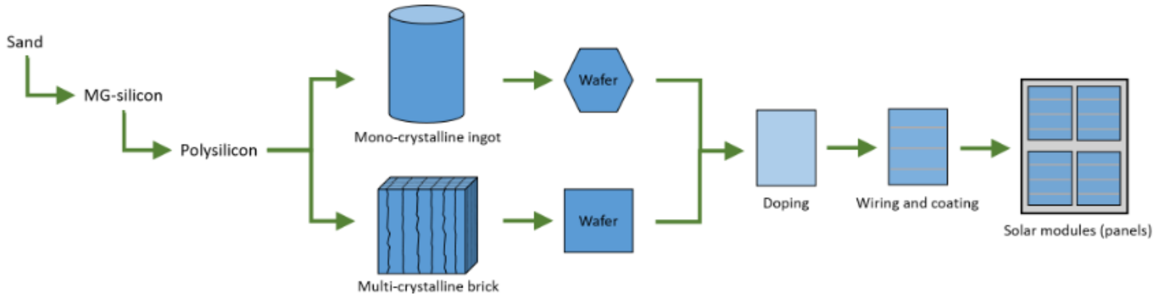


**Figure 2.17**. Made-up processing from the raw material (sand) to the final solar panel [1].

### 2.14.1 From sand to high-quality silicon:

The crystal quality of the silicon is important since the diffusion length must be high to utilize the photons absorbed deep inside the cell. We will look at how silicon is produced in various qualities [1, 10, 43].

### 2.14.2 Metallurgical silicon:

The first step in refining silicon is to take $SiO_2$ (sand) and reduce it to silicon. This process takes place in an electric arc furnace, see figure 2.18. By adding silicon dioxide, coal, and thermal energy at approximately 1800 °C we get the following reaction [1, 10]:

$$2SiO_2 + 4C \rightarrow 2Si + 4CO$$

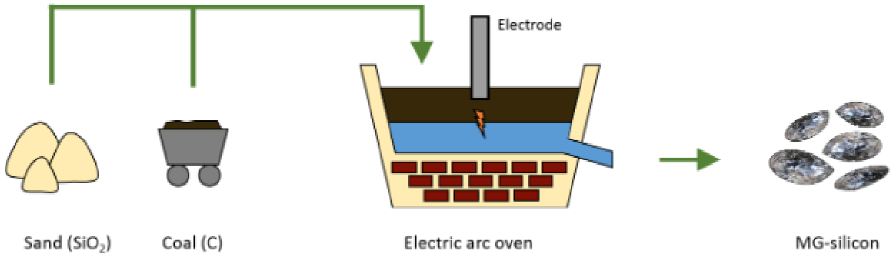


**Figure 2.18.** Production of metallurgical silicon. Coal and $SiO_2$ is added to the electric arc furnace and reduced to silicon and carbon monoxide [1, 10]

From the furnace, we obtain metallurgical silicon with a purity of roughly 98%. This type of silicon is designated metallurgical silicon since its main usage is in the production of steel.

### 2.14.3 Polysilicon

Silicon for solar cells must be purified from the metallurgical silicon form, and this is accomplished through a complex process resulting in polysilicon, see the steps in figure 2.19. First finely ground metallurgical silicon is mixed with hydrochloric acid (HCl) in a fluidized bed reactor. This process results in trichlorosilane ($SiHCl_3$) and thus the process is named the Silane process[1, 10, 31].

$$2Si + 3HCl \rightarrow SiHCl_3 + Si + H_2$$

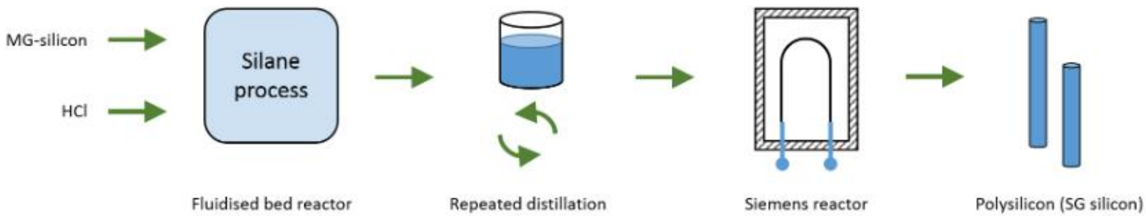


**Figure 2.19**. Production steps leading to polycrystalline silicon [1].

Metallurgical silicon is added to a fluidized bed reactor with hydrochloric acid forming trichlorosilane. The trichlorosilane is repeatedly distilled before the silicon is reclaimed in the Siemens reactor.

After the silane process, the trichlorosilane is further cleaned by repeated distillations eased by the low boiling point (31.8 °C) of trichlorosilane. The now purified trichlorosilane is fed into a Siemens reactor to reclaim the silicon, see Figure 2.19 [1, 10].

The gaseous trichlorosilane is fed past a heated (1350 °C) thin silicon rod onto which highly purified polycrystalline separates from the gaseous phase. The process results in large rods (e.g. 2-meter-long with 30 cm diameter) of at least 99.999 % pure polysilicon. For solar cell manufacturing, 99.999 % purity is considered the minimum acceptable purity. For the semiconductor industry, silicon purity of 99.999999999 % is considered normal for production of computer chips [1, 10, 43]. The polycrystalline silicon now has the desired purity, but the crystalline structure of the material is not good enough for solar cells. For silicon solar cells, either multi-crystalline or monocrystalline silicon is required [1, 10].

### 2.14.4 Multi-crystalline silicon

To produce multi-crystalline silicon, pieces of polycrystalline silicon are added to a graphite crucible and melted, see figure 2.20. Then the crucible is slowly cooled from the bottom, allowing small crystals to form at the bottom. These nanocrystals grow sideways until they touch each other. The vertical cooling profile allows the crystals to grow in columns, eventually resulting in a multi-crystalline ingot. Once the crystallization is completed, the silicon block is divided into cubes, which are then cut into wafers, see figure 2.22[1, 10].

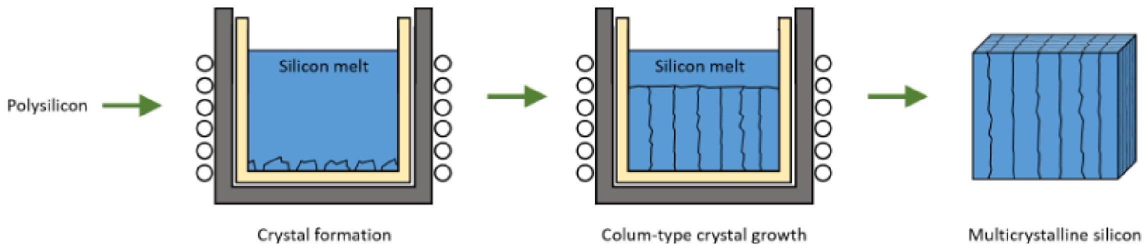


**Figure 2.20.** Production of multi-crystalline silicon [1]

It starts with polysilicon melted in a crucible. At the bottom mono-crystals forms, when the crucible is cooled. Column growth is ensured by cooling the crucible from the bottom. The boundary layers between the different crystal orientations become recombination sites for holes and electrons in the finished solar cells, and therefore it is important to maximize the size of the mono-crystals. Multi-crystalline solar cells are typically 2-3 % less efficient compared to monocrystalline solar cells for this very reason [1, 10].

### 2.14.5 Monocrystalline silicon:

Monocrystalline silicon is most often produced through the Czochralski process, see figure 2.21. In this process, a seed crystal, affixed to a metal rod, is dipped into a bath of molten polysilicon. When the rod is withdrawn fluid, silicon attaches to it and crystallizes. The seed crystal determines the crystal orientation of the forming silicon rod, and the rotation and withdrawal speed determine the size of the resulting monocrystalline rod (ingot). Rods with a diameter of 30 centimeters and lengths are produced in this manner [1, 10, 44].

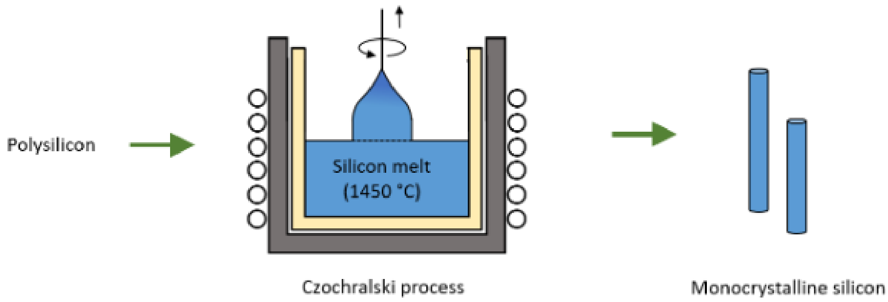


**Figure 2.21**. The Czochralski process[1]

The Czochralski process for the production of monocrystalline silicon involves a bath of molten polysilicon into which a seed crystal is dipped.  Once the seed crystal is withdrawn, it grows and eventually from a full rod of monocrystalline silicon[1, 44].

### 2.14.6 Wafer production

After the production of both monocrystalline and multi-crystalline silicon, the resulting ingots must be sawed into individual sheets (wafers). A wire cutter is typically used for this purpose allowing wafers with a thickness of 180 μm to be cut. Saw losses are unavoidable using this technique, as the wires are typically 100 to 140 μm thick [1, 10, 31, 43, 44].

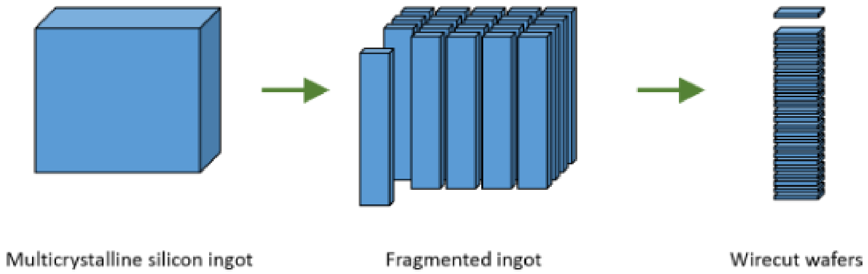


**Figure 2.22.** Multicrystalline wafers[1]

Multicrystalline wafers are produced by first fragmenting the original ingot, and then wire cutting it into individual wafers.

### 2.14.7 Production of standard silicon solar cells

The typical production steps for producing a silicon solar cell includes several steps summarized in figure 2.23. First, the doped silicon wafers are dipped into an etching bath to remove contaminants or crystal damage on the surface. Then the surface is texturized, e.g. using etching. This step improves the light trapping in the cell. After texturizing, the p-n junction is formed using phosphorus diffusion [10, 31].

This step is relatively energy-intensive, requiring temperatures of 800-900 °C. After the $n^+$ doped layer has been established, an anti-reflective coating is applied, and surface passivation is achieved (surface passivation minimizes surface recombination). The anti-reflective coating gives the silicon solar cells their blueish appearance [10, 31].

Contacts are applied using screen-printing, in which a metal paste is applied. The front contacts are made from a silver paste, while the rear contacts are made in two steps. First soldering pads are made from silver paste, then the remainder of the surface is fully covered by aluminum. The contact firing ensures the hardening of the pastes, and the firing ensures contact with the emitter by firing the anti-reflective coating. Additionally, the firing achieves a diffusion of aluminum atoms from the rear contact into the base creating a $p^+$ doped layer that establishes the back surface field [1, 10, 31].

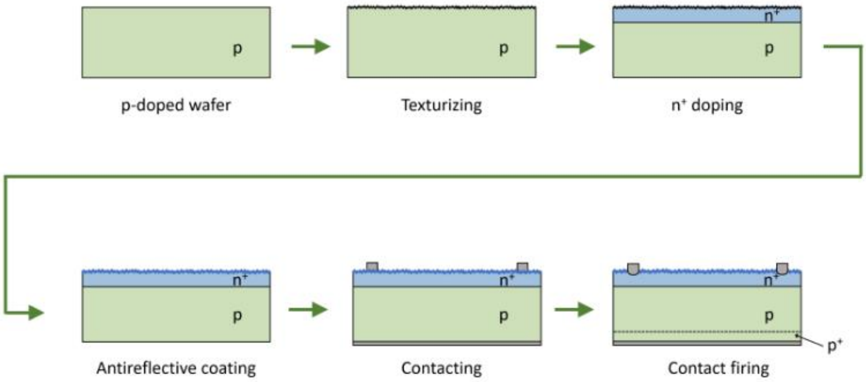


**Figure 2.23.** Process steps for silicon solar cell production[1]

The p-doped starting wafer is texturized, n+ doped, an anti-reflective coating and contacts are applied, and finally, the contacts are fired.

The last step, not shown in Figure 2.23, is the edge insulation to ensure that the front and rear of the solar cell are isolated from each other. The solar cell is thus complete, and most manufacturing processes include a quality control step, where the IV characteristics of the solar cell are measured [1, 10].

### 2.14.8 Solar modules

Single solar cells are fragile and may not produce enough power for a given application, therefore, solar cells typically are integrated into solar modules. In figure 2.24, a typical example of a solar module is seen. The individual cells are connected electrically in series into a cell string using galvanized copper strips. The strings are placed between two sheets of the extremely thin absorber (ETA) [10, 44].
On the front side, a glass window is placed, and a rear-side foil is placed on the back. This sandwich is heated in a laminator and the EVA material softens and flows around the cells, encapsulating them. The structure is then mounted in an aluminum frame, creating the finished solar module[1, 10, 44].

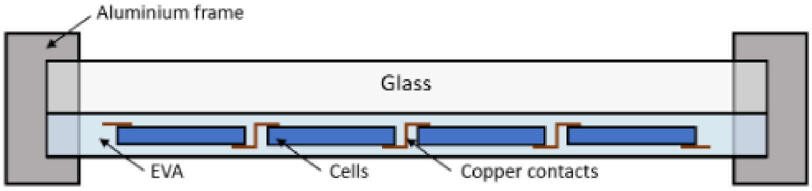


**Figure 2.24.** Structure of a glass-foil module in an aluminum frame[1].

### 2.14.9 Production of CIGS solar cells:

Unlike exemplary crystalline silicon modules, the manufacture of thin-film modules requires the deposition of thin layers of semiconductor material on a surface made of glass, metal or plastic requiring only about a fraction of the semiconductor material used in silicon wafers along with a significantly lower energy requirement. A clear advantage of this production process is that cells do not have to be made individually, rather, they connected as an intrinsic part of the layer structure [1, 10, 44].

Figure 2.25 provides an overview of the development steps for CIGS solar cells. First, the molybdenum back contact is deposited, commonly by sputtering. In addition to serving as contact, the molybdenum layer reflects most unabsorbed light back into the CIGS absorber[1]. After sedimentation, the molybdenum layer is described by a laser to define the cell area [10].

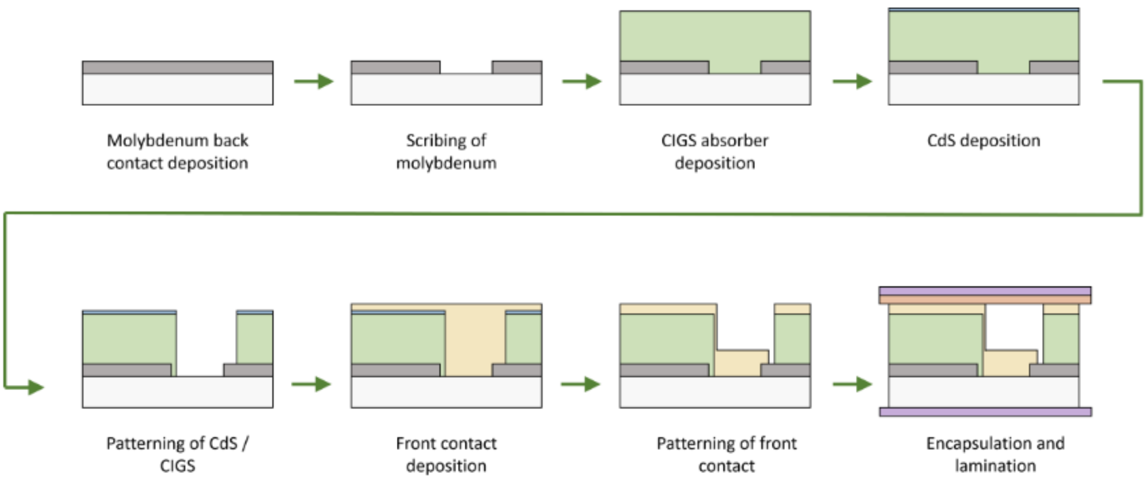


**Figure 2.25** Production steps of a CIGS solar cell[1].

Following the deposition of molybdenum, one of several unique methods is used to plant the p-type CIGS absorber layer (it will be described below). A thin n-type buffer layer (typically CdS) is deposited via chemical bath deposition on top of the absorber. Then the buffer layer and the absorber layer are patterned before the buffer is overlaid with a thin layer of zinc oxide (ZnO) with a thicker layer of (ZnO) doped with aluminum [1, 10].

The inherent ZnO layer is used to protect the buffer layer and the absorber layer from crackle damage while depositing the ZnO aluminum-doped window layer normally deposited by

DC sputtering (a harmful process). Finally, the front contact is patterned and the entire stack is capsulized [1, 10].

### 2.14.10 Absorber layer

There are two main approaches to creating the absorber (CIGS) layer, one-step production or two-step production. All four components (Cu, In, Ga, and Se) are incorporated in the one-step process at once. Copper, Indium, and Gallium are first deposited in a rough form in the two-step process (not the most ideal crystal structure). In a selenization step, selenium is applied where the deposited layer is recrystallized to the final eligible form. Co-evaporation, or co-deposition, is the most prevalent one-step CIGS fabrication technique.

Evaporation drawbacks include problems of uniformity across large areas and the related complexity of co-evaporating components in an inline device [1, 10, 17]. The high temperatures increase the heat budget and the cost. Also, the usage of poor material causes plague co-evaporation (deposition on chamber walls instead of the substrate) and costly vacuum equipment. The theory behind the two-step process is to make the first step inexpensive [1, 10].

This first step is called the precursor step. Nanoparticle printing is one method to achieve the first step. The second step is the selenization steps where selenium is added, and the layer is recrystallized to the final form. The advantage of the two-step process is that it is much simpler and does not require a high degree of control [1, 10].However, films obtained through a two-step process is generally inferior to that obtained with the co-evaporation technique.

### 2.14.11 Working Principle of CIGS Solar Cells

The central idea common to all thin-film solar cells is the use of a single thin deposited layer of semiconductor material to avoid the high costs and energy demand required to produce high-purity silicon wafers. A variety of semiconductor materials can be used to make thin-film solar cells including amorphous silicon (a-Si), cadmium telluride (CdTe) and compounds made of copper, indium, gallium, and selenium (CIGS) [1, 10].

The main semiconductor material used in the CIGS solar cell is the p-doped CIGS layer consisting of copper, indium, gallium, and selenium. It has a chemical formula of $CuIn_xGa_{(1-x)}$ Se2 where the value of x can vary from 1 (pure copper indium selenide) to 0 (pure copper gallium selenide) [1, 10].

The bandgap will vary with x from about 1.0 eV (for copper indium selenide) to about 1.7 eV (for copper gallium selenide). This means the bandgap is close to ideal, given the Shockley-Queisser efficiency limit, see Figure 2.26 [1, 10].

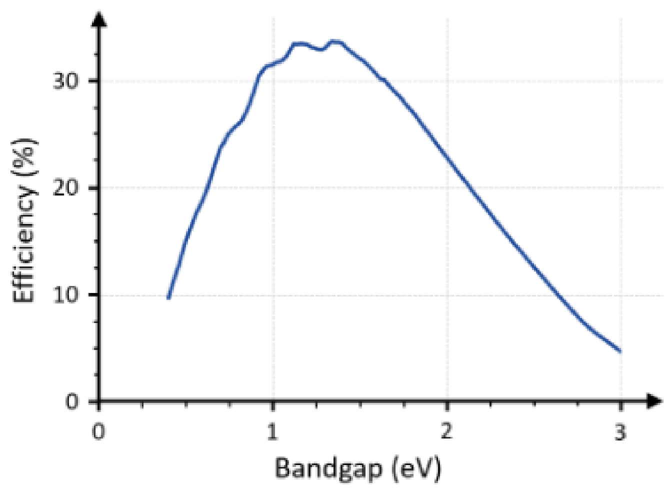


**Figure 2.26**. The Shockley-Queisser limit for the efficiency of a solar cell with a given bandgap [1]

The curve is wiggly because of the absorption bands in the atmosphere.

The typical cell structure for a CIGS solar cell is shown in figure 2.27. The bottom glass acts as a substrate and the molybdenum layer is the rear electrode. The p-n junction of the CIGS cell is formed between the absorber (CIGS) layer and a thin n-type buffer layer (CdS).

Unlike conventional crystalline silicon cells based on a homojunction (a junction between two similar crystalline semiconductors), the structure of CIGS cells is a more complex heterojunction system (a junction between dissimilar crystalline semiconductors). As a direct bandgap material, the CIGS absorber layer has a strong light absorption and a layer of only 1–2 µm is enough to absorb the most light. By comparison, a much greater thickness of about 160–190 µm is required for crystalline silicon [1, 10].

The active CIGS-layer is deposited in a polycrystalline form directly onto molybdenum (Mo). On top of the absorber layer, a buffer layer (CdS) is deposited. The role of the buffer layer in a heterojunction is to form a PN-junction with the absorber layer while admitting a maximum amount of light to the junction region and absorber layer [1, 10].

This layer should have minimal absorption losses and must be capable of driving out the photo-generated carriers with minimum recombination losses and transporting them to the external circuit with minimal electrical resistance[1]. The buffer layer is typically cadmium sulfide (CdS), however, it would be advantageous to replace the cadmium, since cadmium is a heavy metal and potential carcinogen that can accumulate in plant and animal tissue. The top ZnO layer acts as a transparent electrode [1, 10].

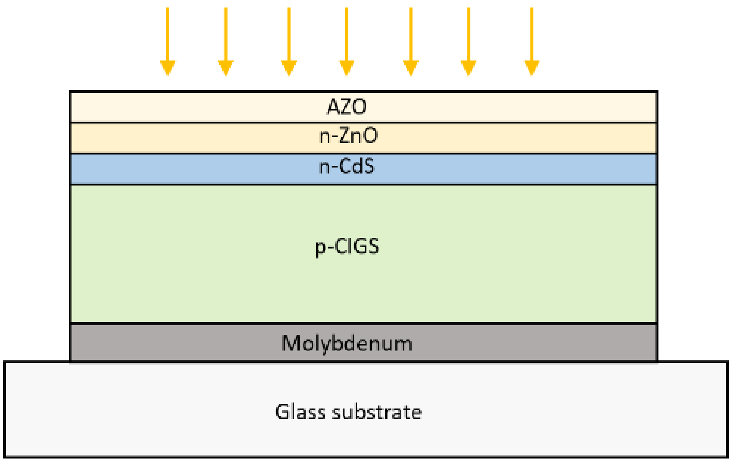


**Figure 2.27.** Structure of a CIGS solar cell [1].

To build a solar panel, as discussed before, several solar cells made of doped silicon are needed. To add the resulting current, these cells are connected in series. This gives clustered cell strips called a module [6, 10].

In cases where a large panel is needed, a single module could be built into a solar panel or combined with others. The solar panel is made of several layers. Those are used to protect soft cells. Below is a figure for the layers [6].

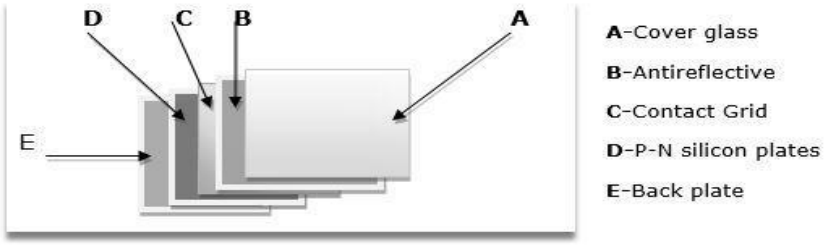


**Figure 2.28.** Illustration of the layers [6]

The layers are the following components: Cover-Glass: this is the top cover and is translucent for the entry of light. This avoids mechanical damage to the cells. It is made of tough glass to ban scratching and some studies on cover glass rely on anti-soiling coatings, the anti-soiling coatings have been effective in reducing soil deposition and removing pollutants of rainwater [6, 45].

Non-reflective layer: Most of the sunlight will be mirrored by the silicone. This layer is therefore used to combat this and to guarantee maximum photon absorption. In other words, this helps enhance absorption, consisting of anti-reflective and reflective layers in which the anti-reflective layer consists of $TiO_2$ pyramids. This construction aims to allow sunlight to enter the cell at any angle with a minimum reflection and absorption of 300–1100 nm wavelength [6, 46].

Contact grid: All the contacts between the top and bottom of the cells are connected together at this layer. The contact expands to the panel's exterior parts, such as charge controller, combiner box and battery storage [6, 47].

P and N Silicon plates: In fact, this layer is a mixture of two layers, the N-doped silicon layer, and the P-doped silicon layer. Back-plate: this is a tough layer to support photovoltaic crystalline panels. Flexible synthetic fibers can sometimes be used for panels of thin-film type. The aluminum frame is used for framing and waterproofing of the panel [6, 47, 48].

The benefits of the frame: this enables the panel to be mounted on surfaces such as rooftops. The frame is strong enough to shield the panel from extreme weather like storms. The solar panel should also be regularly cared for to avoid particles of dust from settling on it. The panels should be fixed at an angle during the installation process to receive maximum light [6].

## 2.15. EFFICIENCY OF PV CELL

The power input/output ratio refers to efficiency. For photovoltaic cells, efficiency is the ratio of electricity output to the incident of solar energy in the cell [6].

The factors affecting the efficiency of photovoltaic cell involve:

- The wavelength of the light.
- Electrons and holes recombination
- Electrical resistance.
- Temperature.
- Fill factor.
- The reflection factor of the material. The cell should, therefore, be designed to have a greater filling area i.e. surface area used to optimize capacity [6].

The location of a solar cell as well defines its output for two causes. First, the level of reflection on the cell is determined by the angle, and secondly, the positioning determines the amount of sunshine collected between 9 am to 3 pm[6]. It is significant to avoid shadows on cells for maximum efficiency. If we want to know the solar cell's output, we need to know how much energy the solar panel receives.

Let us consider the solar cell on Vanguard 1 to calculate the efficiency since we know the power output/luminosity of the sun ($3.828 \cdot 10^{26}$ W) and the distance from the Sun to the Earth (1 AU = $1.496 \cdot 10^{11}$ m). The solar constant ($\sigma$) can then be calculated as the ratio between the power output of the sun and the surface area of a sphere with the Sun/Earth distance as its radius, see figure 2.29 for graphical representation [1].

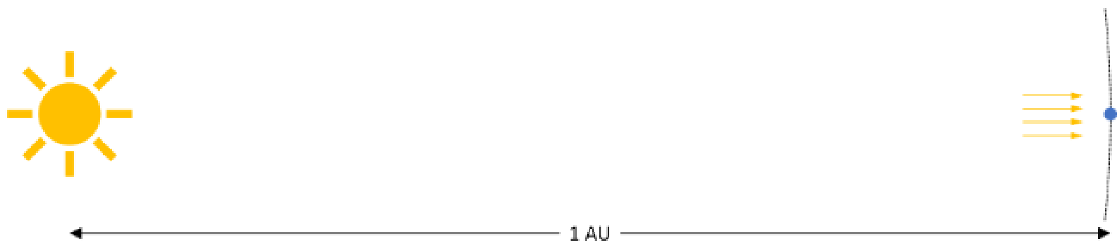


**Figure 2.29**. Earth-sun system. The radius of the sphere represented by the line is 1 AU (astronomical unit) [1]

$$\sigma = \frac{p_{sun}}{4\pi r^2} = \frac{3.828 \cdot 10^{26}}{4\pi\, 1.496 \cdot 10^{11}} = 1361[{}^{W}/_{m^2}] \tag{2.10}$$

To calculate the efficiency of the solar cell on Vanguard 1 **(mentioned in Chapter 2.1)** we know both the area of the solar cells, the incoming power, and the power output. Considering the solar panels produced 1 W using a 100 $cm^2$ area.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{\sigma \cdot A} = \frac{1[W]}{1361[{}^{W}/_{m^2}] \cdot 0.01[m^2]} = 7.35\% \tag{2.11}$$

The Sun itself is a massive fusion reactor in which hydrogen atoms are fused into helium. The energy from this fusion reaction is released into Space in the form of radiation. We have already encountered the value of the radiation power of the sun ($3.828 \cdot 10^{26}$ W), which we used to calculate the solar constant (1361 W/m2) [1].

The number we calculated is the value as measured outside Earth's atmosphere. In figure 2.30, you can see the spectrum both inside and outside the atmosphere. We designate the light as measured outside the atmosphere Air Mass 0 (AM0) since this light has not passed through the atmosphere. The irradiance of this light is the already mentioned 1361 W/m2, the solar constant. When the sunlight passes through the atmosphere the spectrum changes, see Figure 2.30 [1].

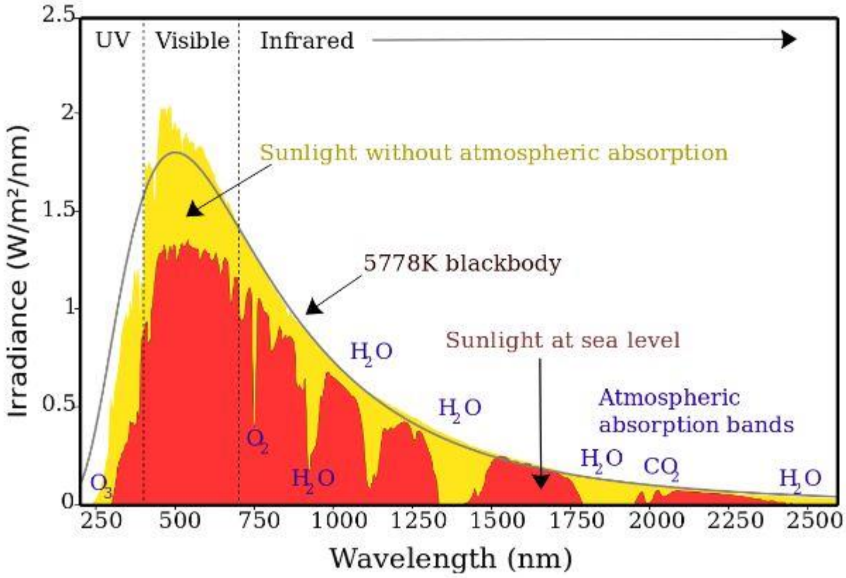


**Figure 2.30**. Solar radiation spectrum for direct light at both the top of Earth's atmosphere (yellow area) and at sea level (red area). As light passes through the atmosphere, some are absorbed by gases with specific absorption bands [1]

There are various reasons for this change:

- Reflection of light: Sunlight is reflected in the atmosphere reducing the radiation reaching the Earth.
- Absorption of light: Gases ($O_2$, $O_3$, $H_2O$, $CO_2$ …) with specific absorption bands absorb a part of the radiation causing gaps in the spectrum (see Figure 2.30).
- Rayleigh scattering: When light falls on particles smaller than the wavelength Rayleigh scattering occurs.
- As the effect is strongly wavelength-dependent, shorter wavelengths are scattered strongly causing the blue color of the sky.
- Scattering of aerosols and dust particles: This effect is a Mie scattering event and concerns particles larger than the wavelength.

The number of aerosols and dust particles depends greatly on location, being greatest in industrial and densely populated areas. As the effect of the atmosphere is dependent on the length of the path through the atmosphere, it is necessary to designate different spectra according to the path through the atmosphere.

Therefore, we use the term Air Mass (AM) followed by a number indicating the distance through the atmosphere. AM0 is the spectrum outside the atmosphere. AM1 is the spectrum after it has traveled the vertical height of the atmosphere.

If the sun is at an angle to the Earth's surface, the effective thickness will be greater. AM1.5 atmosphere thickness corresponds to a solar zenith angle of z=48.2° and indicates that the light has traveled 1.5 times the vertical path through the atmosphere. The specific value of 1.5 has been selected in the 1970s for standardization purposes, based on an analysis of solar irradiance data in the United States. Since then, the solar industry has been using AM1.5 for all standardized testing or rating of terrestrial solar cells or modules. When we sum the energy according to the AM1.5 spectrums in figure 2.30, we find that only 835 W/m2 is received.

Thus, only 61% of the originally available 1367 W/m2 is received at Earth as direct radiation. However, it is important to note that we are now forgetting a large portion of radiation, namely the diffuse radiation caused by the scattering of the light in the atmosphere.
To account for this, we use the AM1.5G spectrum, where G stands for global radiation and is a summation of the direct and diffuse radiation. This is the reason we use 1000 W/m2 as the total irradiance when we determine the peak power of a solar module[1].

## 2.16. PROPERTIES OF SOLAR CELLS

### 2.16.1. Properties of photovoltaic circuits

A photovoltaic cell's equivalent circuit is given below:

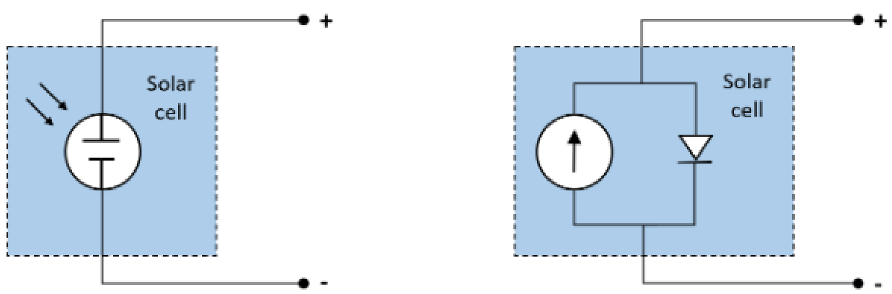


**Figure 2.31** Schematic representation of a solar cell (left) and a simplified electrical equivalent circuit with one diode (right) [1, 49]

To understand the electronic behavior of a solar cell, it can be useful to create an electrically equivalent model. In Figure 2.31 left, you can see a schematic representation of a solar cell, and to the right is a simplified electrical equivalent[49]. We call this the simplified equivalent circuit. The electrical behavior of the equivalent circuit can be expressed mathematically by considering Kirchhoff's circuit law [1].

$$I = I_{ph} - I_D \tag{2.12}$$

$I_{Ph}$ is the photocurrent and $I_D$ is the current running through the diode. By substituting in the formula for the Shockley diode equation, we get the following

$$I = I_{PH} - I_S\left(e^{\frac{V_D}{nV_T}} - 1\right) \tag{2.13}$$

$I_S$ is is the saturation current of the reverse bias, $V_D$ is the diode voltage, $V_T$ is the heating voltage (kT/q, Boltzmann constant times temperature divided by electron charge), and n is the diode ideality factor[1, 49].

(n) Typically varies from 1 to 2 (in some cases can be higher), depending on the fabrication process and semiconductor material. As found in real transistors, the ideality element accounts for imperfect junctions and primarily for carrier recombination [1, 49]. When (n is 1), the equation is called the Shockley ideal diode equation. The characteristic curve shows the current and voltage (IV) characteristics of a solar cell or module giving a detailed description of its solar energy conversion ability and efficiency, (Figure 2.32) [10].

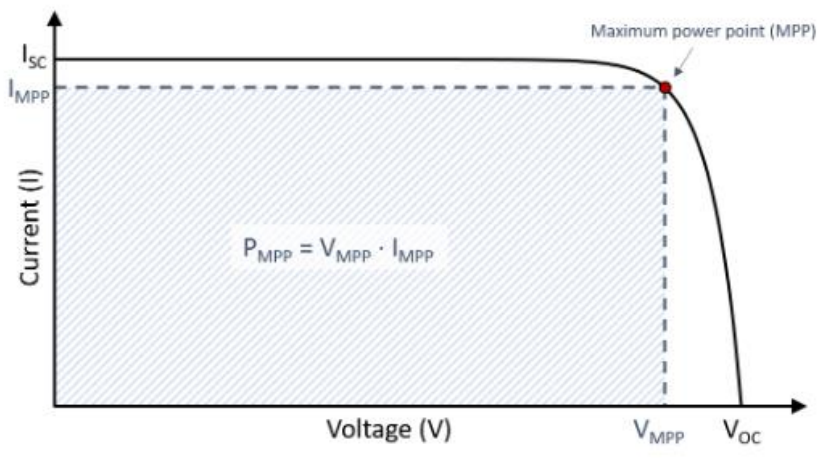


**Figure 2.32** Characteristic I-V curve for solar cell[1, 10].

The short circuit current($I_{SC}$), an open-circuit voltage($V_{OC}$)is marked along with the maximum power point current ($I_{MPP}$) and voltage ($V_{MPP}$) [1, 10]. This characteristics curve is most often called an IV-curve and is basically a graphical representation of the operation of the solar cell or module summarizing the relationship between the current and voltage at the existing conditions of irradiance and temperature. IV curves provide the information required to configure a solar system so that it can operate as close to its optimal peak power point as possible [1, 10, 49].

It is easy to measure two of the characteristic values of the IV curve, namely the open-circuit voltage ($V_{OC}$) and the short circuit current ($I_{SC}$) with a simple multi-meter. The solar cell's open-circuit voltage is the maximum voltage supplied by the solar cell, while a solar cell's short circuit current is the maximum current produced by the solar cell [1].

The problem with the two cases, $I_{SC}$ and $V_{OC}$, is that a solar cell's most interesting aspect is not the current flow with no potential drop, nor the potential drop without current flow, but the result of these two. When either the potential drop or the current flow is zero, the power, being the product of the two, will be zero. Therefore, the maximum power the solar cell can generate is a more interesting aspect. Let us now look at the current of the short circuit and the open-circuit voltage described in the above formula (2.13) [1, 10]**.**

- **Short circuit current:**

As we know from the last module, a short-circuited solar cell (the contacts are directly connected) delivers the short circuit current ($I_{SC}$) and the voltage is zero. With the simplified equivalent circuit equation, this results in

$$I_{SC} = I(V = 0) = I_{PH} - I_S(e^0 - 1) = I_{PH} \qquad (2.14)$$

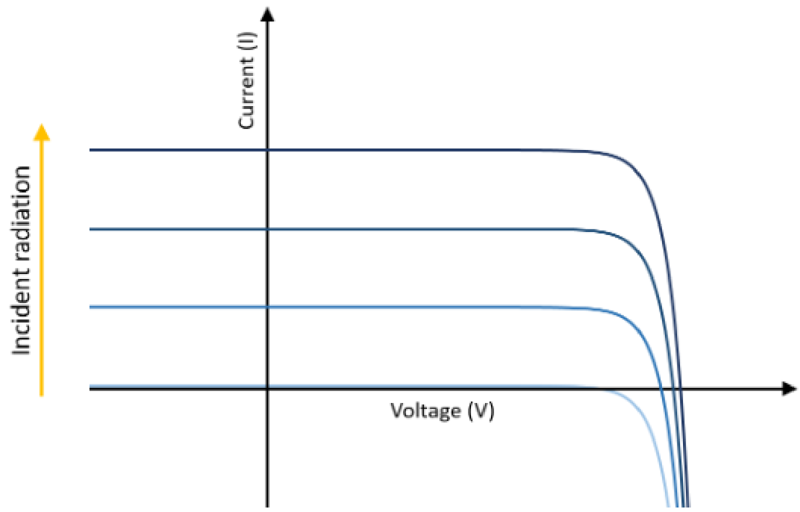


**Figure 2.33** Characteristic curve (IV curve) with increasing incident radiation[1].

In figure 2.33, the characteristic solar cell curve as a function of increased incident irradiance[1, 10]. Thus, we know that the short circuit current ($I_{SC}$) is equal to the photocurrent ($I_{Ph}$). We can, in fact, see this result directly from looking at the equivalent circuit (Figure 2.31**)**, since an external short circuit also short circuits the internal diode (meaning $I_D$=0). The photocurrent is directly proportional to the number of photons hitting the solar cell and thus the short circuit current is proportional to the irradiance [10].

- **Open circuit voltage:**

The other extreme case aside from the short circuit current is the case when the current becomes zero. We call this case the open-circuit voltage, see figure 2.32. To determine the $V_{OC}$, we need to solve the equivalent circuit equation for the case when the current is 0 [1].

$$V_{OC} = V(I=0) = n \cdot V_T \cdot ln\left(\frac{I_{PH}}{I_S}+1\right) = n \cdot V_T \cdot ln\left(\frac{I_{PH}}{I_S}+1\right) \tag{2.15}$$

Remember that the photocurrent equals the short circuit current ($I_{Ph}$=$I_{SC}$). The +1 term inside the logarithm can be ignored for anything above extremely small currents, so an approximate version of the equation can be written as:

$$V_{OC} \approx V(I=0) = n \cdot V_T \cdot ln\left(\frac{I_{SC}}{I_S}\right) \tag{2.16}$$

Thus, we can see that the irradiance dependency of $V_{OC}$ to incident radiation is much lower for $V_{OC}$ as compared to $I_{SC}$. In fact, the open-circuit voltage changes with the natural logarithm of the irradiance (remember that the photocurrent is proportional to the irradiance). You can also see this in figure 2.33, as the $V_{OC}$ is only slightly affected by decreasing irradiance [1, 10, 49].

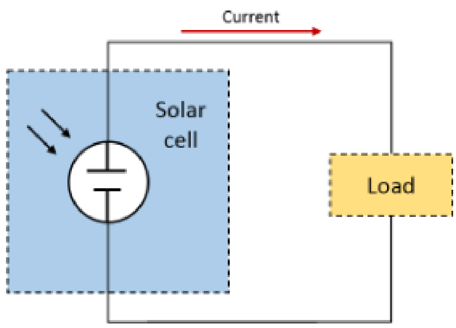


**Figure 2.34** Schematic of the solar cell with a load. An IV curve is obtained when the load is varied and the voltage and amperage is recorded [1]

By increasing the resistive load on a solar cell continuously from zero (short circuit) to a very high value (equivalent to the open circuit) one can determine the maximum power point, see Figure 2.34 Plotting the power as the result of the voltage in the blue curve. See figure 2.35, where the highest point of the power curve is the maximum power point ($P_{MPP}$).

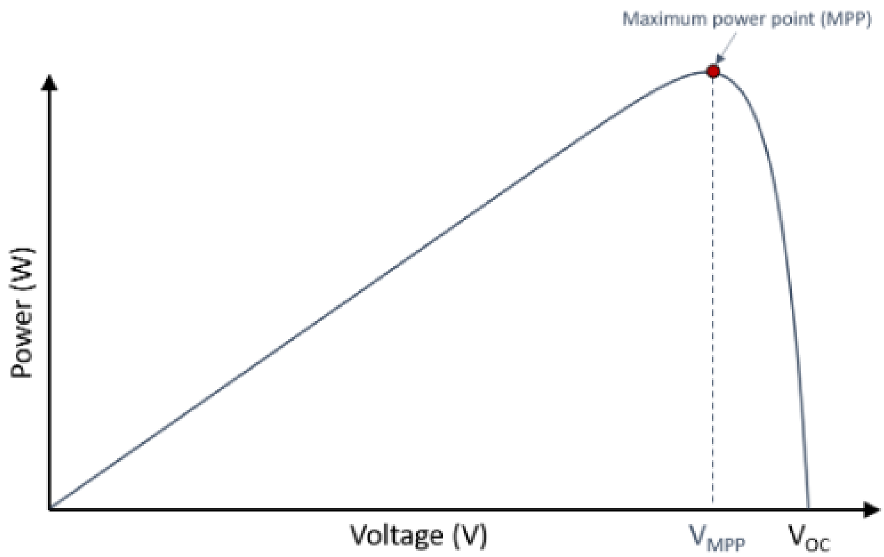


**Figure 2.35** Power curve for a solar cell. The power is the product of the voltage and the current [1]

A high-quality monocrystalline silicon solar cell may produce 0.55 V open-circuit ($V_{OC}$), at 45°C cell temperature (and a slightly higher voltage at lower temperatures), however, the maximum power is typically produced with 75% to 80% of the open-circuit voltage and 90% of the short-circuit current [1, 10].

If solar cell vendors only rate their solar cell "power" as $V_{OC} \cdot I_{SC}$, without giving load curves, the actual performance can be seriously distorted. The value linking the product of $V_{OC}$ and $I_{SC}$ to $P_{mpp}$ (maximum power point) is the fill factor (FF) [10]

$$FF = \frac{P_{mpp}}{V_{OC}.I_{ISC}} \tag{2.17}$$

The fill factor is used as a quality parameter for solar cells and has a value of around 80% for a normal silicon PV cell. The main parameter extracted from the IV curve is the power conversion efficiency (PCE), which characterizes the solar cell's overall efficiency; that is the ratio of electricity generated to incoming light energy [1, 10]. It can also be expressed in terms of the open-circuit voltage, the short circuit current, and the fill factor.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{OC}.O_{ISC}.FF}{P_{in}} \tag{2.18}$$

we now focus on the power output of the solar cell, as we may remember we can express the input power in terms of the area of the solar cell and the solar constant as [1].

$$Pin = \sigma * A \tag{2.19}$$

### 2.16.2. How Can We Measure the I-V curve?

The simplest way is using a resistive load, which is a variable resistor. With this, you are changing the resistance or the impedance that the PV device sees. Now you are changing towards the near-zero resistance so $I_{SC}$, and you change it to almost indefinite resistance, which is the curve's $V_{OC}$ point. If you flip the resistor in the reverse direction, the curve from the $V_{OC}$ to the $I_{SC}$ can be measured. That would be the least expensive and most basic I-V measurement method [1].

You would use something like a two-quadrant electronic charge or a four-quadrant power supply to get a more accurate estimate of the IV curve. One of the purposes, why it is more accurate than a variable resistor, is that you can get a better $I_{SC}$ rating. When using an electronic charge, the PV unit is considered an optimal current source, a stable current source. Thus, the agreement with constant current sources is to load them in voltage. We keep the load in constant voltage mode, we step in voltage and measure current from $I_{SC}$ to $V_{OC}$.

However, the big difference between using a resistive load and electronic load is that we cannot get the full IV curve with the resistive load. First, the $I_{SC}$ value is difficult to obtain because we need high resistance. The other problem is; the full IV curve cannot be obtained because we cannot move below zero volts, and we cannot go beyond the $V_{OC}$ value. By the electronic load, we can do this and we can draw the full IV curve, and from the full IV curve, we can extract more data than we could otherwise [1].

### 2.16.3. Measuring Power Using an Electronic Load

We need to apply a resistive load to the solar cell before we can measure its power production. We will substitute this resistive load with an electronic load, by using a source measure unit. A source measure unit (also called an SMU or source-meter) outputs a voltage and measures the current that flows.

A bench-top power supply would be able to fulfill this role; however, most source measure units are programmable and allow the user to sweep the voltage over a defined range making the IV curve measurement automatic. It is also possible to supply a current and measure the voltage, however, this is not typically done for solar cells since the voltage is typically predictable for a given device[1].

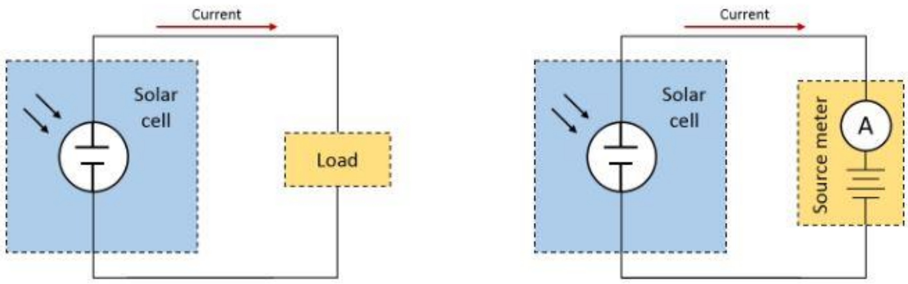


**Figure 2.36** An illuminated solar cell causes a current to flow into the load (left). The source meter acts as a load and sinks the current (right)[1].

A specific advantage of using a source measure unit over a resistive load is that the source measure units can drive the solar cell with negative voltage or voltages higher than the open-circuit voltage of the solar cell. This results in an extended I-V curve

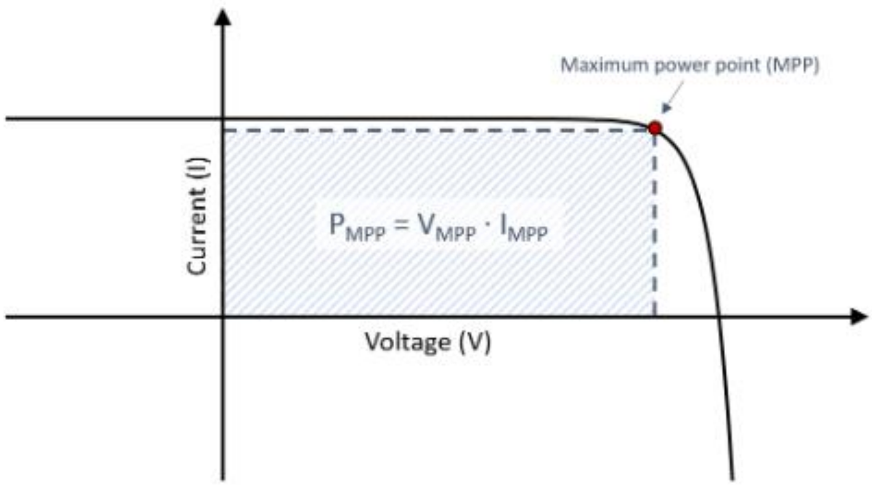


**Figure 2.37** Full IV curve. The maximum power point is shown with a red dot [1]

### 2.16.4. Series and Parallel Connections:

When we use solar cells, we typically connect more than one solar cell to increase the power produced. When we make these connections, it is important to understand how the current and voltage adds together depending on the connection. There are two ways to connect solar cells, parallel and series connections [1].

- **Parallel connection:**

In a parallel connection all cells are forced to have the same voltage, while the currents are added up.

$V = V_1 = V_2 = \cdots = V_n$ and $I = I_1 + I_2 + \cdots + I_n$

Figure 2.38 shows a module of solar cells connected in parallel. On the left you can see the characteristic curves of modules consisting of three, two, and one cell [1, 50].

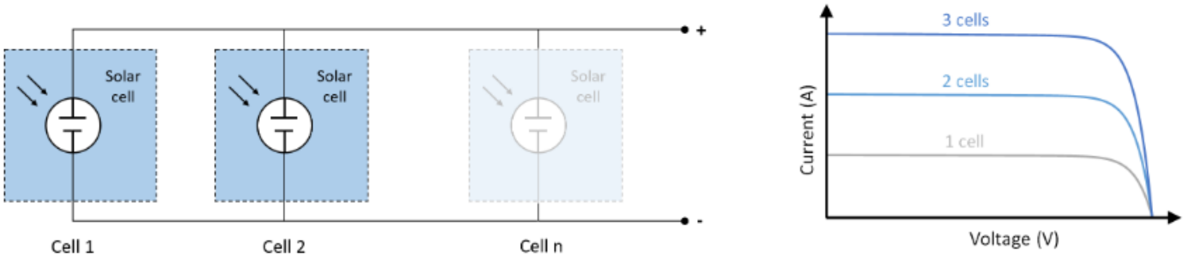


**Figure 2.38** Parallel connection of solar cells. For each cell, the voltage will be the same, while the current is added from each cell [1, 50]

- **Series connection:**

When cells are connected in series the current for each cell will be the same, while the voltages are summed.

$$I = I_1 = I_2 = \cdots = I_n \text{ and } V = V_1 + V_2 + \cdots + V_n$$

In Figure 2.39, you can see a module with serially connected solar cells and a characteristic curve for three, two, and one connected cell [1, 50].

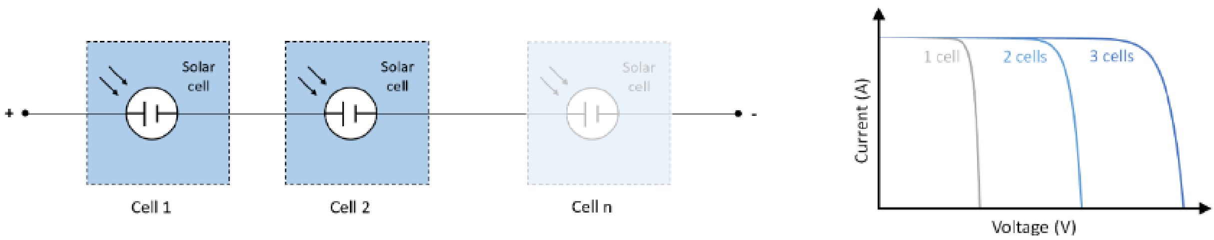


**Figure 2.39** Series connection of solar cell. For each cell, the current is the same, while the voltage is added from each cell [1, 50]

We typically see series connections of cells in modules since this ensures higher voltages. If we try to imagine a solar cell module consisting of 100 cells each having a voltage of 0.6 V and a current of 4 A, we can connect all cells in either parallel or serial connection. In the case of a parallel connection, the module voltage would be 0.6 V and the current 400 A.

In the case of a serial connection the voltage would be 60 V and 4 A., In either case, the power is the same, however, the transport losses would be significantly different. If we consider Ohm's law and the power law, we see that the power loss to a wire scales with the current squared.

Therefore, we would need extremely thick cables if we were to transport high current at low voltages. Conversely, high voltages and low currents give much lower transmission losses high voltages, low currents give much lower transmission losses, and thinner cables are required [1, 50].

### 2.16.5. Shadow Effects:

It is important to consider what happens when one or more solar cells in such connections are in shadow. In figure 2.40 you can see how a shaded cell in a module affects the overall module performance. To draw this plot, it is assumed that the shaded cell is 90% shaded. From earlier we know that a shaded cell's open-circuit voltage varies just a little, while the short circuit current decreases by around 90 %. The overall IV curve for a module decays with roughly the amount of current loss from the one shaded cell. Thus, the overall power loss of the module corresponds to the shaded area. This means that a parallel connection is nicely behaved in partial shading losing only the shaded area [1, 50].

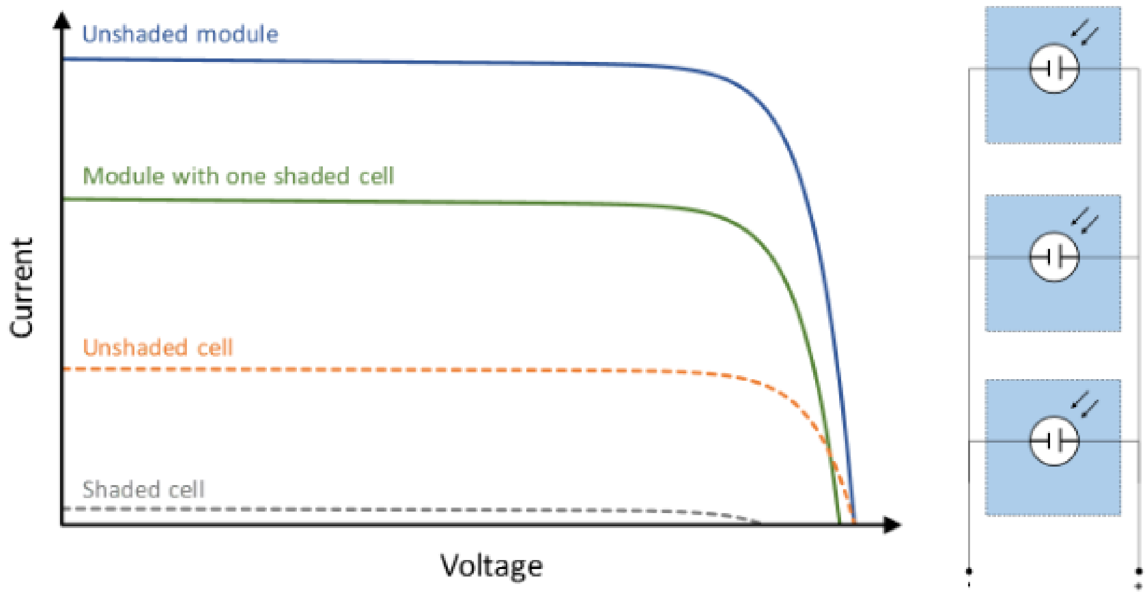


**Figure 2.40** A module consisting of three cells connected in parallel [1, 50]

When all cells are illuminated, the blue IV curve is obtained. When one module is in shadow, the module IV curve corresponds to the green curve. You can see the IV curve of a single unshaded cell (dotted orange) and a single shaded cell (dotted grey).

While the parallel connection is relatively good-natured when it comes to partial shading, the same cannot be said for a series connection, as can be seen from Figure 2.41.

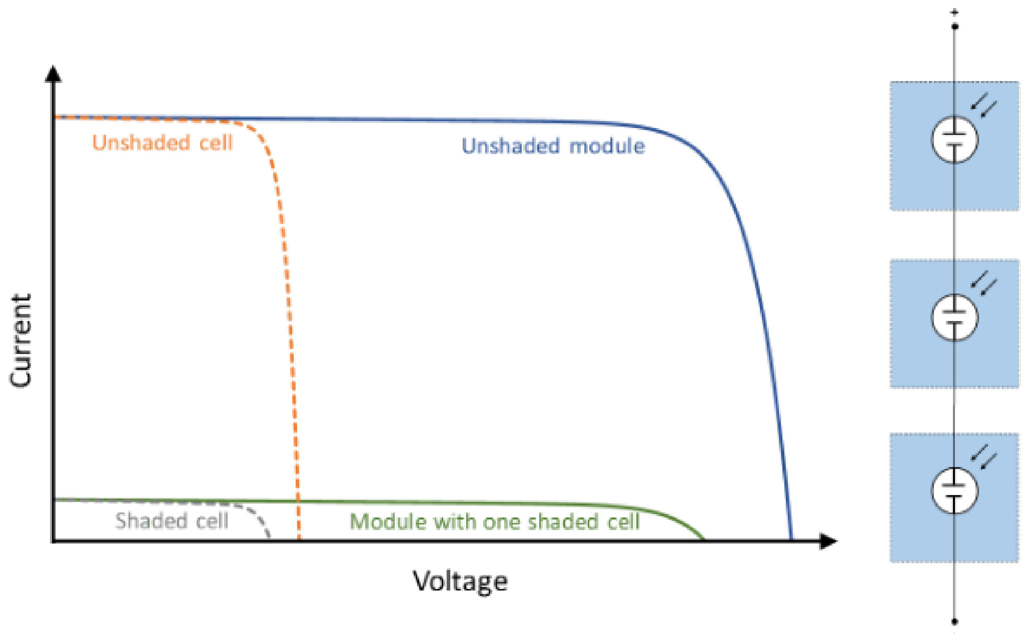


**Figure 2.41** A module consisting of three cells connected in series [1]

With one shaded cell in the series connection, the two other cells must push their current through the shaded cell. This causes a negative voltage over the shaded cell. The current is limited by the shaded cell and therefore the overall current of the module is limited. As can be seen from figure 2.41, this effect reduces the power output from the module with a single shaded cell significantly [1, 50].

When all cells are illuminated, the blue IV curve is obtained. When one module is in shadow, the module IV curve corresponds to the green curve. You can see the IV curve of a single unshaded cell (dotted orange) and a single shaded cell (dotted grey).

A solution to the problem with the series connection is to employ a bypass diode over the shaded cell, see figure 2.42. Bypass diodes allow current to pass shaded cells and thereby reduce the voltage losses through the module. When a module becomes shaded, its bypass diode begins to conduct current through itself.

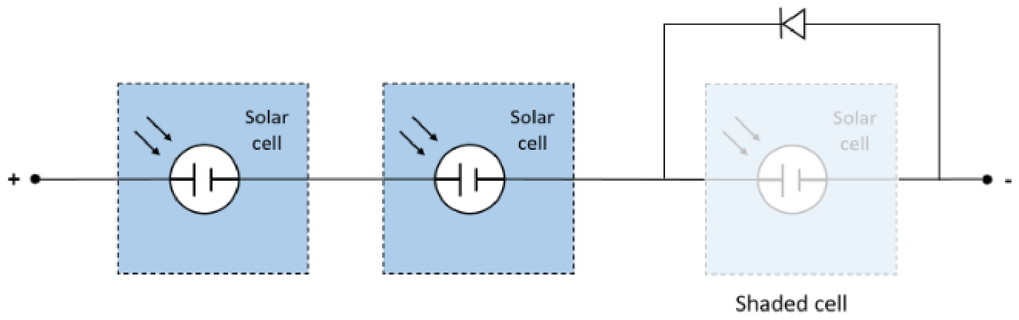


**Figure 2.42** Bypass diode mounted over the shaded cell. The bypass diode drastically reduces the losses caused by the partial shading.[1, 50]

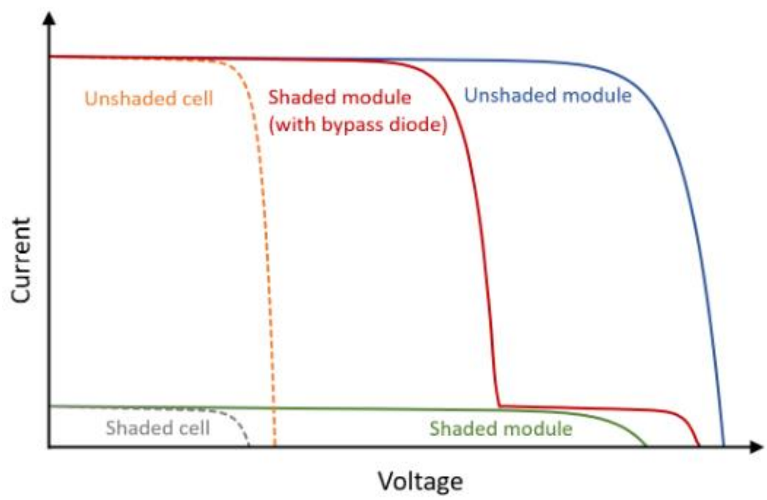


**Figure 2.43** I-V curve of a module consisting of three cells connected in series[1].

With the bypass diode, the current is no longer limited by the shaded cell, and the impact on the overall IV curve is greatly reduced, see Figure 2.43. When all cells are illuminated, the blue IV curve is obtained. When one module is in shadow, the module IV curve corresponds to the green curve without any bypass diode and to the red curve with a bypass diode. You can see the IV curve of a single unshaded cell (dotted orange) and a single shaded cell (dotted grey).

Bypass diodes also serve another purpose, namely the prevention of hotspots. In modules with one shaded cell and no bypass diode, there will be massive heating of the shaded cell caused by the other cells, the usage of bypass diodes alleviates this problem. In real solar modules, bypass diodes are not employed for each cell.

The reason is that the diodes would have to be incorporated into the encapsulation if the solution should be practical. Instead, bypass diodes are employed for strings of cells (e.g. 12, 18, or 24 cells). It is therefore important that modules are not mounted in places were partial shading is expected during the day. Figure 2.44 illustrates how to configure cells into modules and how to connect modules as arrays [1].

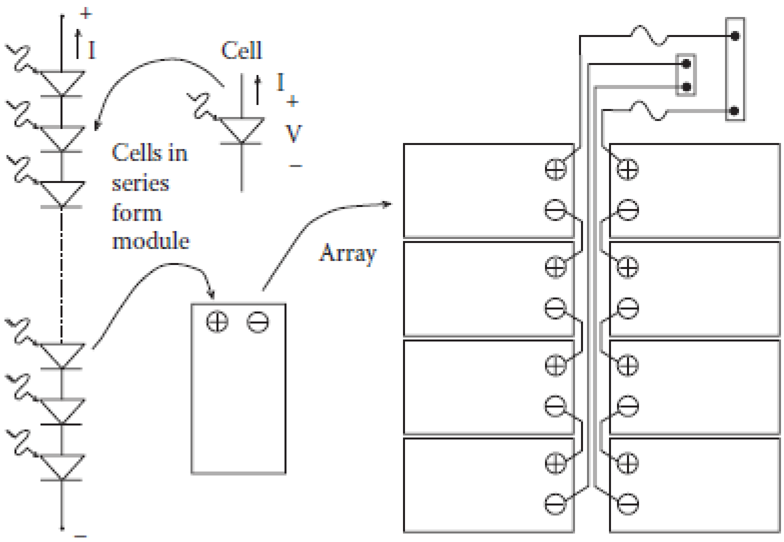


**Figure 2.44** Cells, modules, and arrays[10, 50]Figure 2.45 shows the components of several types of PV systems.

Figure 2.46 shows the ideal I–V characteristics of a typical PV cell.

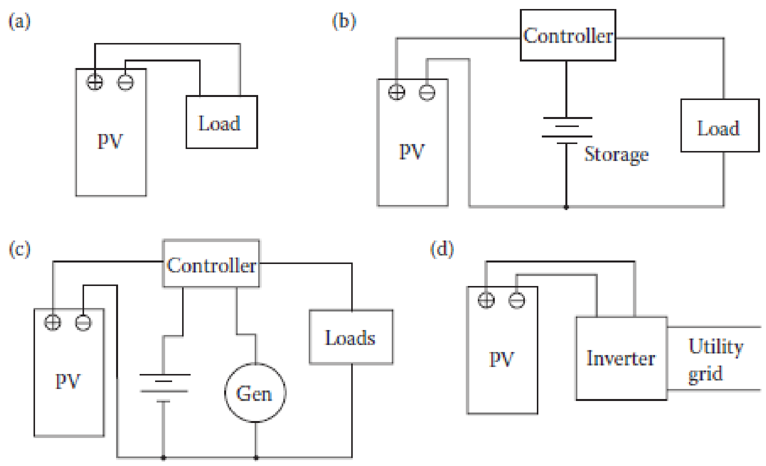


**Figure 2.45** Examples of PV systems. (a) PV connected directly to load. (b) Controller and battery storage included. (c) A system with battery storage and backup generator. (d) Grid-connected system[10].

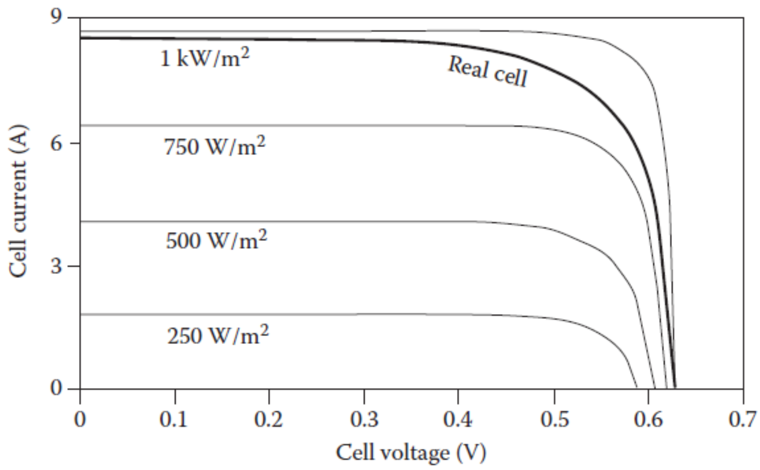


**Figure 2.46,** I–V characteristics of real and ideal PV cells under different illumination levels[10]

Note that the value of voltage and current are obtainable from the cell depends on the level of illumination of the cell.

### 2.16.6. Best Research-Cell Efficiencies Chart:

A record-efficient organic solar cell advanced through an environmentally friendly method by a research team of the Hong Kong University of Science and Technology (HKUST) was placed on the famous chart "Best Research-Cell Efficiencies Chart" by the United States National Renewable Energy Laboratory. On this historic list, which tracks all the best efficiency cells in the world over the past 40 years, this solar cell is built by a Hong Kong institution [51].

The chart that has collected rates of the highest transmutation efficiencies for various kinds of solar cells since 1976, in 2016 posted "Hong Kong UST" as the newest world record for emerging organic solar cells, an organic solar cell with efficiencies of up to 11.5% [51]. A very essential feature of the HKUST solar cell is that it does not involve any toxic substance or use any harmful solvent during the production process, making it the first example of organic solar cells that are manufactured in an environmentally friendly way. While organic solar cells do not involve toxic elements, high-performance cells could only be produced with hazardous solvents, thus hindering the development of such cells.

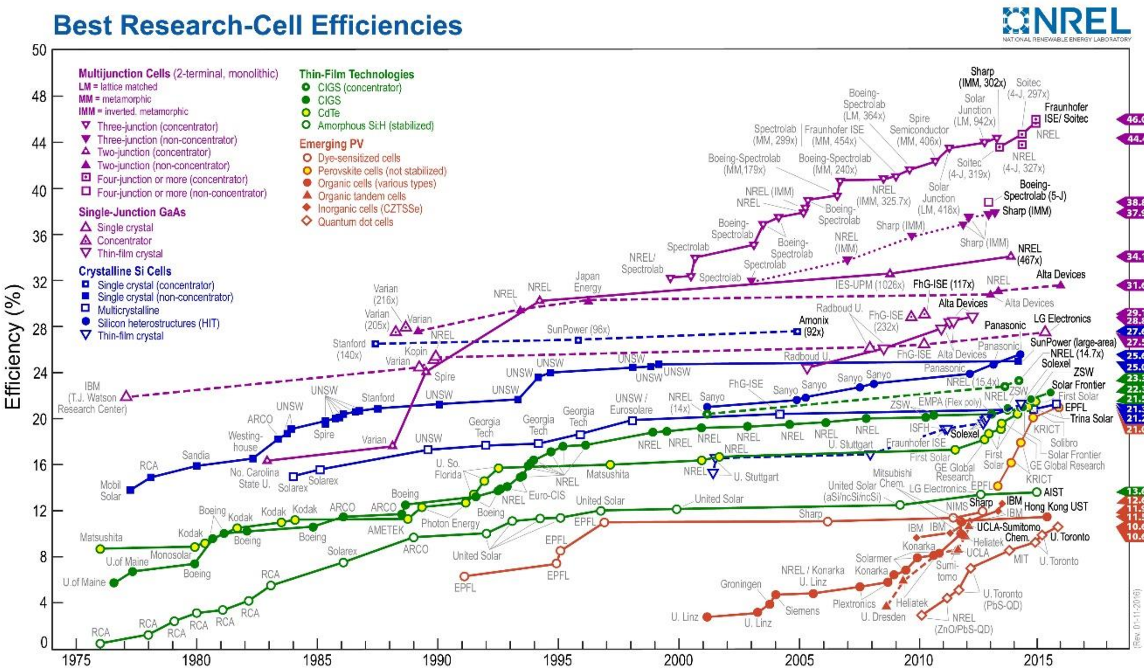


**Figure 2.47** new world-record efficiency of perovskite solar cells [22, 51]

The term perovskite takes place from a metal that was first discovered by Gustav Rose in Russia's Ural Mountains in 1839 and then renamed L by a Russian mineralogist L. A. Perovski (1792–1856) [18].

In inorganic perovskite solar cells, many types of Electron Transporting Layer (ETLs) such as $SnO_2$, $TiO_2$, C60, and $ZnO_2$ are used. However, $TiO_2$ and $SnO_2$ are commonly used. $SnO_2$ is now gaining more interest due to its deeper conductive band and higher electron mobility compared to traditional $TiO_2$, which could boost the transfer of charges from perovskite to electron transport layers and reduce the cumulating of charges at the interface [18]. In the study carried out by Zhou's group, it has been shown that perovskite solar cells (PSCs) based on $SnO_2$ ETL with interfacial layer $MoO_3$ have significantly increased performance, heat stability, light-saving stability and long-term stability [18].

In 2018, the pioneer in perovskite solar cells declared a new world record for its solar cell based on perovskite. The 1 $cm^2$ perovskite-silicon tandem solar cell of Oxford PV has accomplished an efficiency of 28 % authenticated by the National Renewable Energy Laboratory.

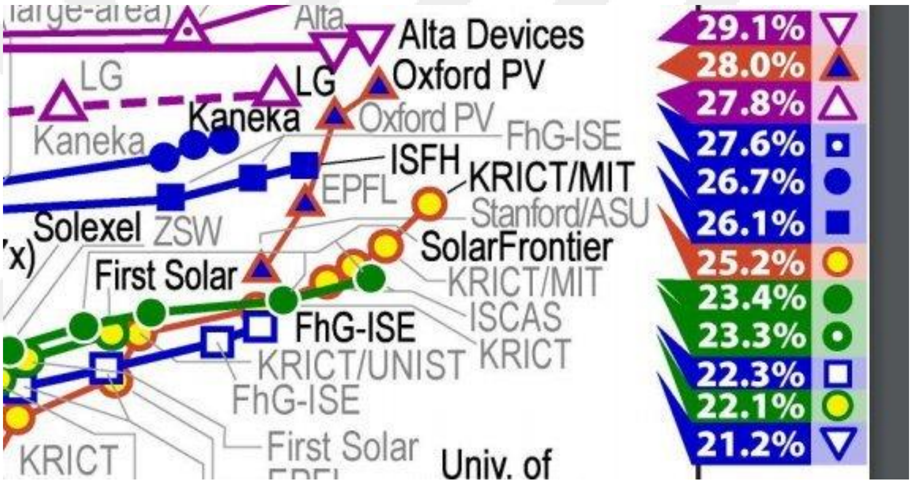


**Figure 2.48** solar cell of Oxford PV

# 3. METHODOLOGY AND METHODS:

## 3.1. SELECTION OF PV MODULES EFFICIENCIES:

There are two technologies are used in photovoltaic technology: Crystalline shape and amorphous silicon. The amorphous is indeed a new study and can, therefore, take a longer time to achieve optimal implementation. There are two types of photovoltaic cells in the crystalline silicon technology, which are Mono-crystalline cells and Poly-crystalline cells:

### 3.1.1. Monocrystalline Cells

Monocrystalline solar cells are made of a sliced disk of single-crystal to create all the wafers in the panel. It features a uniform blue color. Other attributes involve:

- Efficiency 15-20 % of solar panels technologies nowadays.
- Most costly cells because it is improved from purely crystal.
- The cells are solid and must be properly placed and mounted on a solid upholding [6, 57].

### 3.1.2. Polycrystalline Cells

These are renowned as multy-crystalline cells and are produced in a square module by casting the silicon. Then the consequent cast is sliced into several square wafers. The square block consists of several crystals consisting of a range of blue differences. This technology causes the brilliant, gemstone-like surface of some solar panels on the market nowadays of some panels. Polycrystalline cells have distinguishing characteristics, such as:

- 13-16 % efficiency somewhat less effective than monocrystalline cells.
- Less expensive than monocrystalline.
- Less loss of material (purified silicon).
- The polycrystalline panel is a little wider than the monocrystalline counterpart for the same design [6, 57].

So choosing the most appropriate solar photovoltaic panels, I made calculations about many different panels. Moreover, get the two most suitable ones, which are both producing electricity maximum, and cheap price. As we know, the most efficient one's mono and poly–Crestline panels and I will show at the table.

**Table 3.1** specification of two solar panels type [58]

| **Mechanical Characteristics** | | |
|---|---|---|
| Name | Yingli Solar YL210P-29b | Solar world Sunmodule Plus SW 280 Mono |
| Type | Polycrystalline Silicon | Monocrystalline |
| Module Efficiency | 12,7 | 16,7 |
| Frame Color | Clear | Clear |
| Length | 1.650mm (65in) | 65,94in (1675mm) |
| Width | 990mm (39in) | 37.44in (951mm) |
| Depth | 50mm (2in) | 1,22in (31mm) |
| Weight | 19,8kg (43,6lb) | 39.5 lbs (17.9 kg) |
| **Warranty and Certifications** | | |
| 80% Power Output Warranty Period | 25yrs | 25yrs |
| Workmanship Warranty Period | 5yrs | 10yrs |
| Price ($) | 320 | 400 |

Generally, monocrystalline panel types most efficient panel. Usage is also in Europe again the percentage the highest one and we are going to use our project's most efficient one this mono-crystalline panel. As price suitable, installation of panel easier etc.

## 3.2. TRACKING THE SUN:

### 3.2.1. General Description:

Let me introduce you to (active solar tracking system) AST-02&3 from MIDDLETON SOLAR, which can automatically track the sun to an accuracy of 0.02°, see Figure 3.1.

**Figure 3.1,** AST-02 active solar tracking system [54]

The AST-02 and AST-03 Active Solar Trackers have a Pan & Tilt Gearbox with integrated Single Board Computer and Global Positioning System (GPS). The included high-contrast Eye allows the Tracker to always stay locked onto the sun for effective real-time active tracking. It is designed to accurately point solar radiometers at the sun throughout the day [54].

The AST-02 has a single horizontal arm; The AST-03 type has dual horizontal arms. The horizontal axis and the vertical axis are each rotated by a stepper motor that is directly connected to a harmonic gearhead with zero backlashes. The Eye responds only to a narrow bandwidth of near-infrared radiation, to give a very high contrast between clear sun and cloud, for excellent sun tracking in real-time.

The GPS signal is used to automatically configure the Tracker for any geographic location and to provide precise time synchronization. Whenever the sun is obscured (by clouds) the system defaults to open-loop passive tracking using GPS position information.

Whenever the sun is detected by the Eye the system actively tracks the sun under closed-loop control, and any accrued passive position error is corrected. The Tracker halts shortly after sunset, then at midnight (solar time) reverses to the dawn position ready to resume tracking shortly before sunrise.

The Tracker operates on 12VDC, and has a low power requirement of 10W, making it suitable for solar-powered sites. The User interface consists of a single Status light to provide information about the normal operation of the Tracker and also indicate warning or error states [54].

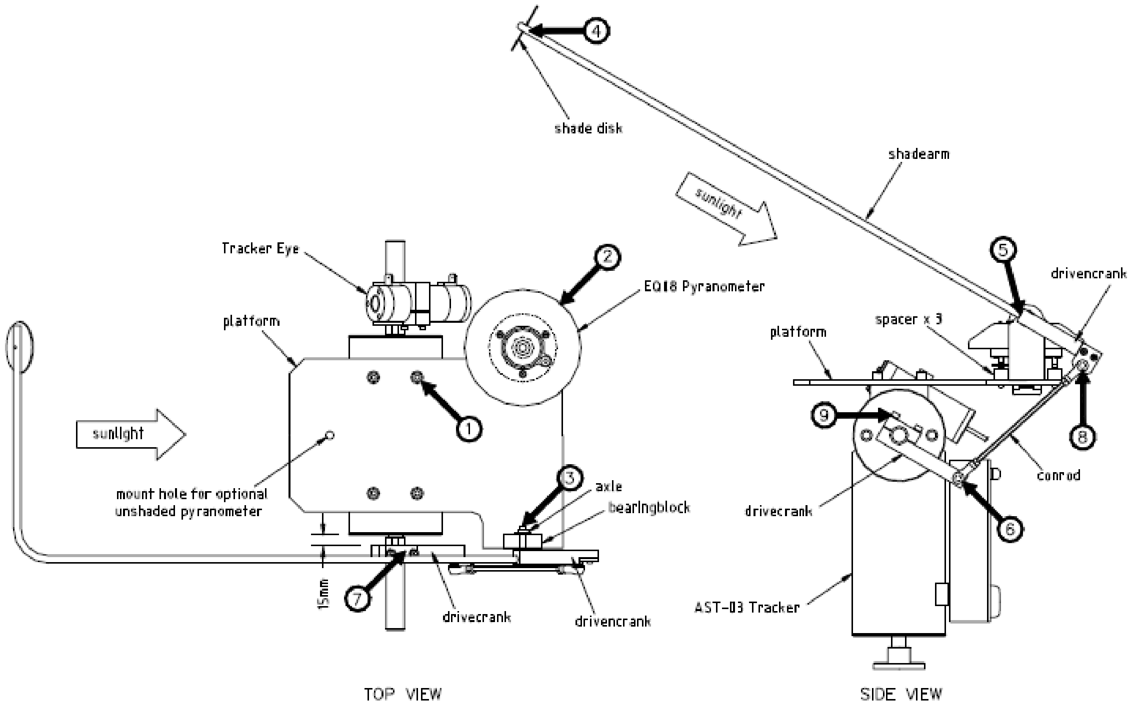


**Figure 3.2,** components of AST-03 active solar tracking system[54]

Available options include:

- LS01 Levelling Stand;
- LP01 Levelling Plate;
- PA01 Pan Axle Extension (25mm diameter);

- PM02 Pyrheliometer Mount;
- PM04 Dual Pyrheliometer Mount;
- PY01 Pyranometer Tilt Mount;
- SA02 Shading Arm Assembly, with instrument platform (for diffuse solar measurement by pyranometer).
- Status Output Lead (see Appendix G)

Middleton Solar radiometers that are suitable for the AST-02/3 Tracker include:

- DN5/E Pyrheliometers;
- SP02/L Sun photometers;
- EQ08/E & EQ08-S/E Pyranometers.

The figure above shows the AST-03 Tracker with the optional SA02 Shading Arm Assembly, and the optional LS01 Levelling Stand. The SA02 Shading Arm Assembly is an accessory for the AST-03 Active Solar Tracker, it can also be adapted for use on the AST-02 Tracker, The SA02 provides a means to measure diffuse solar radiation with a pyranometer by continuously shading it from direct solar radiation [54].

### 3.2.2. Performance Specification of AST-02&03:

**Table 3.2**, performance specification of AST-02&03[54]

| | |
|---|---|
| tracking accuracy | active (sunshine), 0.02°<br>passive (no sunshine), 0.15°(passive accuracy valid for sun elevation > 5°) |
| angular velocity | 9°/sec. (max.) |
| Rotation | vertical/pan/azimuth axis = ±250° (0° = true North/South) horizontal/tilt/zenith axis = +100°, -15° (0° = horiz, 90° = vert) |
| torque (at 12VDC) | AST-02 = 12Nm<br>AST-03 = 12 x 2 = 24 Nm |
| Payload | AST-02 = 10kg<br>balanced AST-03 =<br>20kg balanced |

### 3.2.3. Advantages of AST-02&03:

It locks onto the sun using a quadrant Eye and a smart positioning algorithm. Ideal for sun-photometers, diffuse pyranometers, and pyrheliometers (DN5 Pyrhelio-meter requires PM02/4 pyrheliometer mount; EP08 series Pyrano-meters require SA02 Shade Arm Assembly). In-built computer controller, with GPS for automatic location configuration. Very low power requirement; ideal for solar-powered battery operation.

### 3.2.4. Detailed Specification Of Active Solar Tracker:

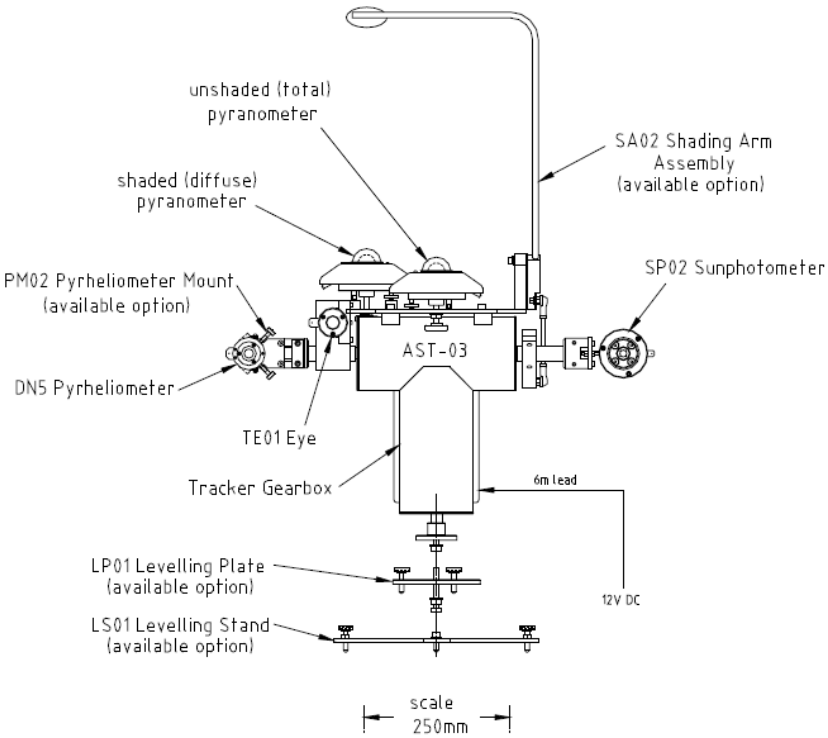


**Figure 3.3,** components of AST-03 active solar tracking system[54]

Swaps between active tracking and passive tracking depending on cloud cover. The eye responds only to narrowband NIR so it does not react to bright sun blurred by thin cloud. Four M8 threaded holes provided on top for fitting available options such as the SA02.

### 3.2.5. General Specification of AST-02&03:

**Table 3.3**, General Specification of AST-02&03[54]

| | |
|---|---|
| drive mechanism | direct harmonic gearing, zero-backlash |
| motor | stepping motor |
| horizontal axle | Ø25 x 130mm (AST-02 = 1, AST-03 = 2) |
| active tracking | quadrant Eye, real-time closed-loop control |
| active sunshine threshold | varies with solar zenith (sun elevation angle) |
| operating temperature | 0 to +50°C |
| power requirement | 12V DC nominal (11-16VDC), <10W continuous |
| power lead | 2-core, 6m |
| control method | in-built computer controller with GPS |
| user interface | status indicator LED; internal USB port |
| sealing | IP 65, all-weather |
| construction | aluminum & stainless steel |
| weight (standard configuration) | AST-02 = 10Kg; AST-03 = 12kg |
| shipping size & weight | 47x43x28cm; AST-02 = 12kg; AST-03 = 14kg |
| prices | AST-02: 15600$ , AST-03: 17400$ |
| standard configuration | Tracker Gearbox & Control Box, and TE01 Eye |
| available options(AST-02 type can accommodate either SA02 or PM02/4; use AST-03 type if both SA02 and PM02/4 are required) | LS01 Levelling<br>Stand LP01<br>Levelling Plate<br>PA01 Pan Axle Extension<br>(Ø25mm) PM02 Pyrheliometer<br>Mount<br>PM04 Dual Pyrheliometer<br>Mount PY01 Pyranometer<br>Tilt Mount<br>SA02 Shade arm Assembly &<br>Platform Status Output Lead (TTL<br>or RS232) |

### 3.2.6. Tracker Control States:

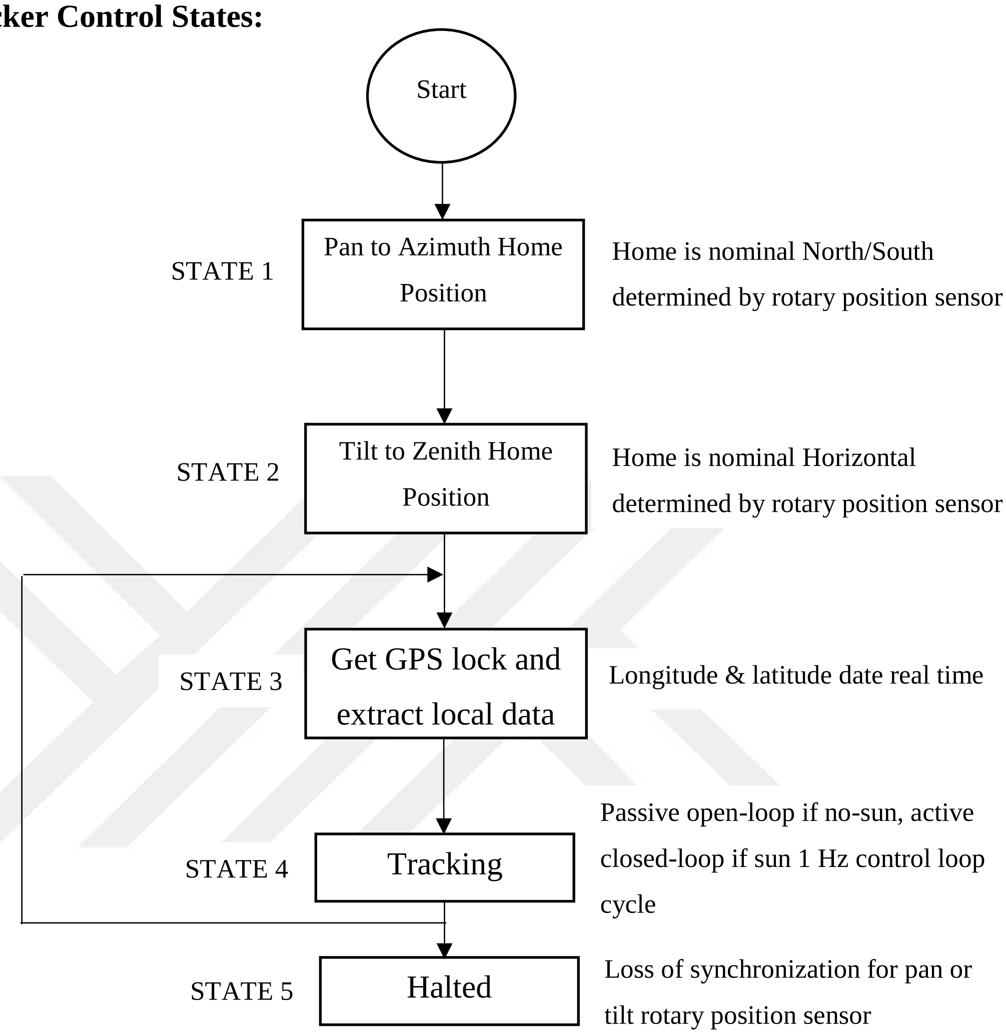


**Figure 3.4**, Tracker Control States

### 3.2.7. Dimensions:

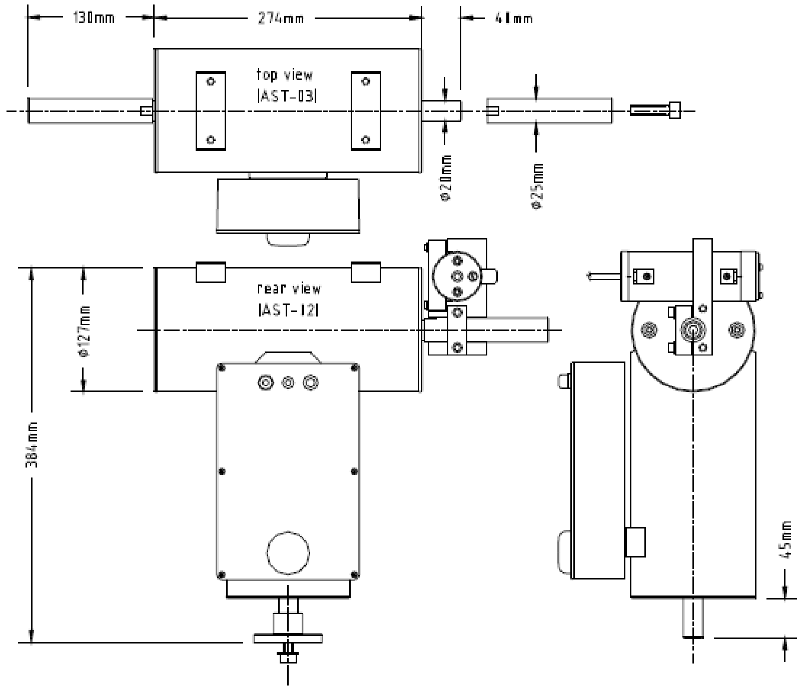


**Figure 3.5,** dimensions of AST-02[54]

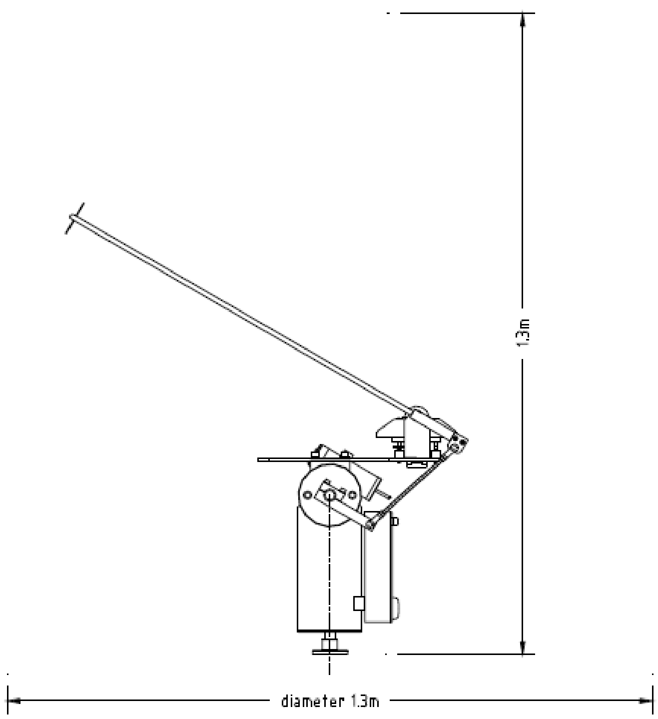


**Figure 3.6,** dimensions of AST-02[54]

### 3.2.8. How can we take advantage of this device?

Thanks to MIDDLETON SOLAR because they made it an open-source with an RS232 Type Status Output Lead, this lead provides access to a continuous RS232 stream of 26 internal Tracker control parameters, in CSV format, updated every second. Actually, we need to buy one device and we have to supply the panels with a Pan and Tilt Gearbox similar to the gearbox of AST-03, So we can take the orders that the CPU provides to gearboxes of panels.

The tracking method provides an increase of approximately 20 % in the solar energy received on the collector compared to the fixed-tilt arrangement of the latitude angled array [55].

## 3.3. AVOIDING SHADING FOR FIXED TILT OF SOLAR PANELS:

Indeed a small quantity of shadow on a panel can considerably decrease the efficiency of the panel. It is therefore essential to select a location for the photovoltaic system where the panels remain unshaded for as long as possible [50].

This is simple if there are no items that could shade the panels, but on someday of the year, the location will likely have objects that could shade the panels. And also the designer of the panels must, therefore, use his familiarity with the Sun place to define when panels may be shaded [10, 50].

I have already talked about shaded cells before in **Section 2.16** but the solution that I mentioned is not enough, so we have already chosen a location (hill) where we are avoiding shading from the buildings but also we have to be aware from shading panels to each other when we are setting up them.

The first step is to solve Equations **(2.7)** and **(2.8)** for the Sun position and the array of panels is existing at 35°N latitude ($\phi$) and that it is wished to space between rows and columns such that panels do not shade each other between the hours of 8:30 a.m. and 3:30 p.m. Since the worst case will be on December 21, one only needs to know $\delta$, $\phi$=35°N, and $\omega$ for 8:30 a.m. Sun time to solve for $\alpha$ and $\psi$ [10].

Actually I will do it in the rows and columns of the array of solar panels, each row will be shifted by (x) with the previous one to be ensured there is no shading at all, also each column will be shifted by (x). Solving for δ and ω from (2.2) and (2.4) yields.

$\delta = 23.45^{\circ} \sin\left[\frac{360(n-80)}{365}\right], while\ n = 355$ Because 21 of December is the 355th of the year.

Thus $\delta = -23.45^{\circ}$

Moreover:

$$\omega = 15(12 - \mathrm{T}) = 15(12 - 8.5) = 52.5° \text{ ; T=8.5, it is 8:30 am.}$$

Thus, from Equation (2.7)

$$sin\ \alpha\ = \sin(-23.45)\ sin\ \phi + cos(-23.45)\ cos\ \phi\ \ cos\ 52.5 = 0.23$$

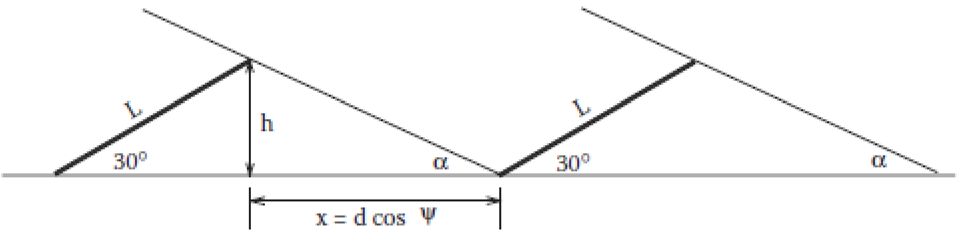


**Figure 3.7** determining the spacing between rows and columns of PV modules [10].

And, from Equation (2.8)

$$cos\ \psi\ = \frac{sin\ \alpha\ sin\ \phi - sin\ \delta}{cos\ \alpha\ cos\ \phi}\ = \frac{0.23\ sin\ 35 - \sin(-23.45)}{\cos(\sin^{-1} 0.23)\ \ cos\ 35} = 0.66$$

Thus, α = 13.3° and ψ = 48.7° east of south.

Next, the length of a shadow d can be found using a bit of trigonometry. If the length of the PV panel is L, then h = L sin 30°, and d = h/tan α = L sin 30°/tan α. So, if length of our panel is L = 167.5cm, then d = (354.28 cm) the projection of the shadow to the north will give a distance of x= 354.28 * cos (48.7°) = 233.82 cm which will be the minimum row and column spacing.

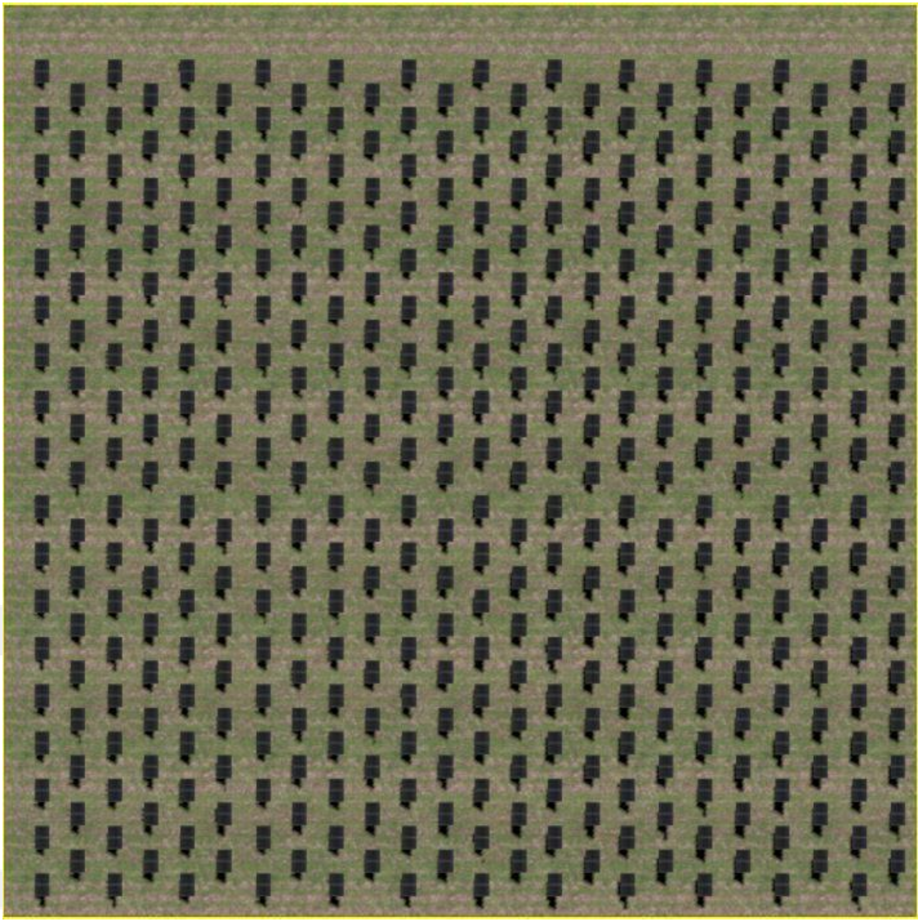

**Figure 3.8** Distribution of solar panels[56]

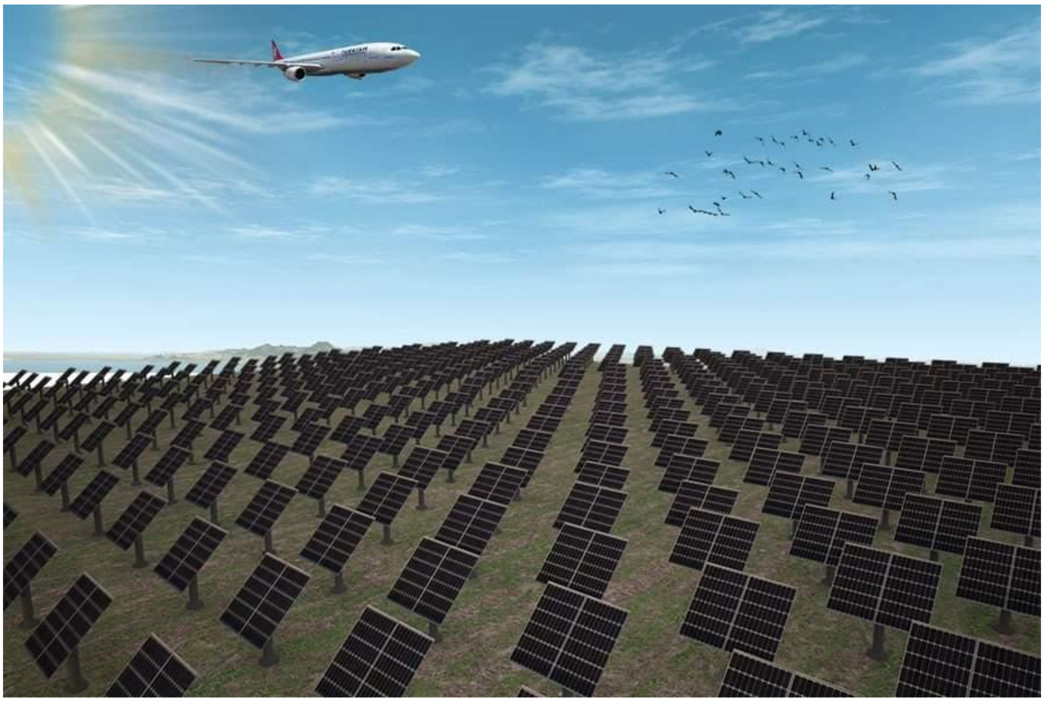

**Figure 3.9** 3D max drawing[56]

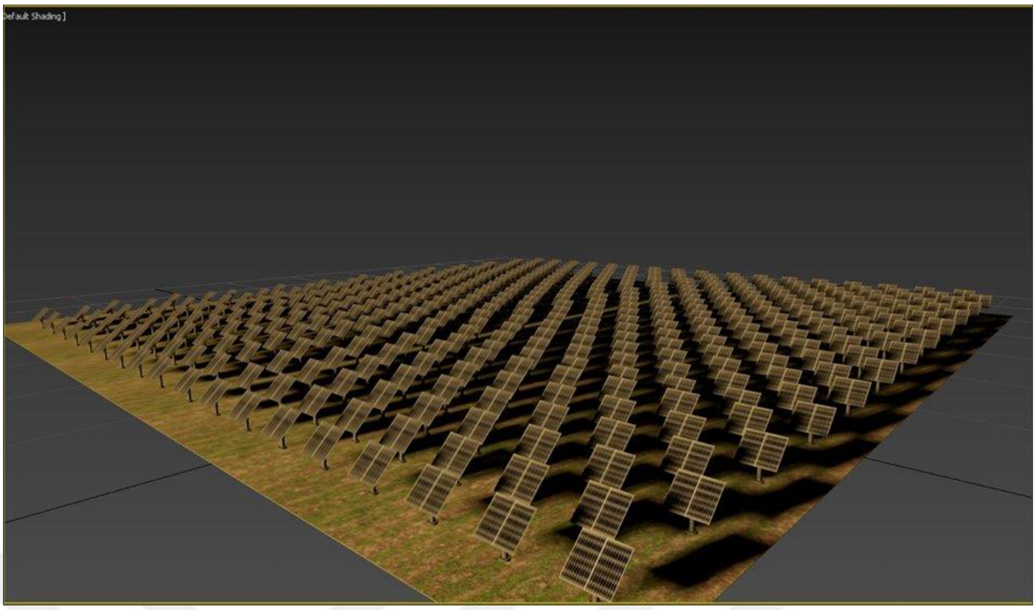


**Figure 3.10** solar panels at sunset hour[56]

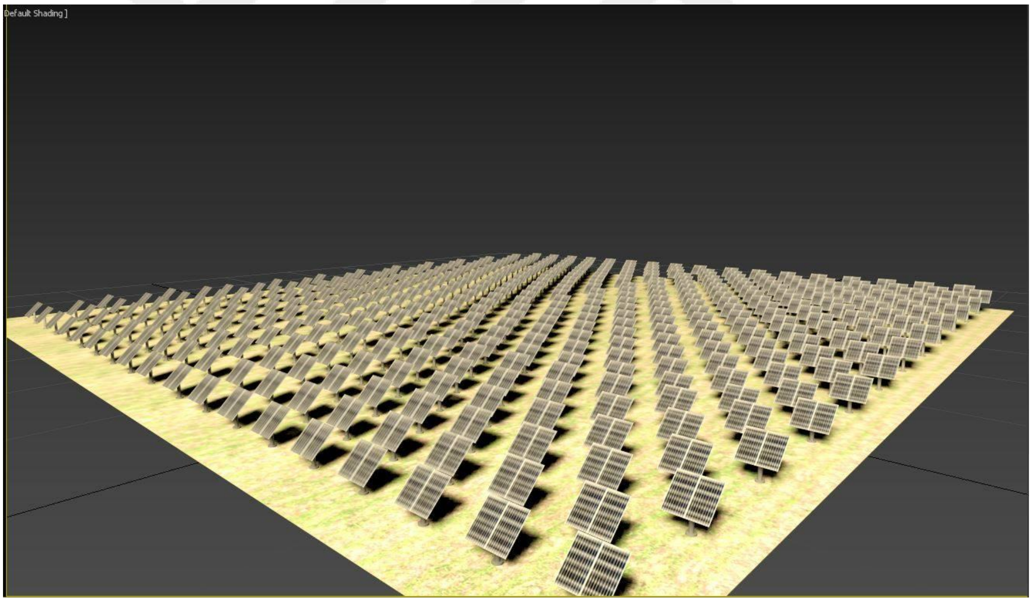


**Figure 3.11** the solar panels while the sun directly hits the panels [56]

### 3.4. IRRADIANCE AND SUNSHINE DURATION OF OUR CASE:

In my city (Hama, Syria) we have monuments of a castle that located on a hill, we used to use it as a park but after the war, it became a useless region (dry land without any trees), so now I'm thinking about using this zone to set up our solar panels. Actually, the big benefit of this location is the hill, by the hill we won't have any shading from the buildings and the other benefit is there is a neighborhood very close to it, see Figure 3.1.


**Figure 3.12** the place that we want to install our solar panels [52]

I depended on the NASA database to get the average for a set of meteorological data between 1984 and 2013 through the power data access viewer radiation values on the tilted surface of panels.

**Table 3.4** Monthly and annual Radiation value of our region[53]

| Months | Daily Radiation Value | Day | Monthly Radiation Value kWh/$m^2$ - month) |
|---|---|---|---|
| January | 3.48 | 31 | 107.88 |
| February | 3.84 | 28 | 107.5 |
| March | 5.06 | 31 | 156.86 |
| April | 5.81 | 30 | 174.3 |
| May | 6.8 | 31 | 210.8 |
| June | 7.59 | 30 | 227.7 |
| July | 7.38 | 31 | 228,78 |
| August | 6.75 | 30 | 202.5 |
| September | 6.19 | 31 | 191.89 |
| October | 5.32 | 30 | 159.6 |
| November | 4.05 | 31 | 125.55 |
| December | 3.26 | 30 | 97.8 |
| Total Annual Radiation | | | 1991 |

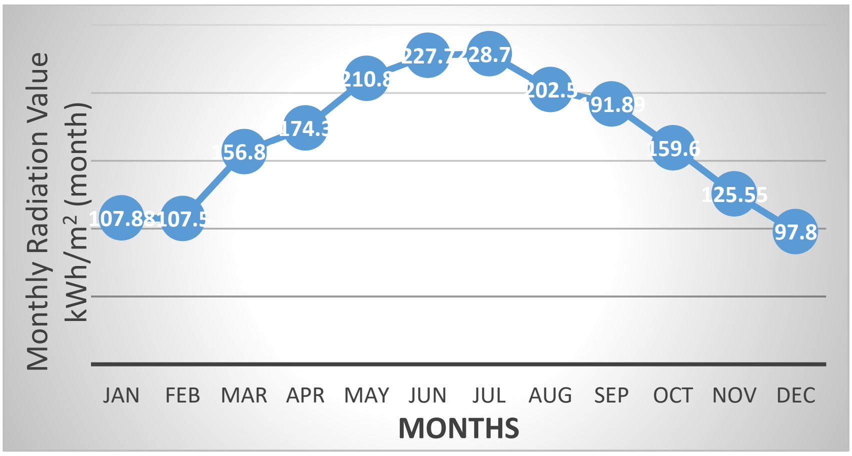


**Figure 3.13**, Monthly Radiation value of our region

Moreover, if we take the average value of the monthly radiation we can print the curve:

In addition, I could get an average of insolation times (sunshine duration):

**Table 3.5** Monthly and annual sunshine duration of our region[53]

| Months | Daily Sunshine Duration *Day | Monthly Sunshine Duration (hours - month) |
|---|---|---|
| January | 3.6 * 31 | 111.6 |
| February | 4.78 * 28 | 133.34 |
| March | 6.01 * 31 | 186.31 |
| April | 7.15 * 30 | 214.5 |
| May | 7.87 * 31 | 243.97 |
| June | 8.15 * 30 | 244.5 |
| July | 7.74 * 31 | 239.94 |
| August | 6.97 * 30 | 209.1 |
| September | 6.01 * 31 | 186.31 |
| October | 4.81 * 30 | 144.3 |
| November | 3.58 * 31 | 110.98 |
| December | 3.2 * 30 | 96 |
| Total annual sunshine duration | | 2120.85 |

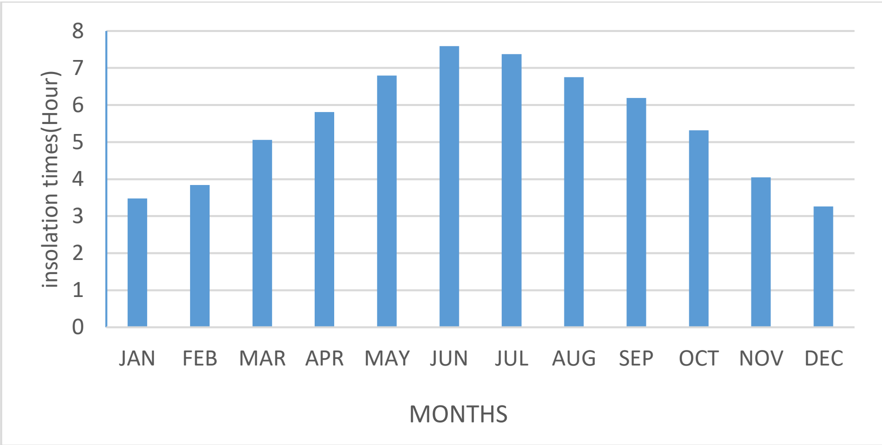


**Figure 3.14**, Monthly and annual sunshine duration of our region

From the data above, we can say that the location is very good for setting up our solar system and, to take full advantage of the daily solar radiation I decided to add a solar tracking system to our module that follows the sun from sunrise to sunset.

### 3.5. HOW CAN WE MEASURE THE AREA NEEDED?

Starting from the equation of the efficiency of the panel:

$$\eta = \frac{P_{out}[W]}{P_{in}\,[W]}$$

Since we can express the ( $P_{in}$ ) by: $P_{in} = \sigma \cdot A$ ;

$\sigma$ : The solar constant that is equal to 1000 $\left[{}^{W}/_{m^2}\right]$.

$A$ : The area of solar panels [m$^2$].

$$\eta = \frac{P_{out}[W]}{P_{in}\,[W]} = \frac{P_{need}[W]}{\sigma \cdot A}$$

Therefore, the area needed can be measured by:

$$A\,[m^2] = \frac{P_{need}[W]}{\eta \cdot \sigma\,\left[{}^{W}/_{m^2}\right]}$$

### 3.6. COOLING THE SOLAR PANELS

Do you know that the solar panels are not at their best behavior when they are too hot? that is true while solar PV may be amazing devices that produce energy and have no moving components because they are a little sensitive about high temperature, the hotter they get the lesser they perform [60, 61].

They can lose nearly twenty to twenty-five percent of their efficiency because of high temperatures, which can reach more than 80-degree centigrade, so a 200-watt panel would be making only 150 watts at most, and it gets really hot over the scale of installation and over the lifetime of the panels, which is thirty years. This could mean a significant loss of energy, so what can be done about this, fortunately, there are a few solutions:

### 3.6.1. Thin-film panels

For hot regions they are perfect compared to crystalline silicon, for example, gallium arsenide panel, are much less sensitive to heat, they hold their performance even in very hot regions.

**Figure 3.15** Thin Film Panels[62]

### 3.6.2. Water Spray

This solution is often used, it is an initiative not taken by solar panel manufacturers but by people themselves. It will be automated systems have been created, that switch on water space once the panels get too hot, the water soaks up the heat and cools the panels down, however, this may an easy solution but not the most efficient as a speak and dropped unevenly on the panels. Furthermore, you can lose a lot of water and this system also uses power, although it has to be mentioned that the power it requires each move is much less than what it can recruit [60].

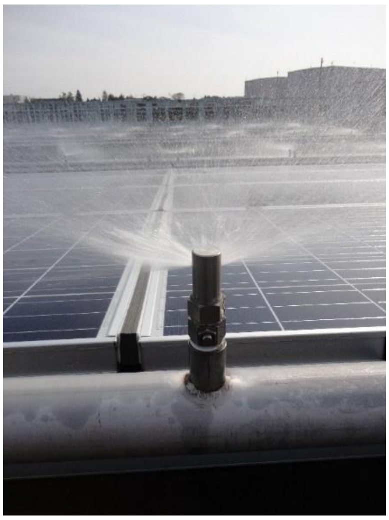

**Figure 3.16** water spray with panels[63]

### 3.6.3. Aluminum Water Jacket

It made out of aluminum, this is a very strong solution, but it is expensive. The panels are placed on what is essentially cold plate water circulates through the plate using a pump. It collects the excess heat from the panels and dissipates it using a cooling tower or a connector [15, 60, 61].

**Figure 3.17** Aluminum water jacket[15, 60]

### 3.6.4. Phase Change Material (PCM)

It is the most exciting solution, which you may have come across in household products the quality of this material is that it can absorb a lot of heat without raising the temperature.

**Figure 3.18** PCM[61, 64]

(PCM) can later release the heat when the ambient conditions change or become colder there are a variety of PCM products available with different temperature ranges you can select the PCM for the temperature you would like an object to remain in the desert environment. PCM is used to absorb extra heat released during the day by electronic and electrical machinery then this heat is dissipated later during the night.

PCM is the ideal match to be used in conjunction with solar panels, packets of PCM can be placed underneath the panel, which will not allow the heat to build up during the day, and they will release the heat during the night when the panels are not in operation. Plus-ice is an example of PCM products that can be used in conjunction with solar panels. It should be noted that if the solar panel temperature remains below the rated maximum temperature then research has shown that their lifetime can be extended from 30 years to 50 years.

For our case, I prefer to use water spray because there is a very close river to our location, and we can get the benefit of this method with cleaning the panels from the dust by water spray, also we will not worry about the pump because it will be supplied with power by our energy system.

# 4. RESULTS AND DISCUSSION

## 4.1. HOW MUCH AREA DO WE NEED?

Let us calculate the area needed to cover the energy consumption ($P_{need}$ =1 MW) considering the efficiency of solar cells $\eta$ =16.7%. Since we know the solar constant in the Earth to be $\sigma$ =1000 W/m$^2$, from **(2.10) and (2.11)** the area needed can be calculated by:

$$A = \frac{P_{need}[W]}{\eta \cdot \sigma[^{W}/_{m^2}]} = \frac{1 \cdot 10^6}{0.167 \cdot 1000} = 5{,}988\ [m^2]$$

To calculate a realistic area on Earth needed to cover our energy consumption we need to add some assumptions to consider the day/night cycle, as well as atmospheric conditions. If we assume eight hours of average daylight and that 70% of all days have sunshine, we can calculate a realistic area needed to supply our energy need with solar power:

$$A = 5{,}988\ [m^2] \cdot \frac{1}{0.7} \cdot \frac{24}{8} \cong 25{,}662\ [m^2]$$

## 4.2. CALCULATION OF THE ANNUAL SOLAR ENERGY OUTPUT:

The formula below is used to estimate the electricity output of solar panels:

E = A * r * H * PR

E = Energy (kWh)

A = Total solar panel Area (m$^2$)

r = solar panel yield (%)

H = Annual average solar radiation (shadow is not considered)

PR = Ratio of performance, the coefficient for losses (range between 0.5 and 0.9).

**A:** is the cell area I am going to use an efficient panel area and writing down the area of the one panel in m$^2$. **r:** is the annual of the solar panel electrical power (in $kW_p$) of one solar panel divided by the area of one panel. our solar panel annual of a PV module of 280 $W_p$ with an area of 1675 mm * 951 mm = 1.593 $m^2$ with efficiency 16.7%[59].

**H**: Solar radiation data, we are going to take to the value of (**H**) is 1991 $kWh/m^2$ (per year).

**PR**: (Performance Ratio) is a very important value to evaluate the quality of a photovoltaic installation because it performs the installation suddenly of the orientation, inclination of the panel. It includes all losses[59]. Example of losses details that give the PR value (depend on the site, the technology, and sizing of the system):

- Inverter losses (4% to 15 %)
- Temperature losses (5% to 18%)
- DC cables losses (1 to 3 %)
- AC cables losses (1 to 3 %)
- Shadings 0 % to 50%! (Specific to each site)
- Losses weak radiation 3% to 7%
- Losses due to dust, snow... (2%)
- Other Losses (?)

Estimation of all losses are considering and we can get the value of the PR = 0.80

E = A * r * H * PR

E = 1.593 $m^2$ * 16.7% * 1991 $kWh/m^2$ * 0.80

E = 423.73 (kWh/year) Kilowatt hour (for one year)

From one panel we are going to produce that amount of kWh.

Electricity Generation in Terms of Months (based on **Table 3.4 for H)**:

**Table 3.6** Electricity Generation in Terms of Months

| Months | | |
|---|---|---|
| January | 22.95 | kWh |
| February | 22.87 | kWh |
| March | 33.38 | kWh |
| April | 37.09 | kWh |
| May | 44.86 | kWh |
| June | 48.46 | kWh |
| July | 48.70 | kWh |
| August | 43.10 | kWh |
| September | 40.83 | kWh |
| October | 33.96 | kWh |
| November | 26.72 | kWh |
| December | 20.81 | kWh |

**4.3. ESTIMATION OF NUMBER OF PANELS AND OUTPUT ENERGY:**

We have the 280-Watt panel with area 1.593 $m^2$, and the total area of our case is 30,000 $m^2$, if we divided these two values with themselves:

$$\#panels = \frac{30000}{1.593} = 18832\ panels$$

Nevertheless, we have to consider gaps between panels, the minimum row and column spacing (2.33 m). These are all loose of $m^2$ and this means a decreasing number of panels.

$$\frac{30000}{(1.675 + 2.33) * (0.951 + 2.33)} = 2283\ panels$$

The two numbers 1.675 and 0.951 are the dimensions of the panel, therefore; we can put that number of panels.

If one panel is 280 Watt, 2283 panels are 639.240 $kW_p$. Remember the average of a sunshine duration, which was 5.9 hours. Find out the Kilowatt-hour value 639.240 $kW_p$ * 5.9 hour =

3771.516 kWh/day if there is no loss, we can obtain 3771.516 kWh * 365 days/year = 1376603.34 kWh / year - we can take maximum loose assumption as percentage of 40 - 1376603.34 kWh / year * 0.60 = 825962.004 kWh / year = 825 MWh/year.

If we call back the formula E = A * r * H * PR multiplying it by the number of panels (2283) we will produce energy: E= 423.73*$10^3$ * 2283 = 967 MWh/year.

Let us consider a typical PV solar power plant similar to mine, for example with panel 200 Watt (with 1 $m^2$ area and 13% efficiency) and for example, we have (2000) panels we would get 400 kWp and the average of sunshine duration time is 7 hours, we will get Kilowatt-hour value 2800 kWh/day. If there any loose could not, we can produce 2800 kWh * 365 days/year = 1022 MWh/year we can take maximum loose assumption as a percentage of 40, 1022 MWh/year * 0.60 = 613.2 MWh/year.

In additional, if we call back the formula E = A * r * H * PR multiplying it by number of panels (2000) thus: E = 1 $m^2$ * 13% * 1991 kWh/$m^2$ * 0.80 = 207.064 from 1 panel 200 watt then multiplying by (2000) we will get 414 MWh/year.

We can conclude that: the output energy in the formula depends on the area and efficiency of the panels and irradiance but the second method depends on the Power of panels.

Since 825 MWh/year corresponds to 94.178 kW of power. Because of the gaps between this was the power achieved. More area needed to get 1 MW.

# 5. CONCLUSION AND RECOMMENDATION

## 5.1. CONCLUSION

Finally, I have reached after the entire calculations and researches monocrystalline panel is the most suitable and efficiently panel for our location. From those wholesale solar websites, it is easy to predict panel and estimation of the panel behavior, which photovoltaic panel, is most suitable for which region. The tilt angles of the panels affect the solar irradiance that falls on its surface therefore; I supported the panels with tracking solar systems.

Also, many positive effects will happen. Some of our; produce clean energy, reduce our electricity consumption of the next-door neighborhood, and earn money from this system for decreasing the cost of our location. We could satisfy our cost and electricity consumption about a 1 to 4 ratio.

Getting an expert to assess your particular case would be the best way to detect which kind of solar panel would be better for your house. Some of the standard situations that we see:

- **The area is tight:** For those who have an insufficient area for thin-film solar panels, or if you need to reduce the area their PV system takes up, crystalline solar panels are your best choice (and they would probably be your best option even if you had additional space). At this point, there are not many solar technicians and suppliers offering thin-film solar panels to homeowners.

The solar panels of 180, 200 and 220 watts are usually of the same physical size so you can choose from various sizes of solar panels. They are made completely in the same way, but under or over-perform when examined, resulting in different power output categories. If the size is essential, you must get the highest evaluated power output for a special physical size.

Both mono and polycrystalline solar panels provide similar benefits. While polycrystalline solar panels seem to be less spatially efficient and monocrystalline solar panels tend to generate more electricity, this is not always the answer. Without a closer examination of the solar panels and your situation, the recommendation for one or the other would be almost impossible.

Monocrystalline solar panels are marginally more expensive, but also more area-efficient. If you had one polycrystalline and one monocrystalline solar panel, two are rated 220 watts, they would produce the same amount of energy, but the one that is made of monocrystalline silicon would need less space. We keep an up to date list of today's most efficient solar panels: What are the most successful solar panels?

- **Lowest expenses:** If you want to pay as little as possible for a certain amount of electricity, you should analyze whether thin-film solar panels could be a better choice than mono or polycrystalline solar panels.

## 5.2. RECOMMENDATION:

To make our study better I recommend the following, like study more about wires that will be needed in our system, also support our system with the appropriate batteries to take advantage of the stored energy during the night and out of electricity.

Make a good survey about types of inverters and decide which one is perfect for our system, I think MPPT type is the best one for power supply and charging the batteries. The MPPT can be especially helpful at irradiance rates around the start and stop irradiance rates, for example, if a power supply for the light is demanded to be optimized for all illumination rates, it will allow the light to turn on at a higher irradiance level and turn off at a lower irradiance level.

The exciting part of the trade-off here is whether it will cost less to include an MPPT with a smaller module than to use a larger module to achieve a similar performance of the system.

# REFERENCES:


1. Coursera. *Introduction to solar cells | Coursera* 2019 [cited 2019 2019]; Available from: "https://www.coursera.org/learn/solar-cells".
2. Perera, F., et al., *Towards a fuller assessment of benefits to children's health of reducing air pollution and mitigating climate change due to fossil fuel combustion.* Environ Res, 2019. **172**: p. 55-72.
3. Poudyal, R., et al., *Mitigating the current energy crisis in Nepal with renewable energy sources.* Renewable and Sustainable Energy Reviews, 2019. **116**: p. 109388.
4. OECD *Green Growth Studies Energy*. 2011.
5. Carvajal-Romo, G., et al., *Assessment of solar and wind energy potential in La Guajira, Colombia: Current status, and future prospects.* Sustainable Energy Technologies and Assessments, 2019. **36**: p. 100531.
6. Tutorialspoint. *Solar Energy - Introduction* 2019 [cited 2019 2019]; Available from: "https://www.tutorialspoint.com/renewable_energy/solar_energy_introduction.htm".
7. Curriculum, H.E. *Introduction to Solar Cells* 2016 [cited 2019 2019]; Available from: 'https://www.horizoncurriculum.com/supportmaterial/introduction-to-solar-cells/'.
8. RESOURCES, P. *Photovoltaics - Introduction and Terms Origin*. 2015 2015 [cited 2019; Available from: http://www.pvresources.com/en/introduction/introduction.php.
9. Bethel Afework, J.H., Kailyn Stenhouse, Brodie Yyelland, Jason Donev. *Photovoltaic cell - Energy Education*. 2018 [cited 2019 December 17, 2019]; Available from: https://energyeducation.ca/encyclopedia/Photovoltaic_cell.
10. Roger, A.A.a.M., *Photovoltaic Systems Engineering Fourth Edition*. Vol. 13: 978-1-4987-7277-8 (Hardback). 2017: Taylor & Francis Group, LLC.
11. Society, A.C. *Energy from the Sun*. 2019 [cited 2019; Available from: https://www.acs.org/content/acs/en/climatescience/energybalance/energyfromsun.html .
12. Service, N.W. *The Earth-Atmosphere Energy Balance*. 2019 [cited 2019; Available from: https://www.weather.gov/jetstream/energy.
13. Wikipedia. *Solar energy*. 2019 [cited 2019; Available from: https://en.wikipedia.org/wiki/Solar_energy.
14. Belessiotis, V. and E. Delyannis, *Solar drying.* Solar Energy, 2011. **85**(8): p. 1665-1691.
15. Sakhr M. Sultan, M.N.E.E., *Review on recent Photovoltaic/Thermal (PV/T) technology advances and applications.* ScienceDirect, 2018. **173**: p. 939-954.
16. Xiang, C., et al., *A solar tube: Efficiently converting sunlight into electricity and heat.* Nano Energy, 2019. **55**: p. 269-276.
17. Padoan, F.C.S.M., P. Altimari, and F. Pagnanelli, *Recycling of end of life photovoltaic panels: A chemical prospective on process development.* Solar Energy, 2019. **177**: p. 746-761.
18. Ouedraogo, N.A.N., et al., *Stability of all-inorganic perovskite solar cells.* Nano Energy, 2019: p. 104249.
19. L.M., F. *History of Solar Cell Development. In: Low-Cost Solar Electric Power*. Springer, Cham, 2014. 1-12 DOI: https://doi.org/10.1007/978-3-319-07530-3_1.
20. RICHARDSON, L. *History of Solar Energy: Timeline & Invention of Solar Panels*. 2018 [cited 2019; Available from: https://news.energysage.com/the-history-and-invention-of-solar-panel-technology/.
21. wikipedia. *Timeline of solar cells*. 2016 [cited 2019; Available from: https://en.wikipedia.org/wiki/Timeline_of_solar_cells.

22. Staff, S.P.A. *History of Solar Cells: How PV Panels Evolved*. 2019 [cited 2019; Available from: https://www.solarpowerauthority.com/a-history-of-solar-cells/.
23. Rahman, F.A., et al., *Pollution to solution: Capture and sequestration of carbon dioxide (CO 2 ) and its utilization as a renewable energy source for a sustainable future.* Renewable and Sustainable Energy Reviews, 2017. **71**: p. 112-126.
24. Tverberg, G. *World Energy Consumption Since 1820 in Charts*. 2012 [cited 2019; Available from: https://ourfiniteworld.com/2012/03/12/world-energy-consumption-since-1820-in-charts/.
25. wikipedia. *Exponential growth*. 2015 [cited 2019; Available from: https://en.wikipedia.org/wiki/Exponential_growth.
26. Malthus, T. *The Ecology of Human Populations*. 2019 [cited 2019; Available from: https://evolution.berkeley.edu/evolibrary/article/0_0_0/history_07.
27. Lee, E., et al., *Potential of Denver Basin oil fields to store CO2 and produce Bio-CO2-EOR oil.* International Journal of Greenhouse Gas Control, 2019. **81**: p. 137-156.
28. Kirby, D.S. *BTU Defined*. 2013 [cited 2019; Available from: https://energy.ces.ncsu.edu/btu-defined/.
29. Britannica, T.E.o.E. *British thermal unit | unit of measurement*. 2019 [cited 2019; Available from: https://www.britannica.com/science/British-thermal-unit#accordion-article-history.
30. Atems, B. and C. Hotaling, *The effect of renewable and nonrenewable electricity generation on economic growth.* Energy Policy, 2018. **112**: p. 111-118.
31. Zhuang, Y.F., et al., *Application of SiO2 passivation technique in mass production of silicon solar cells.* Solar Energy Materials and Solar Cells, 2019. **193**: p. 379-386.
32. Yuri D. Arbuzov, V.M.E., Olga V. Shepovalova, *Angle-depended Photocurrent Characteristics of Upper-Limit Efficient Cascade PV Cells on the Base of Homogeneous Semiconductor.* VIESH-RENEWABLE ENERGY SOURCES, 1-st Veshnyakovsky proezd. 2, Moscow, 109456, Russia, 2017. **119**: p. 980–989.
33. Museum, C.H. *1940: Discovery of the p-n Junction*. 2019 [cited 2019; Available from: https://www.computerhistory.org/siliconengine/discovery-of-the-p-n-junction/.
34. Today, U. *What is Earth's Axial Tilt?* 2016 [cited 2019; Available from: https://www.universetoday.com/47176/earths-axis/.
35. Herald-Post, E.P. *Amy's Everyday Astronomy*. 2019 [cited 2019; Available from: https://elpasoheraldpost.com/amys-everyday-astronomy-to-every-thing/.
36. Irwanto, M., *Solar irradiance and optimum tilt angle of photovoltaic module in Tanjung Morawa, North Sumatera, Indonesia.* International Journal of Research in Advanced Engineering and Technology, 2015.
37. Topics, S. *Solar Position - an overview*. 2018 [cited 2019; Available from: https://www.sciencedirect.com/topics/engineering/solar-position.
38. Jerin Kuriakose Tharamuttam , A.K.N., *Design and Development of an Automatic Solar Tracker.* 2017. **143**: p. 629-634.
39. planner, T.s. *Calculating the Sun's Path and Solar Array Orientation*. 2012-2013 [cited 2019; Available from: 'https://www.thesolarplanner.com/array_placement3.html'.
40. Wikipedia. *Typical meteorological year*. 2019 3 January 2019 [cited 2019; Available from: https://en.wikipedia.org/wiki/Typical_meteorological_year.
41. Antonanzas, J., et al., *Optimal solar tracking strategy to increase irradiance in the plane of array under cloudy conditions: A study across Europe.* Solar Energy, 2018. **163**: p. 122-130.
42. Lee, J.S. and G.B. Cleaver, *The relativistic blackbody spectrum in inertial and non-inertial reference frames.* New Astronomy, 2017. **52**: p. 20-28.
43. Engineering, L. *How do Solar cells work?* 2018 [cited 2019; Available from: https://www.youtube.com/watch?v=L_q6LRgKpTw.

44. López-Escalante, M.C., F. Martín, and J. Ramos-Barrado, *Grouping by bulk resistivity of production-line mono-crystalline silicon wafers and its influence on the manufacturing of solar cells modules.* Solar Energy, 2016. **131**: p. 61-70.
45. Jesus, M.A.M.L.d., et al., *Anti-soiling coatings for solar cell cover glass: Climate and surface properties influence.* Solar Energy Materials and Solar Cells, 2018. **185**: p. 517-523.
46. Tabrizi, A.A. and A. Pahlavan, *Efficiency improvement of a silicon-based thin-film solar cell using plasmonic silver nanoparticles and an antireflective layer.* Optics Communications, 2020. **454**: p. 124437.
47. Udo Römer, N.S., Zhongtian Li, Yang Li, Xueling Zhang, Yuan Shengzhao, Pierre J. Verlinden, Alison Lennon, *Decoupling the metal layer of back contact solar cells – optical and electrical benefits.* sciencedirect, 2017. **124**(7th International Conference on Silicon Photovoltaics, SiliconPV 2017): p. 907-913.
48. Dang, C., et al., *Detailed structural and electrical characterization of plated crystalline silicon solar cells.* Solar Energy Materials and Solar Cells, 2018. **184**: p. 57-66.
49. Sesa, E., et al., *A building-block approach to the development of an equivalent circuit model for organic photovoltaic cells.* Organic Electronics, 2018. **58**: p. 207-215.
50. Robles–Campos, H.R., et al., *Detailed modeling of large scale photovoltaic power plants under partial shading conditions.* Solar Energy, 2019. **194**: p. 485-498.
51. Technology, T.H.K.U.o.S.a. *HKUST Develops Environmentally Friendly Organic Solar Cells with Record Performance*. 2016 [cited 2019; Available from: https://www.ust.hk/news/research-and-innovation/hkust-develops-environmentally-friendly-organic-solar-cells-record.
52. *Google Earth*. 2012 [cited 2019; Available from: https://earth.google.com/web/@35.13600719,36.7509383,278.56202707a,932.05313354d,35y,-0h,0t,0r/data=OgMKATA?authuser=0.
53. NASA. *How to get solar radiation data anywhere in the world for free?* 2019 [cited 2019; Available from: https://power.larc.nasa.gov/data-access-viewer/.
54. SOLAR, M., *<AST2man.pdf>*. 2015.
55. A.Thorat, P., et al., *Effect of sun tracking and cooling system on Photovoltaic Panel: A Review.* Materials Today: Proceedings, 2017. **4**(14): p. 12630-12634.
56. Autodesk, *Autodesk 3Ds Max*. 2020, Autodesk.
57. informative, e. *Which Solar Panel Type is Best? Mono- Polycrystalline or Thin Film?* 2012 [cited 2019; Available from: https://energyinformative.org/best-solar-panel-monocrystalline-polycrystalline-thin-film/.
58. İŞAL, M., *CONSTRUCTION OF A SOLAR PHOTOVOLTAIC SYSTEM: CASE OF ISTANBUL BILGI UNIVERSITY*, in *Energy System Engineer*. 2016, istanbul bilgi University: istanbul bilgi University.
59. Academia.edu, S.Y.-. *(DOC) CALCULATIONS OF SOLAR ENERGY OUTPUT*. 2016 [cited 2019; Available from: https://www.academia.edu/9005661/CALCULATIONS_OF_SOLAR_ENERGY_OUTPUT?auto=download.
60. Files, S. *4 Different Methods for Cooling Solar PV Panels*. 2017 [cited 2019; Available from: https://www.youtube.com/watch?v=lT6GJxcG-RM&list=PLu0us5KazgRltRm3qlolgLiCxBkAXHfpB&index=20&t=0s.
61. M, R., et al., *Experimental investigation on the abasement of operating temperature in solar photovoltaic panel using PCM and aluminium.* Solar Energy, 2019. **188**: p. 327-338.
62. Sunlight, P.F. *Flexible Thin Film Solar Panels: Technology and Different Applications of Bendable Solar Panels*. 2016 [cited 2019; Available from: https://www.powerfromsunlight.com/flexible-thin-film-solar-panels-technology-different-applications-bendable-solar-panels/.

63. XTECH, N. *Water Spray Melts Snow, Cools Hot Panels at Solar Plant*. 2015 [cited 2019; Available from: https://tech.nikkeibp.co.jp/dm/english/NEWS_EN/20150530/420900/.
64. Teappcm. *PCM Phase Change Material Materials Manufacturers*. 2019 [cited 2019; Available from: https://www.teappcm.com/.