Renewable Energy Systems

Assist. Prof. Dr. Ali DURUSU

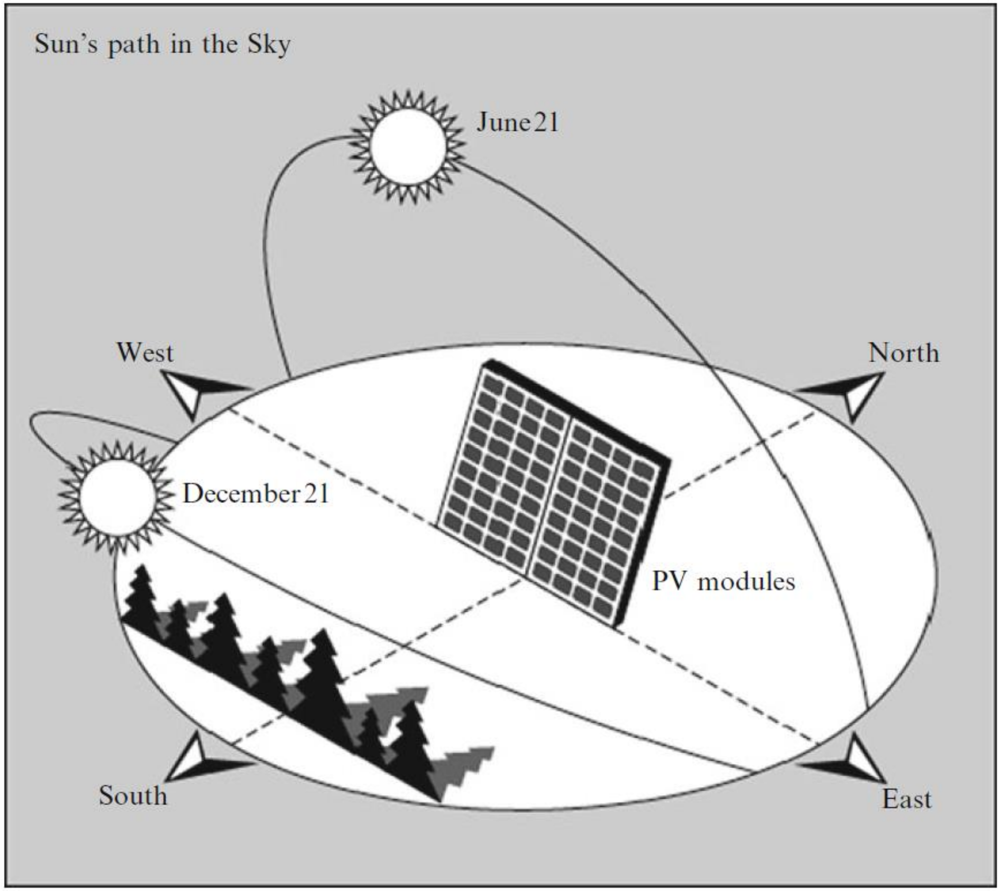
Lecture IV – Solar Power

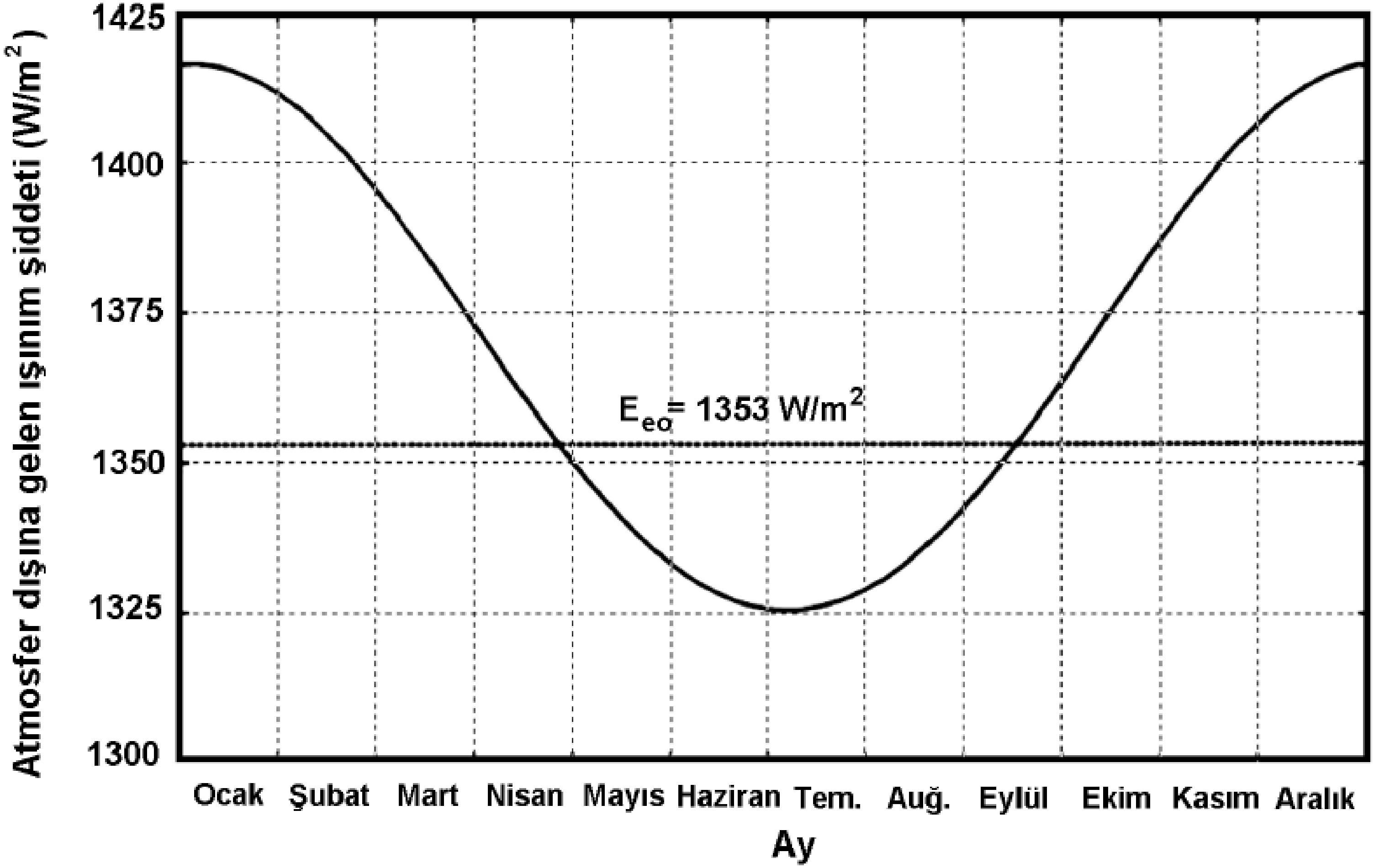
Introduction to Solar Energy

- The sun is about 1.4 million kilometers (about 870,000 miles) in diameter and its interior temperature is about 15 million degrees Kelvin (about 27 million degrees F). This high temperature, combined with a pressure that is 70 billion times higher than atmospheric pressure on the earth, creates ideal conditions for fusion reactions. The fusion reaction in the sun involves two hydrogen atoms combining to form a helium atom, releasing the energy in the process. This energy is released in the form of high-energy gamma radiation.
- As gamma rays radiate from the center to the outside of the solar sphere, they react with the solar media and are transformed into lower-energy radiations, primarily in the visible light and heat portions of the energy spectrum. The sun has been producing energy in this manner for around 5 billion years, and will continue to do so for several more billion years.
- The amount of solar energy reaching a specific location on the surface of the earth at a specific time is called "**insolation**", and its value depends on several factors. If the sun is directly overhead, and the sky is clear, the radiation on a horizontal surface is about 1,000W/m^2.

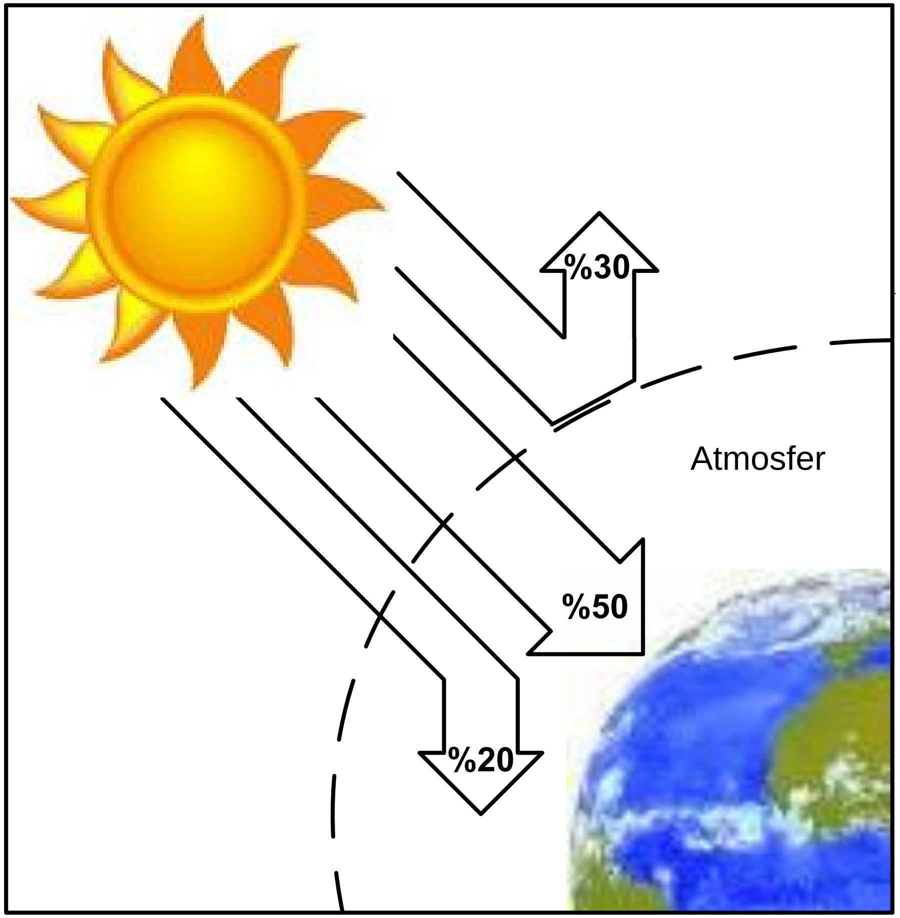
Seasonal Variation of Solar Energy

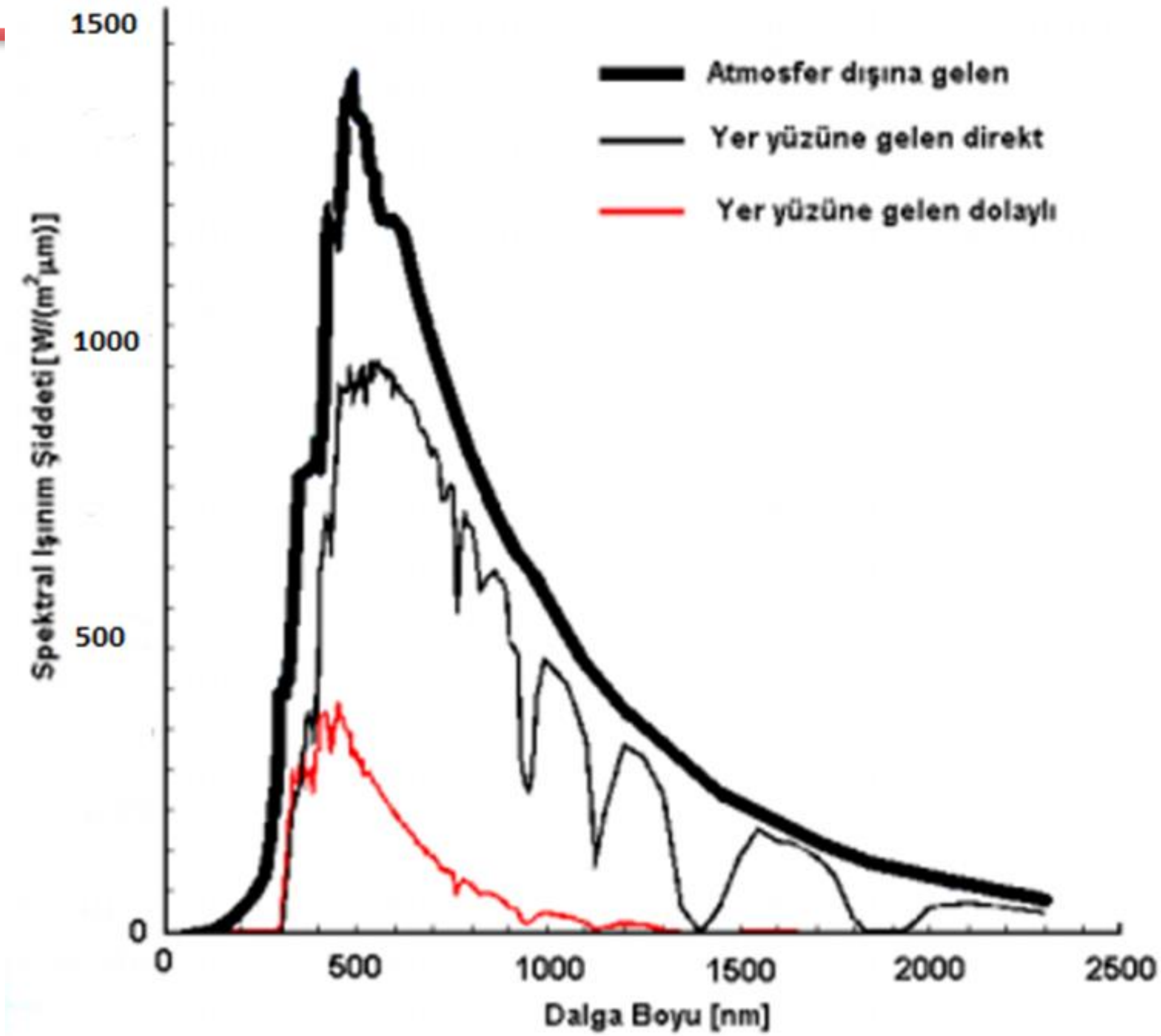
The earth spins around its axis once per day, and rotates in an elliptical orbit around the sun once per year. The axis around which the earth rotates is tilted to 23.5^0 from the solar plane toward the sun at one end of its orbit and away from the sun at the other end. This gives rise to the seasons: when the earth's axis is tilted toward the sun, the northern hemisphere receives more direct solar radiation (summer). Six months later, when the axis is tilted away from the sun, the southern hemisphere experiences summer. In between are spring and fall, when the tilt of the earth's axis is neither toward nor away from the sun.



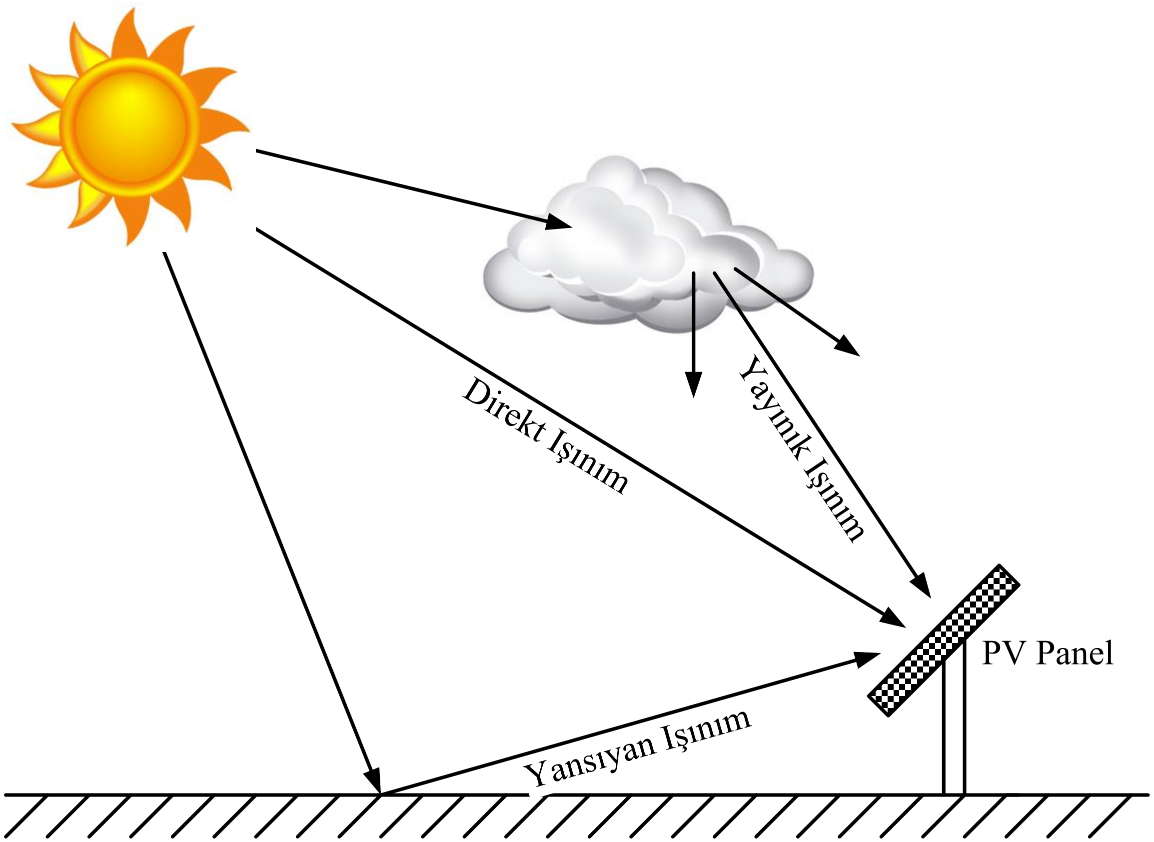


Atmosfer dışına gelen ışınım şiddeti (W/m²)
1425
1400
1375
1350
1325
1300
E_{eo}= 1353 W/m²
Ocak
Şubat
Mart
Nisan
Mayıs
Haziran
Tem.
Auğ.
Eylül
Ekim
Kasım
Aralık
Ay

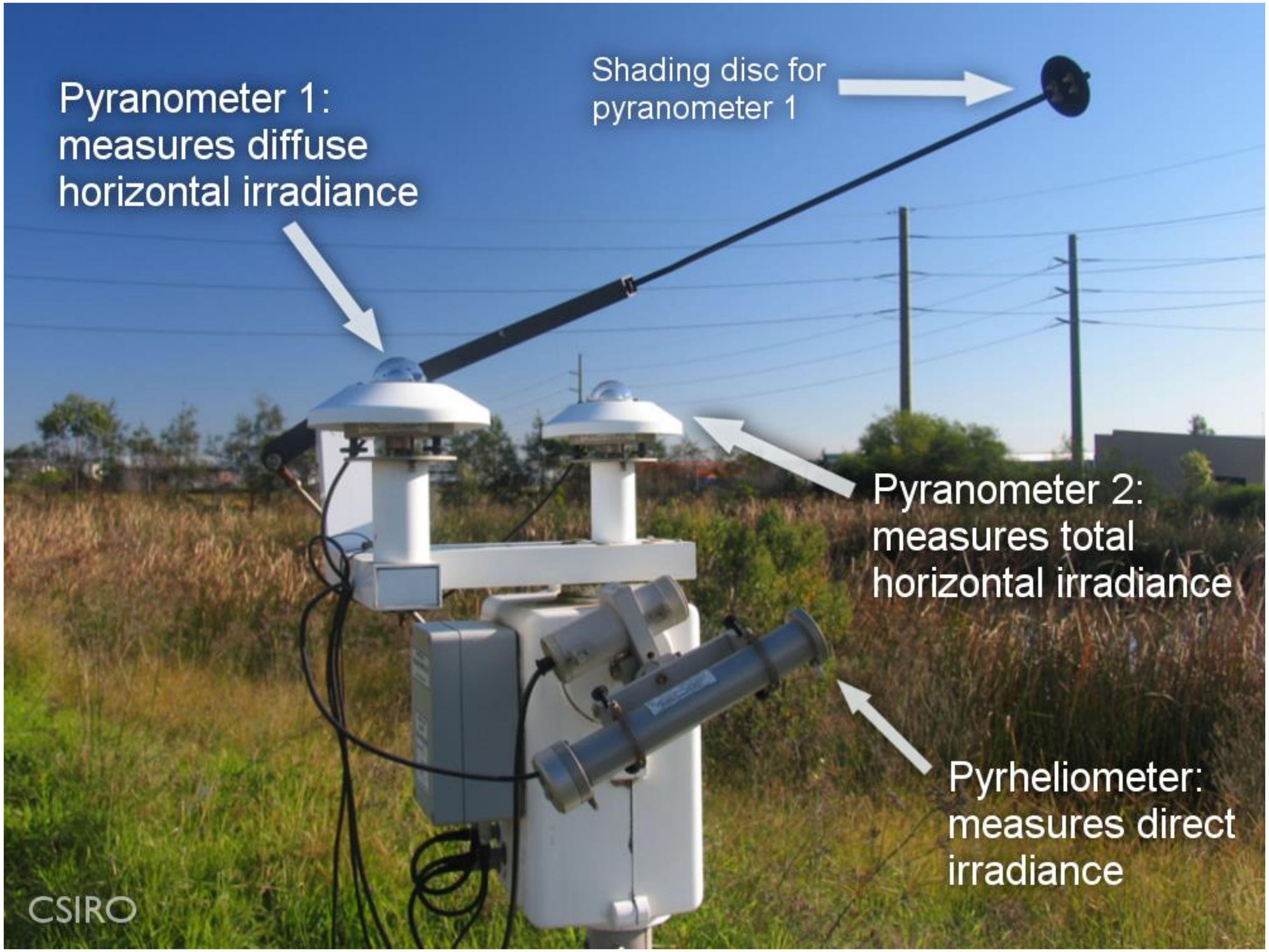

%30
Atmosfer
%50
%20



1500
1000
500
0
Spektral Işınım Şiddeti [W/(m²µm)]
Atmosfer dışına gelen
Yer yüzüne gelen direkt
Yer yüzüne gelen dolaylı
0
500
1000
1500
2000
2500
Dalga Boyu [nm]



$I_T = I_B$(*direkt) + I_D(*yaygın/yayınık) + I_R(*yansıyan)



Shading disc for pyranometer 1
Pyranometer 1: measures diffuse horizontal irradiance
Pyranometer 2: measures total horizontal irradiance
Pyrheliometer: measures direct irradiance
CSIRO

Use of Solar Energy

- Throughout the history, humans have used the heat from sunlight to dry grains, cook food, and heat water and homes. The concept and the use of solar thermal energy started in 1767 when the Swiss scientist, Horace de Saussure, invented the world's first solar collector, or "hot box". Renowned astronomer, Sir John Herschel, used solar hot boxes to cook food during his expedition to Southern Africa in the1830s.
- Today, solar collectors can gather solar thermal energy in almost any climate to provide reliable, low-cost source of energy for many applications including heating water for homes and residential heating systems. Various other industries, such as laundries and food processing companies, also utilize solar energy. In recent years, utilities have begun to use solar thermal energy to generate electricity by using steam turbines. The steam is produced by concentrating the solar energy into a water boiler.
- Another and currently the most popular way of utilizing solar energy is the use of photovoltaic (PV) cells to convert the solar energy directly into electrical energy.

Photovoltaic Cells

Photovoltaic term is composed of two terms that are mainly Greek: “Phos” that means light and “voltaic” that means electric. Photovoltaic term took its place in English literature in 1849.

Photovoltaic (PV) cells convert the solar energy directly into electricity. PV based systems are commonly known as “solar cells,” and are currently used in a number of devices including calculators, watches, and emergency radios. Large scale units can be used to provide power for pumping water, communications equipment, satellites, and lighting homes.

Photovoltaic Cells

Photovoltaic cells use semiconducting materials to capture the energy of sunlight, which is composed of photons. These photons contain an energy corresponding to their wavelengths in the solar spectrum. When sunlight or photons strike a PV cell, three events occur:

1. Photons pass straight through the cell. This depends on the band gap energy of the material (The band gap energy is discussed in the following section). Photons with energy less than the band gap energy pass through the PV cells.

2. Photons reflect off the surface. This depends on the surface characteristics of the material.

3. Photons are absorbed by the PV cell. Only photons with a certain level of energy are able to free electrons from their atomic bonds. By leaving this position, the electron causes a "hole" to form. The electrons from nearby atoms will move into this hole, and the process will continue until it reaches the external electrical circuit. If the energy of the absorbed photons is higher than the band gap energy, sometimes heat is generated, depending on the band structure.

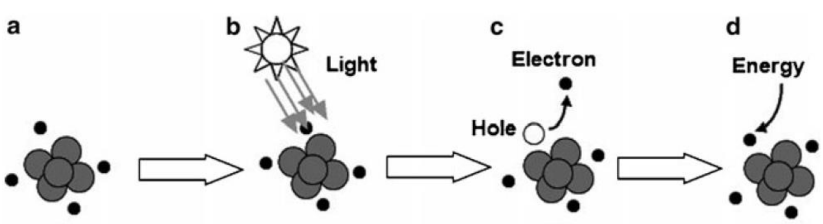
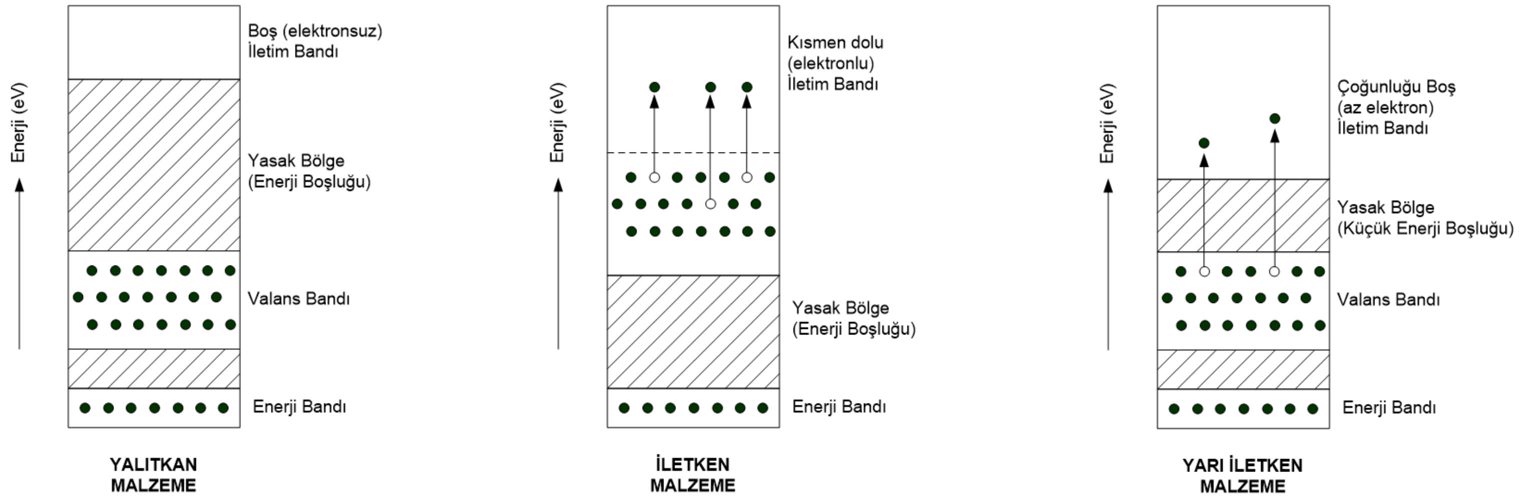


Fig. The interaction of photons with a semiconductor material. (**a**) The atom of the semiconductor material, (**b**) Interaction of the atom with sunlight or photons, (**c**) The ijection of electron and creation of the hole, (**d**) Absorption of energy

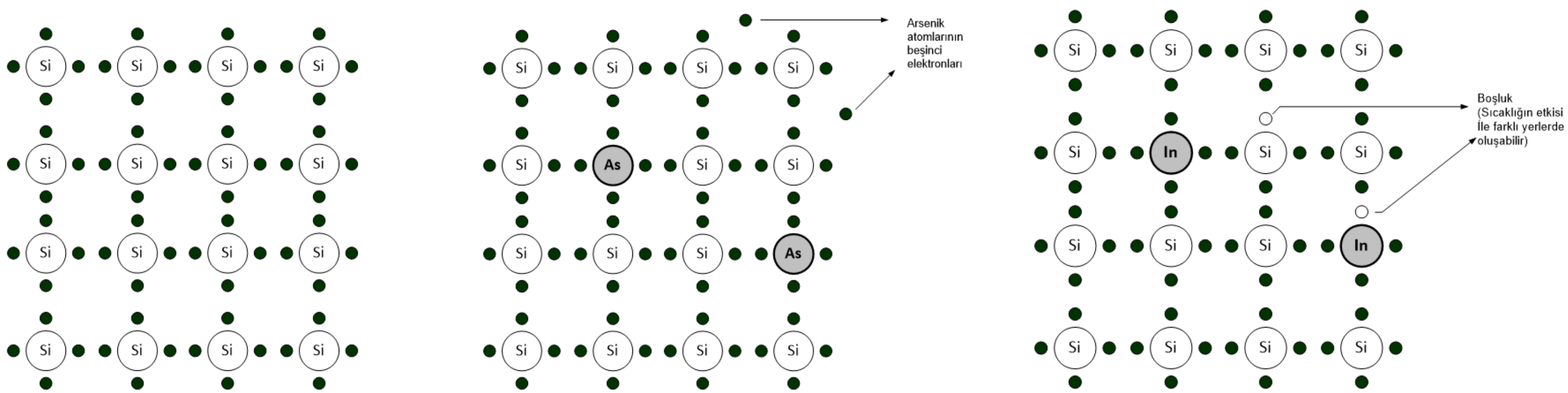
FOTOVOLTAİK GÜNEŞ ENERJİ SİSTEMLERİ (PV)
YALITKANLAR, İLETKENLER, YARI İLETKENLER



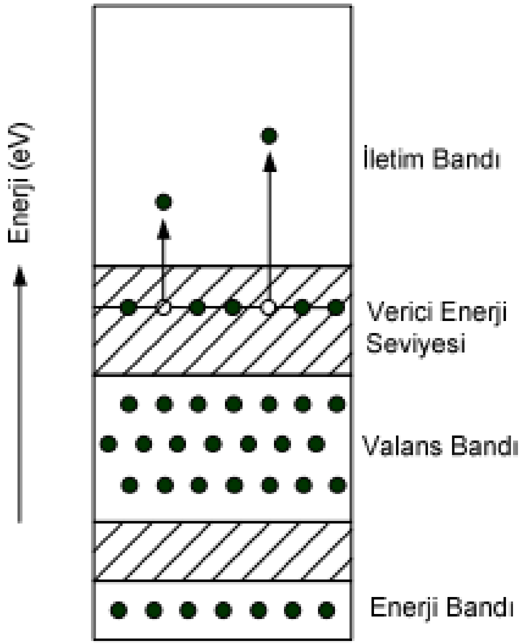
Farklı malzeme guruplarına ilişkin enerji bandlarının şematik gösterimi

FOTOVOLTAİK GÜNEŞ ENERJİ SİSTEMLERİ (PV)

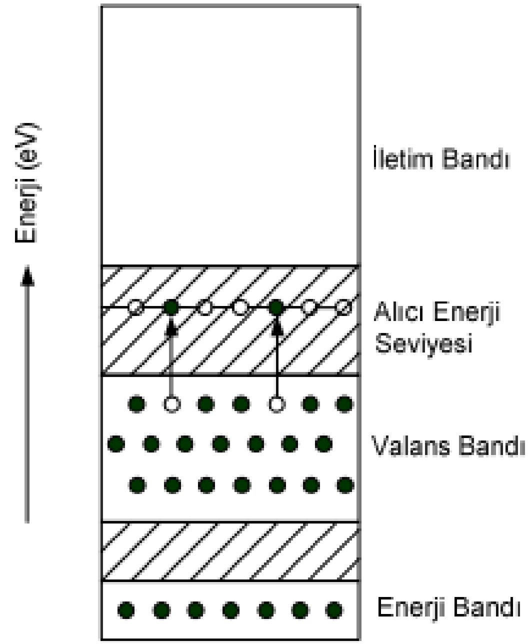
YARI İLETKENLER



Silikonların oluşturdukları kovalent bağ, arsenik katkısı ile elde edilmiş n-tipi malzeme ve indiyum katkısı ile elde edilmiş p-tipi malzeme



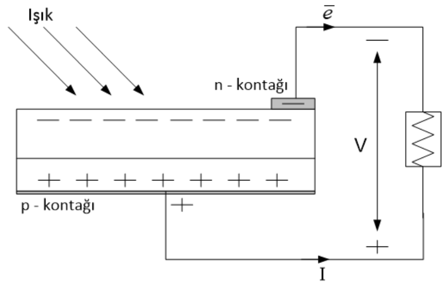
n-tipi yarı iletken

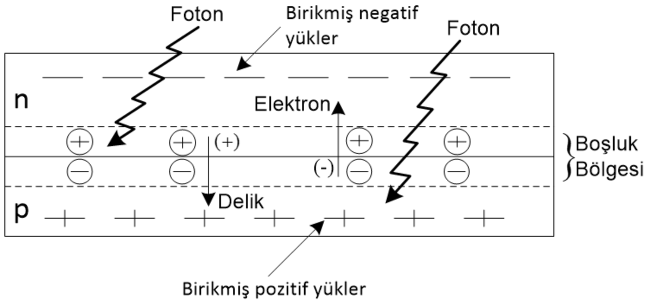


P-tipi yarı iletken

FOTOVOLTAİK GÜNEŞ ENERJİ SİSTEMLERİ (PV)

PV HÜCRELERİNİN YAPISI VE ÇALIŞMA PRENSİBİ

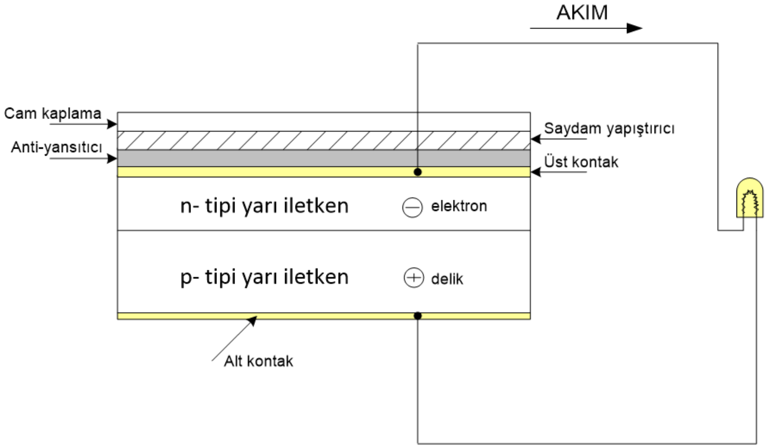




Panel üzerinde jonksiyon bölgesine düşen ışık devrede bir akım akmasını sağlar.

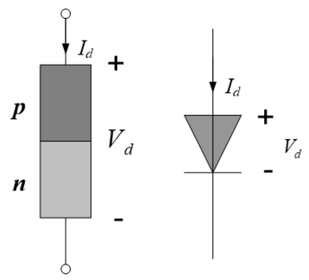
Yük üzerinden akan akım $I^2.R$ kaybını oluşturur.

Elektrik enerjisine dönüşmeyen foton enerji ise PV hücrenin sıcaklığını arttırır.



p-n Jonksiyonlu Diyot

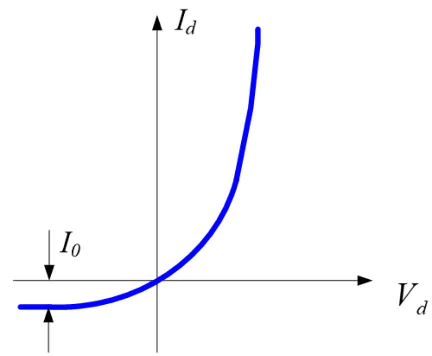
p-n jonksiyonlu diyot:



p-n diyot gösterimi

p-n diyota ilişkin akım-gerilim karakteristiği:

$$I_d = I_o\left(e^{\frac{q \cdot V_d}{k \cdot T}} - 1\right)$$



I_d→iletim yönündeki diyot akımı (A)

V_d→ p-n diyot uçları yönünde oluşan gerilim (V)

I_0→Ters doyma akımı (A)

k→Boltzman sabiti (1.381x10^{-23} j/k)

T→ Kelvin olarak jonksiyon sıcaklığı

q→elektron yükü (1,602x10^{-19}C)

25°C jonksiyon sıcaklığı için $\frac{q \cdot V_d}{k \cdot T}$ katsayısı düzenlenirse;

$$\frac{q \cdot V_d}{k \cdot T} = \frac{1{,}602 \times 10^{-19}}{1{,}381 \times 10^{-23}} \cdot \frac{V_d}{(273+25)} = 38{,}9 \times V_d$$

$I_d = I_O(e^{38{,}9 \cdot V_d} - 1)$ (25°C 'de)

Photovoltaic Cells

PV materials with different band-gap energies have been developed to capture the various energy levels:

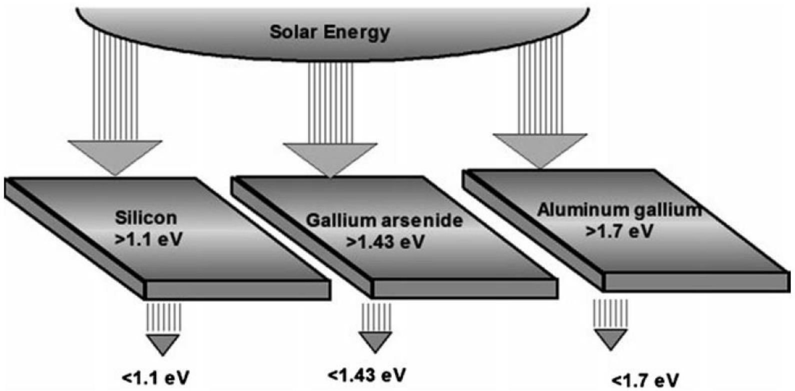


Fig. Band gap energy of various PV materials

Silicon

Silicon is the most popular solar-cell material for commercial applications because it is readily available and cheap. However, to be useful in solar cells, it must be refined to 99.9999% purity. Silicon can be used in three different forms in PV cells.

- Single Crystal
- Amorphous Silicon
- Polycrystalline Silicon Thin Film

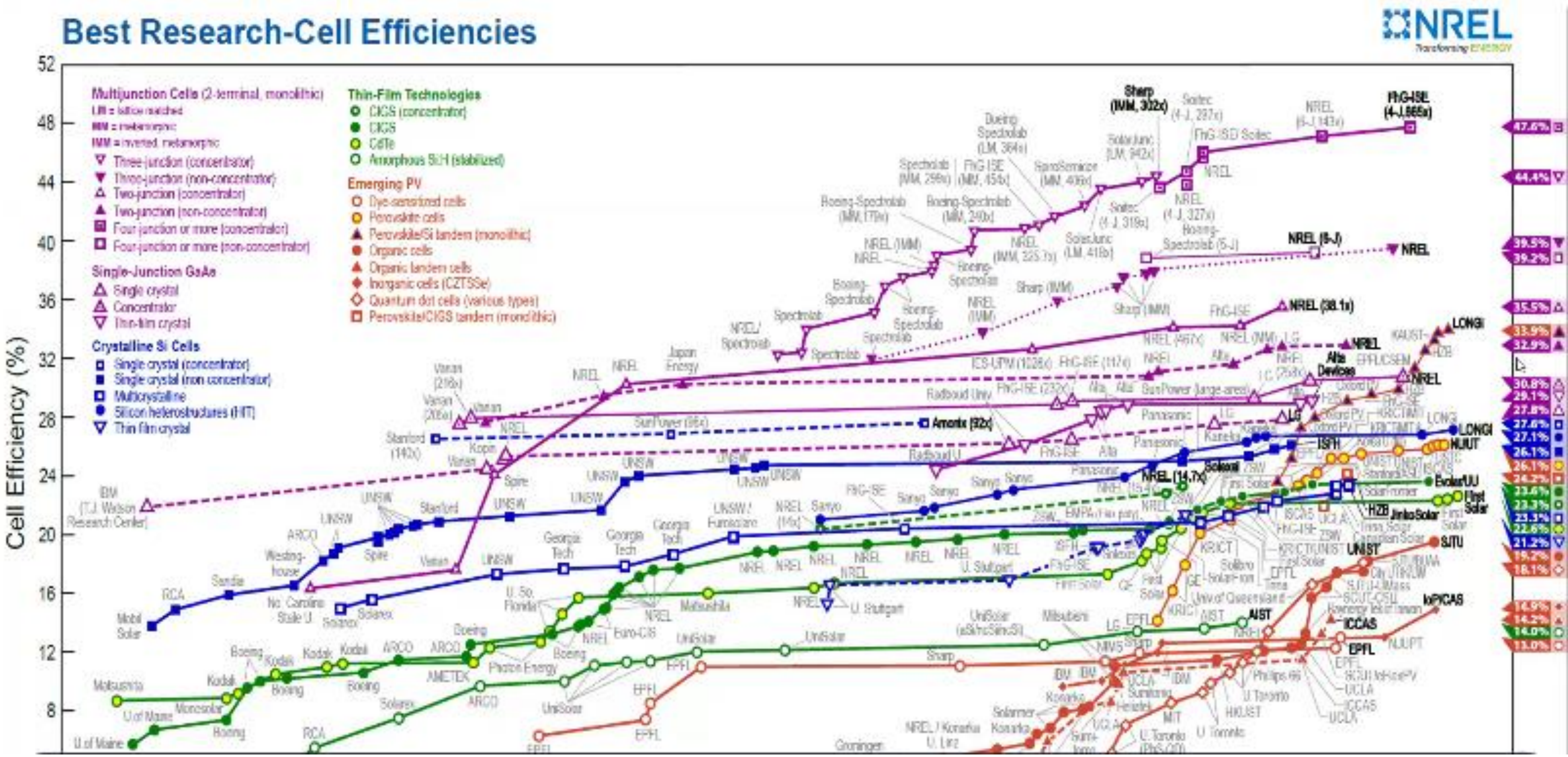
Gallium Arsenide

Gallium arsenide (GaAs) is another material proposed as a semiconducting materials for PV cells. It has several advantages over silicon based PV cells. GaAs is especially suitable for use in multijunction and high-efficiency solar cells for several reasons:

1. The GaAs band gap is 1.43 eV, nearly ideal for single-junction solar cells.
2. GaAs has high absorptivity requiring only a few microns thick film to absorb sunlight. (In comparison, crystalline silicon requires a layer 100 m or more in thickness.)
3. GaAs cells can withstand high temperatures and are less sensitive to heat compare to silicon, making it more suitable for solar concentrator type applications.
4. Other types of gallium based semiconductors can be prepared using aluminum, phosphorus, antimony, or indium that have characteristics complementary to those of gallium arsenide, allowing great flexibility in cell design.
5. GaAs is resistant to radiation damage making it very desirable for space applications.

The disadvantages are cost and toxicity of raw materials.

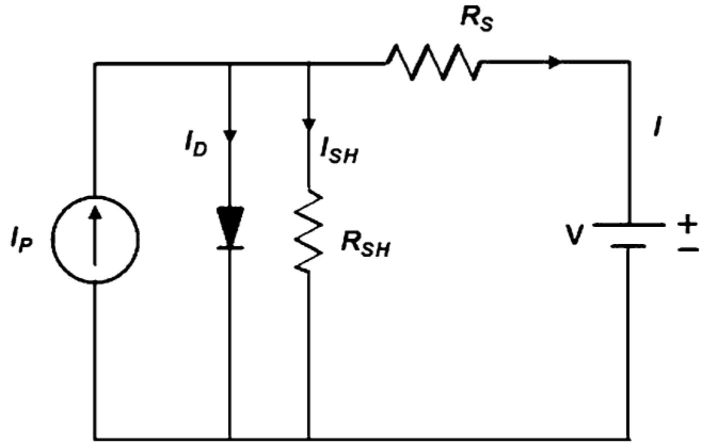
PV Cell Efficiences



Photovoltaic Cells

The current and voltage generated in a solar cell depend on a host of factors. To calculate the current and voltage from solar cells, an equivalent electrical circuit may be considered.

The output current (*I*) from a solar cell is given by:



$$I = I_P - I_D - I_{SH}$$

where, I_P = photon generated current due to photoelectric effect

I_D = diode current
I_{SH} = shunt current

The diode current, assuming an ideal diode, can be expressed by the Shockley diode equation as:

$$I_D = I_0\left(e^{\frac{qV_D}{kT}} - 1\right)$$

where I_0 is the saturation current of the diode, q is the elementary charge (1.6×10^{-19}C), k is the Boltzmann constant (1.38×10^{-23}J/K), T is the cell temperature in Kelvin, and V_D is the measured cell voltage that is either produced (power quadrant) or applied (voltage bias).

The shunt current is given by:

$$I_{SH} = \frac{V_D}{R_{SH}}$$ where, R_{SH} is shunt resistance.

Photovoltaic Cells

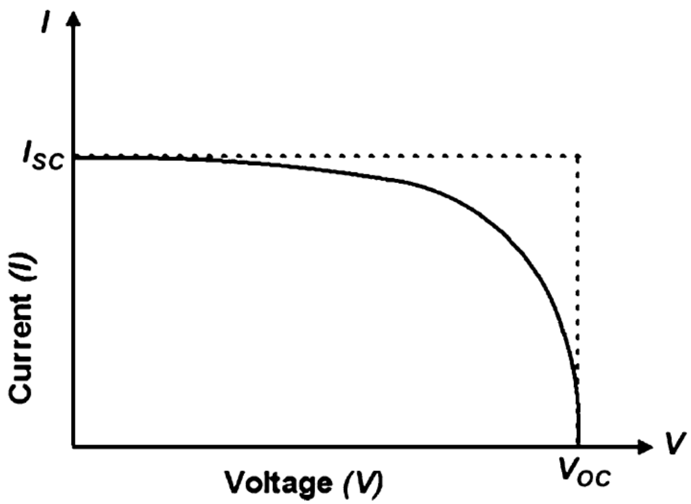
The output voltage (V) from the cell is given by

$$V = V_D - IR_S$$

where, V_D is voltage across both the diode and the shunt resistor, and R_S is the load. Combining all equations gives

$$I = I_P - I_0\left[e^{\frac{q(V+IR_S)}{nkT}} - 1\right] - \frac{V + IR_S}{R_{SH}}$$

A typical I -V curve represented by the above given equation for a semiconductor when illuminated is shown below:



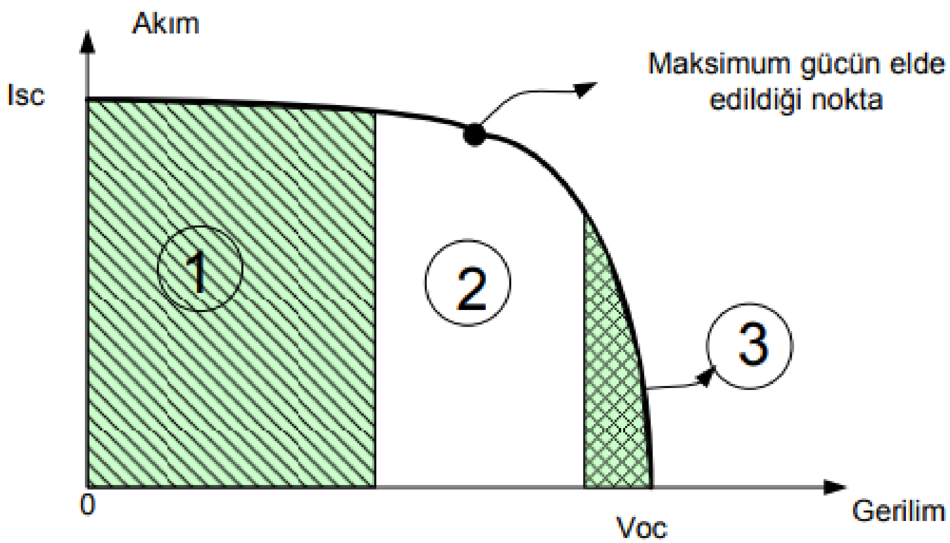
Many performances related parameters for the cell can be determined from this I -V curve:

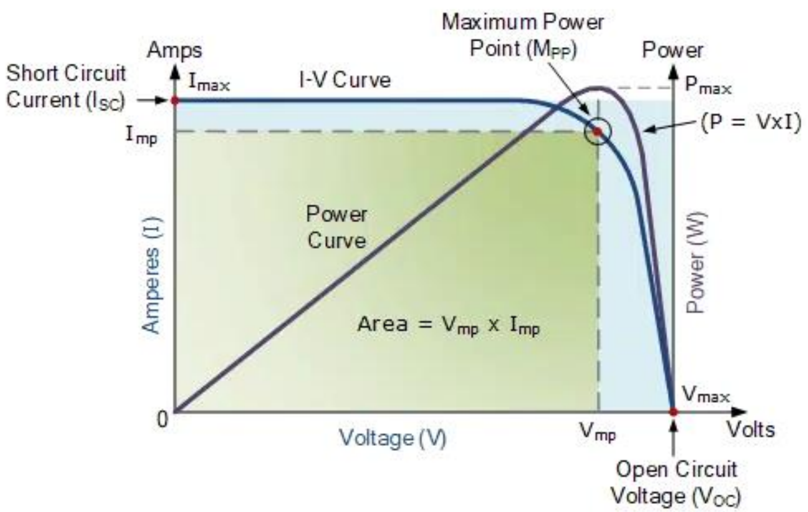
Short Circuit Current (I_{SC})

This refers to the current from a solar cell when the top and the bottom(negative and positive leads) leads are connected in a short circuit. In this situation, the impedance is low and the voltage equals zero.

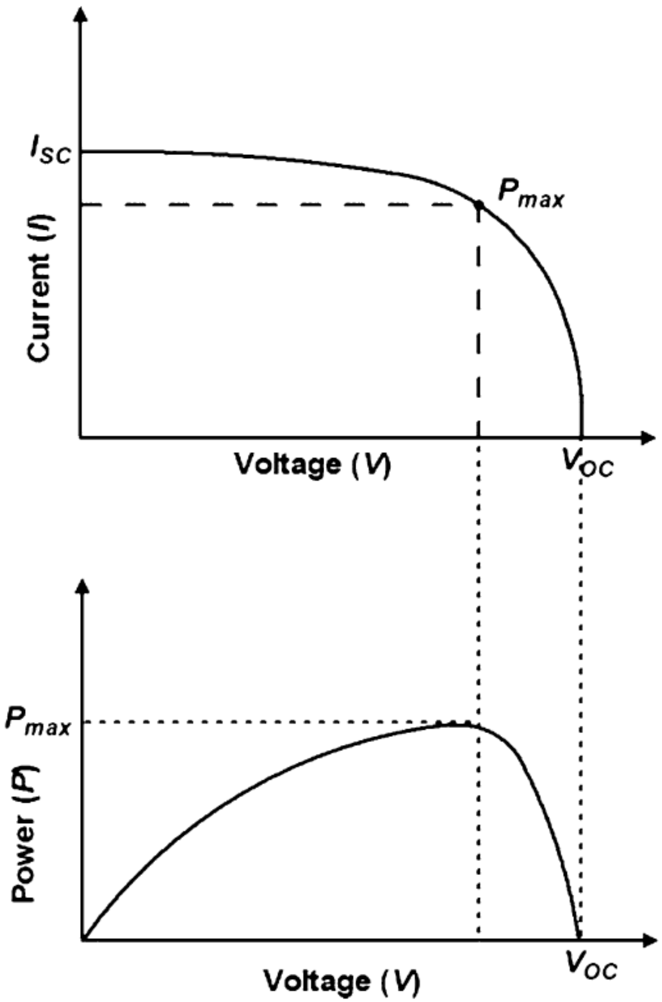
Open Circuit Voltage (V_{OC})

The open circuit voltage (V_{OC}) occurs when there is no current passing through the cell.


Akım
Isc
Maksimum gücün elde edildiği nokta
1
2
3
0
Voc
Gerilim


Maximum Power Point (MPP)
Amps
Power
Short Circuit Current (ISC)
Imax
I-V Curve
Pmax
(P = VxI)
Imp
Power Curve
Amperes (I)
Power (W)
Area = Vmp x Imp
Vmax
0
Voltage (V)
Vmp
Volts
Open Circuit Voltage (VOC)

Photovoltaic Cells



Maximum Power (P_{max})

The power is calculated from $P=IV$. Therefore, at I_{SC} and V_{OC}, the power will be zero, and the maximum value for power will occur between these two values. The voltage and current at this maximum power point are denoted as V_{MP} and I_{MP}, respectively.

Fill Factor

Fill factor is defined as the ratio of the maximum power (P_{max}) to the theoretical power (P_T). The theoretical power is given by the product of open circuit voltage and short circuit current. The fill factor (FF) is considered to be a measure of the quality of a solar cell.

$$FF = \frac{P_{\max}}{P_T} = \frac{I_{MP}\,V_{MP}}{I_{SC}\,V_{OC}}$$

Both series and shunt resistances, which are discussed below, affect the fill factor. An increase in the shunt resistance (R_{SH}) or a decrease in the series resistance (R_S) has a positive effect on the fill factor, resulting in a greater efficiency. Typical fill factors range from 0.5 to 0.82.

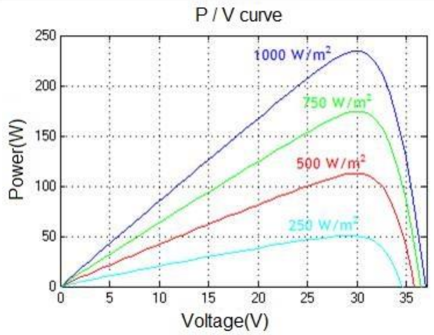
Shunt Resistance

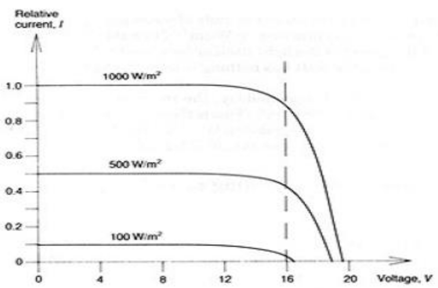
The efficiency of solar cells is reduced by the dissipation of power across internal resistances. The shunt resistance arises from physical defects (scratches), improper emitter formation, metallization over-firing, or material defects, All of them can provide alternative paths for electrons to flow.

Series Resistance

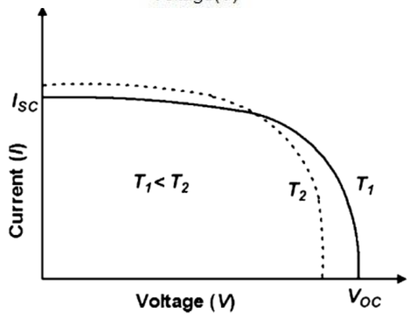
This is caused by metal grids and other similar components of a PV cell. The series resistance may be decreased by using a large cross sectional area for the grid.

Photovoltaic Cells



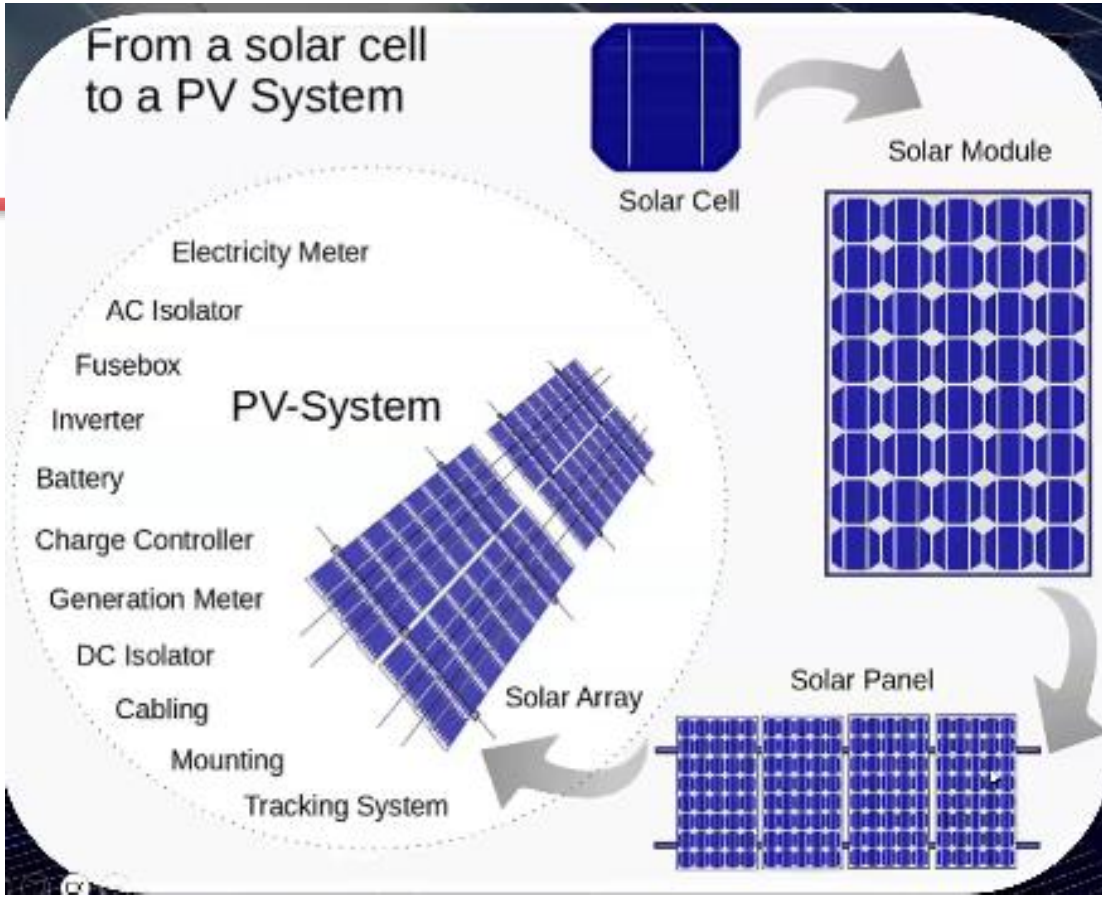


The produced PV power is directly proportional to solar radiation and inversely proportional to temperature.

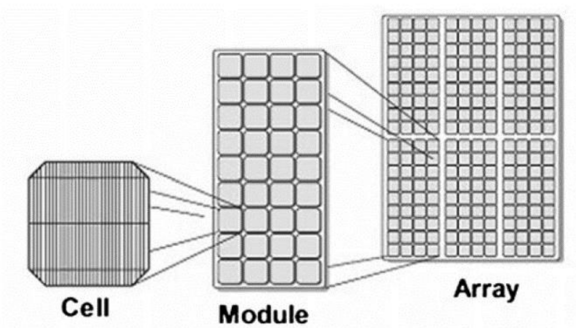


The *shift* in the I-V curve due to higher temperature

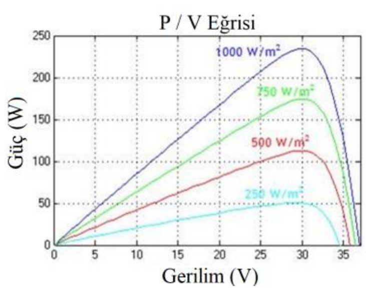
The efficiency of PV cells depends on the temperature at which they are operating. The effect of temperature on an I -V curve is shown in the Figure. When a PV cell is exposed to higher temperatures, I_{SC} increases slightly, while V_{OC} decreases more significantly, and the overall effect is the reduction in efficiency. As a result, higher temperatures decrease the maximum power output P_{max}.

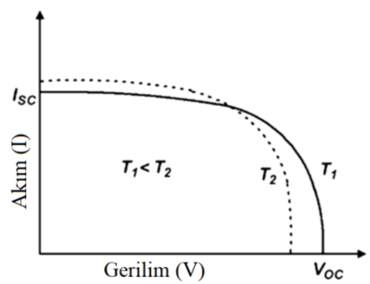


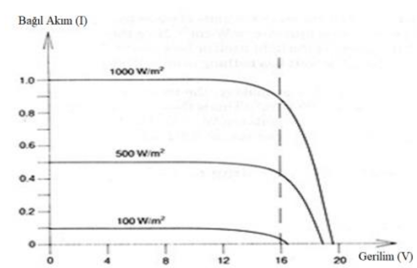
An individual PV cell is the basic unit of a PV system. An individual PV cell typically produces between 1 and 2W. Therefore, a number of individual cells are connected together to form larger units called modules. Modules are then connected to form larger units known as arrays. Several arrays are next joined together to produce large scale power units.

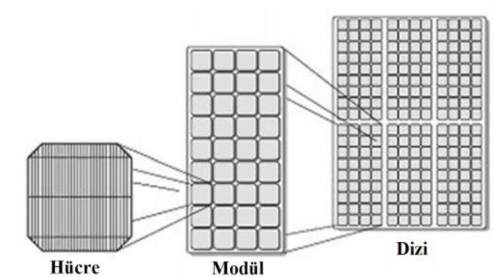


- $I_{SC(T)} = I_{SC} \cdot [1 + \alpha_{Isc} \cdot (T_{hücre} - 25)]$
- $I_{mp(T)} = I_{mp} \cdot [1 + \alpha_{Isc} \cdot (T_{hücre} - 25)]$
- $V_{OC(T)} = V_{OC} \cdot [1 + \beta_{Voc} \cdot (T_{hücre} - 25)]$
- $V_{mp(T)} = V_{mp} \cdot [1 + \beta_{Vmp} \cdot (T_{hücre} - 25)]$
- $P_{mp(T)} = V_{mp(T)} \cdot I_{mp(T)} = FF \cdot V_{OC(T)} \cdot I_{SC(T)}$
- $T_{hücre} = T_{ortam} + \left(\frac{T_{nom} - 20}{0,8}\right) \cdot \mathrm{G}$









Elektriksel Özellikler (STC)

Model		SPE 545	SPE 550
Maksimum Güç	Pmax	545 Wp	550 Wp
Maksimum GüçteGerilim	Vmpp	41.96 V	42.15 V
Maksimum Güçte Akım	Impp	13.01 A	13.07 A
Açık Devre Gerilimi	Voc	49.66 V	49.74 V
Kısa Devre Akımı	Isc	13.80 A	13.86 A
Verimlilik	ηm	21.1 %	21.3 %
Pozitif Güç Toleransı		~ +5W	

Standart Test Koşulları (STC): Işınım 1000 W/m², Hava Kütlesi 1.5, Hücre Sıcaklığı 25°C
Ölçüm Toleransı ± %3

Elektriksel Özellikler (NOCT)

Model		SPE 545	SPE 550
Maksimum Güç	Pmax	410 Wp	413 Wp
Maksimum Güçte Gerilim	Vmpp	38.90 V	39.00 V
Maksimum Güçte Akım	Impp	10.55 A	10.60 A
Açık Devre Gerilimi	Voc	46.70 V	46.80 V
Kısa Devre Akımı	Isc	11.13 A	11.18 A

Nominal Hücre Çalışma Sıcaklığı: Işınım 800 W/m², Hava Kütlesi 1.5, Rüzgar Hızı 1 m/s

Sistem Özellikleri

Maksimum Sistem Gerilimi	1500V DC
İşletme Sıcaklığı	-40°C~ +85°C
Maksimum Seri Sigorta Değeri	30 A
Maksimum Statik Yük	2400 Pa (Rüzgar), 5400Pa (Kar)*
Güvenlik Sınıfı	II
Yangın Sınıfı	UL Type 1
Bifacial Oranı**	%70±10

* Kurulum kılavuzunda belirtilen şekilde montaj yapıldığında

** (Pmax (arkayüzey) / Pmax (önyüzey)) x 100

Termal Özellikler

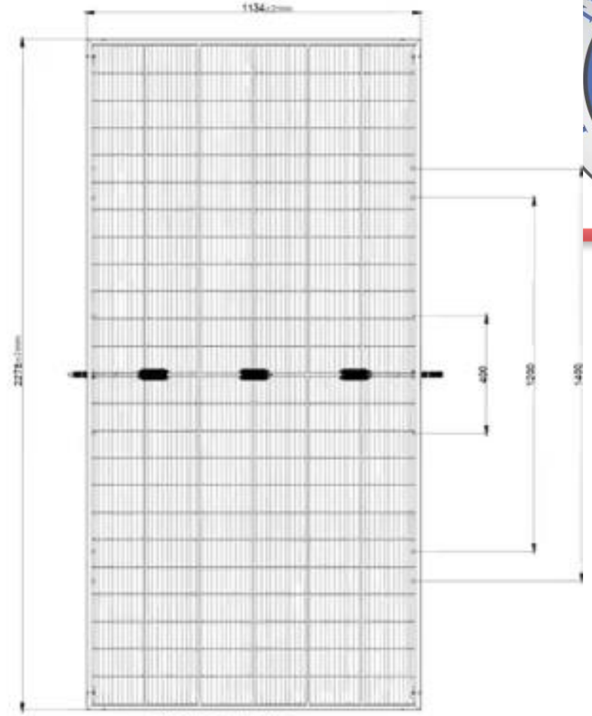
NOCT	45 ±2	°C
Sıcaklık Katsayısı Pmpp	-0.341	% / °C
Sıcaklık Katsayısı Isc	+0.045	% / °C
Sıcaklık Katsayısı Voc	-0.269	% / °C

Mekanik Özellikler

Panel Ölçüleri	2278mm x 1134mm x 35mm
Hücre	Monokristal PERC M10
Hücre Sayısı	144 yarım hücre
Ağırlık	28kg ±1kg
Ön Cam	3.2mm, Yüksek geçirgenlik ve düşük demir oranına sahip temperlenmiş cam
Çerçeve	Eloksal kaplamalı alüminyum
Bağlantı Kutusu	Koruma sınıfı IP68 (3 bypass diyotlu)
Kablo	4 mm² solar kablo, Uzunluk: 400mm (+), 300mm (-) / Uzunluk 1500mm (+), 1300 mm (-)*

* Montaj şekline bağlı olarak kablo uzunluğu değişiklik gösterebilir

Panel Çizimi

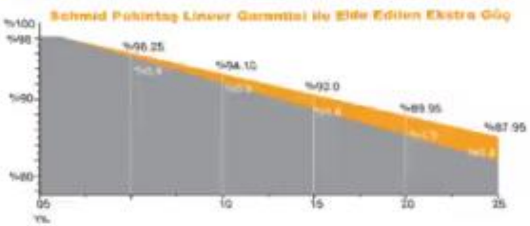


Ölçü Birimi Milimetre

ARKA YÜZEY BIFACIAL GÜÇ KAZANIMI

Kazanım	Modül Tipi	SPE 545	SPE 550
% 5	Panel Gücü (Pmax)	572 Wp	578 Wp
	Panel Verimliliği STC (%)	22.1	22.4
% 15	Panel Gücü (Pmax)	627 Wp	633 Wp
	Panel Verimliliği STC (%)	24.3	24.5
% 25	Panel Gücü (Pmax)	681 Wp	688 Wp
	Panel Verimliliği STC (%)	26.4	26.6

Garanti



Photovoltaic Cells

The PV systems have advantages compared to other common power sources as follows:

- They have long usable lifetime more than 20 years.
- They can be operated in all meteorological conditions and can respond instantly to solar radiation.
- They have a structure that is reliable, modular, robust and has low maintenance requirement.
- They have a quiet operation.

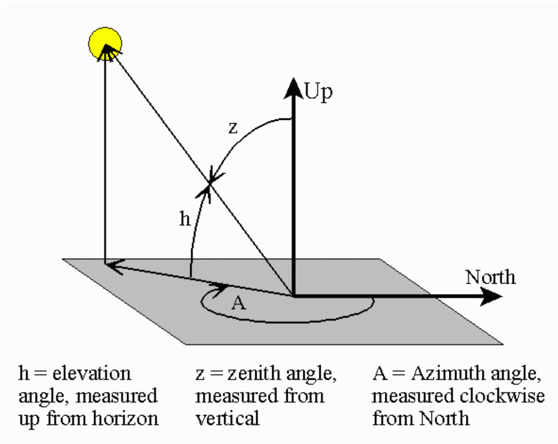
They also have different disadvantages:

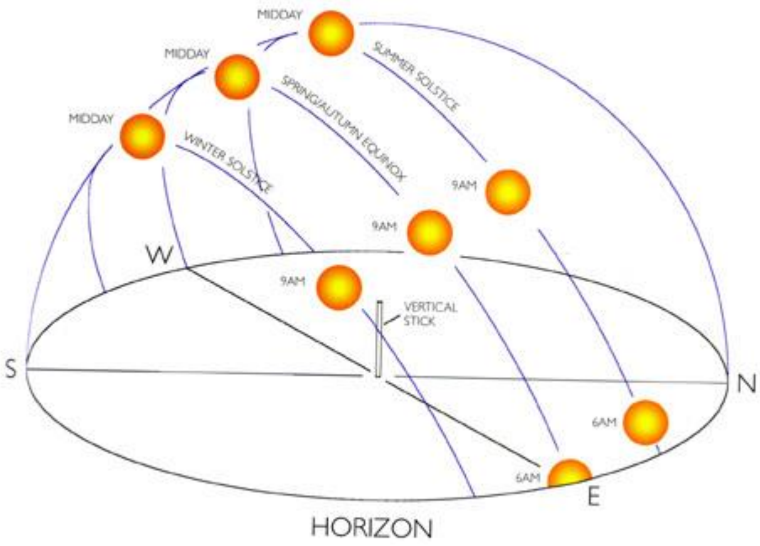
- They have a high installation cost. Their power production is also dependent on meteorological conditions and therefore they mostly require an energy storage system. This further increases the installation cost.
- The efficiency of PV systems is lower than many energy systems.
- The PV system performance reduces due to time due to aging factor in semi-conductor material in its structure.
- Due to partially reflection effect of PV module to solar light, there occurs also additional losses.

FV Sistemlerde Verim Artırıcı Uygulamalar:

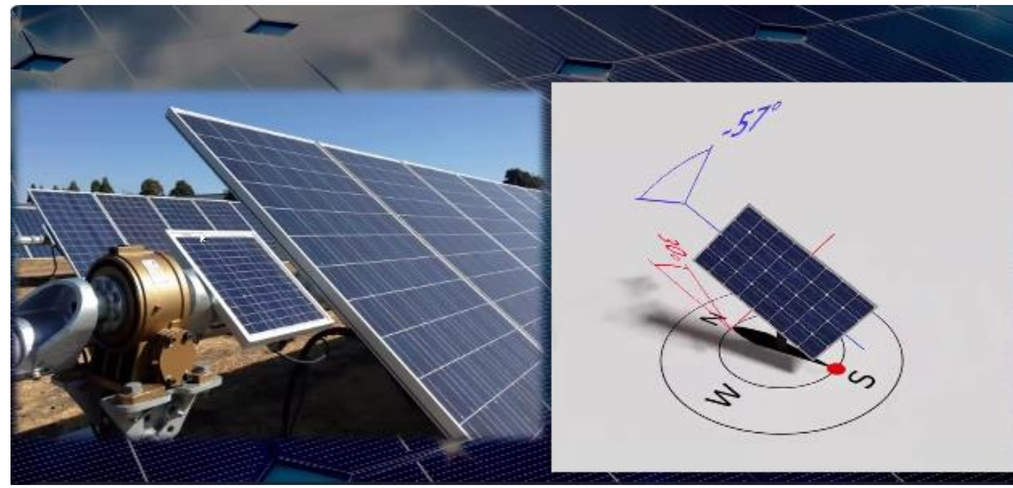
- Güneş Takip Sistemleri
- Maksimum Güç Noktası Takibi (Maximum Power Point Tracking-MPPT)
- Optimum Konumlandırma

➢Güneş Takip Sistemleri



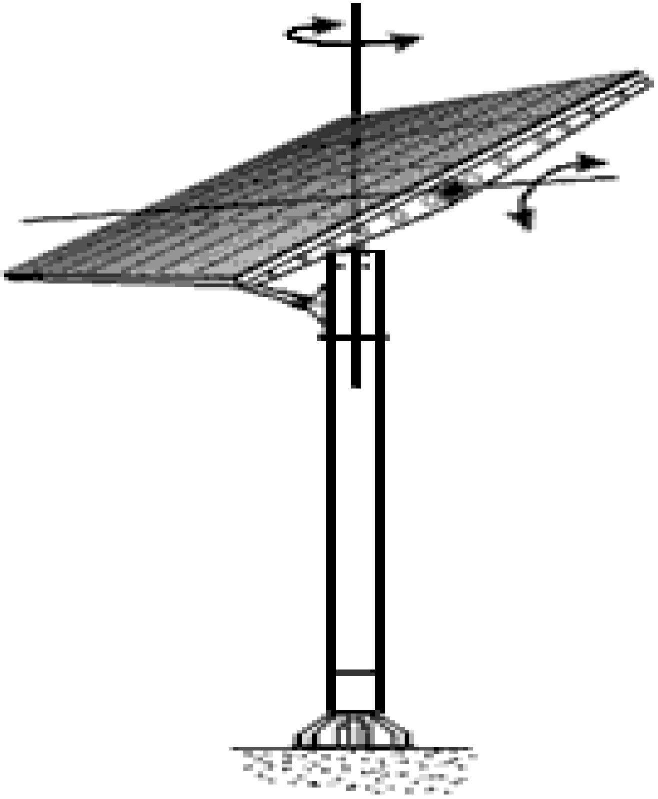


- Sabit Eğim Açılı Sistemler
- Tek Eksende Güneş Takibi
- Çift Eksende Güneş Takibi

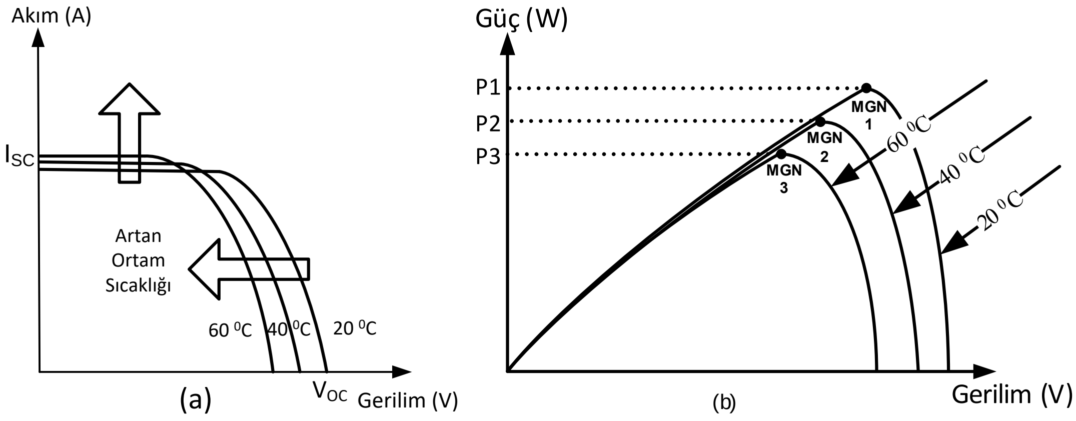


- ***Sabit Eğim Açılı sistemler***

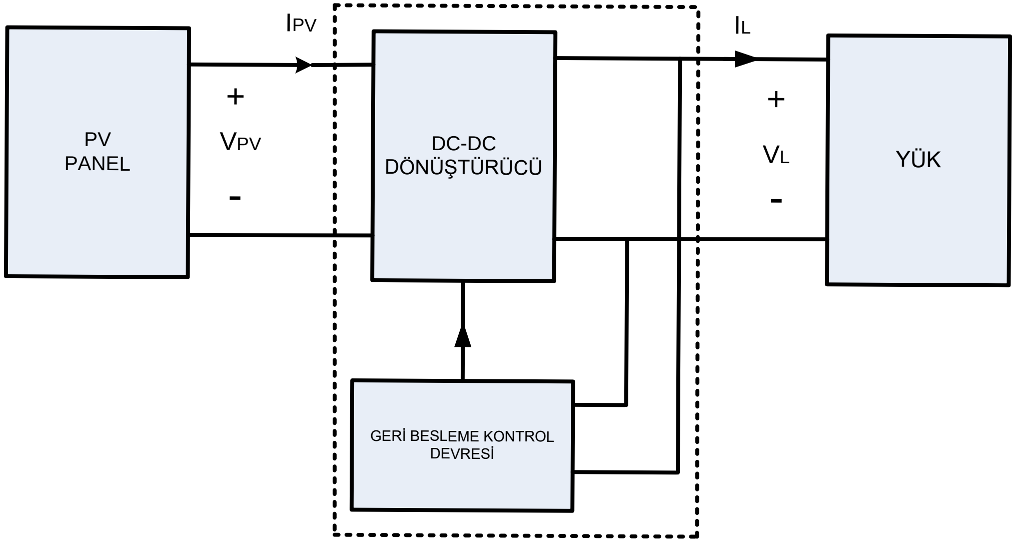
- ***Tek eksende güneş takibi yapan düzenekler***



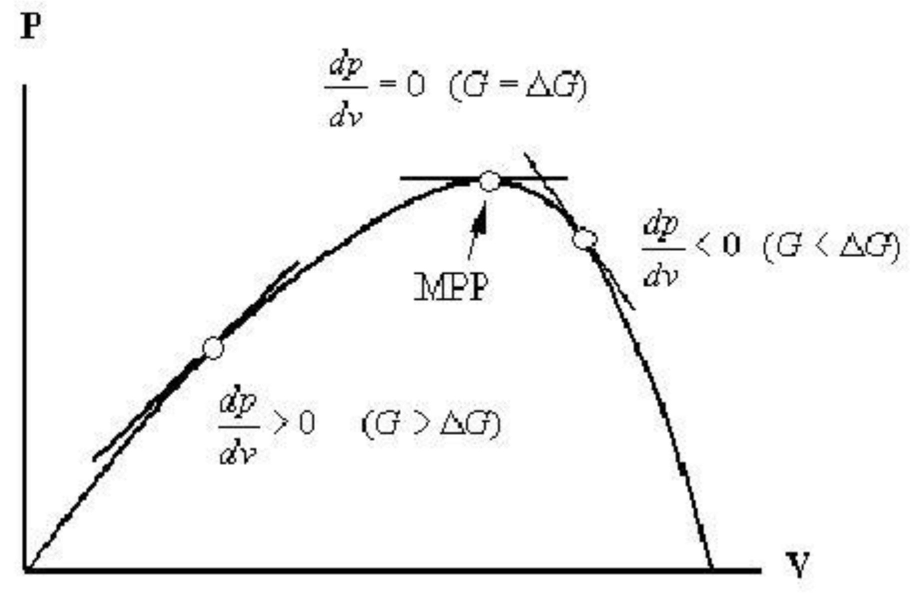
- FV yapılar güneş ışınımı altında çalıştıkça jonksiyon sıcaklıkları artar. Artan sıcaklığa bağlı olarak FV sistemin Akım-Gerilim eğrisi, Güç-Gerilim eğrisi ve Maksimum Güç Noktası (MGN) değişir.



- MPPT devreleri şekilde gösterildiği gibi bir DC-DC dönüştürücü ve bir kontrol devresinden meydana gelir. Bu devreler FV panel ile yük arasındaki gerilim uyuşmazlığını ortadan kaldırarak FV panelin maksimum güç noktasında çalışmasını sağlar.



- Mppt algoritmalarının temel felsefesi, FV yapıdan en fazla gücün bataryaya veya şebekeye aktarılmasının sağlanmasıdır.



SUN2000-100KTL-M1

Smart PV Controller

HUAWEI

10
MPP Trackers

98.8% (@480V)
Max. Efficiency

String-level
Management

Smart I-V Curve Diagnosis
Supported

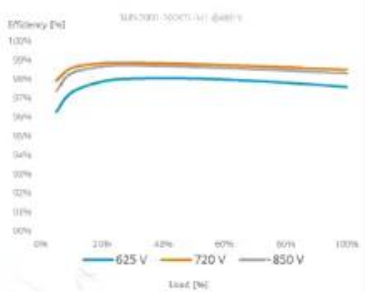
MBUS
Supported

Fuse Free
Design

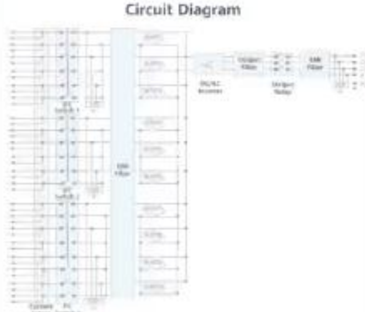
Surge Arresters for
DC & AC

IP66
Protection

Efficiency Curve



Circuit Diagram

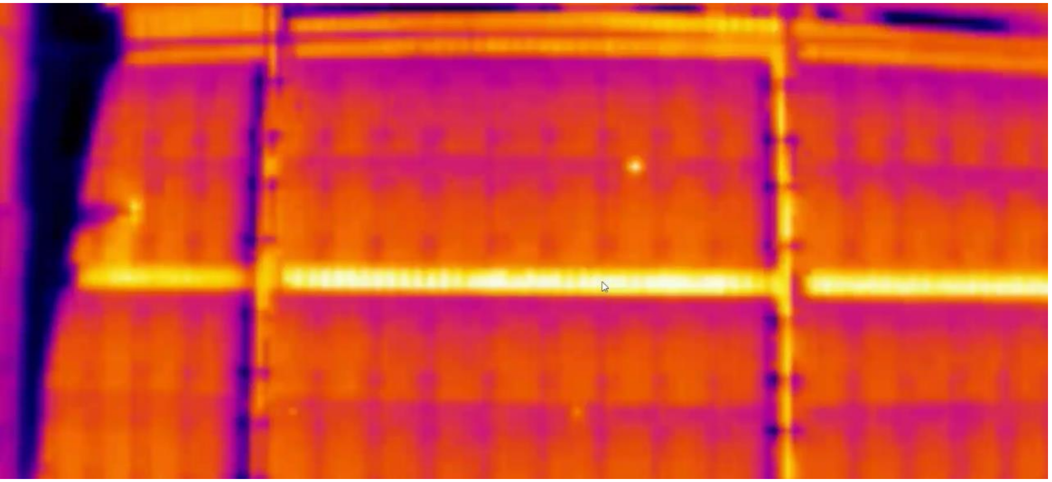
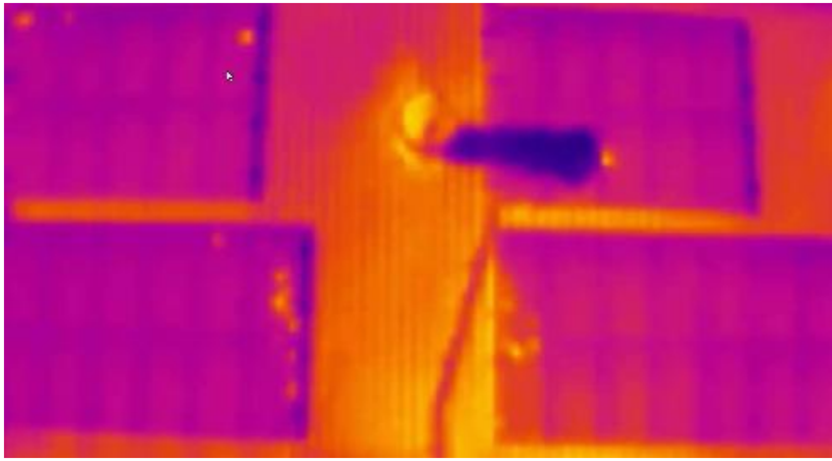


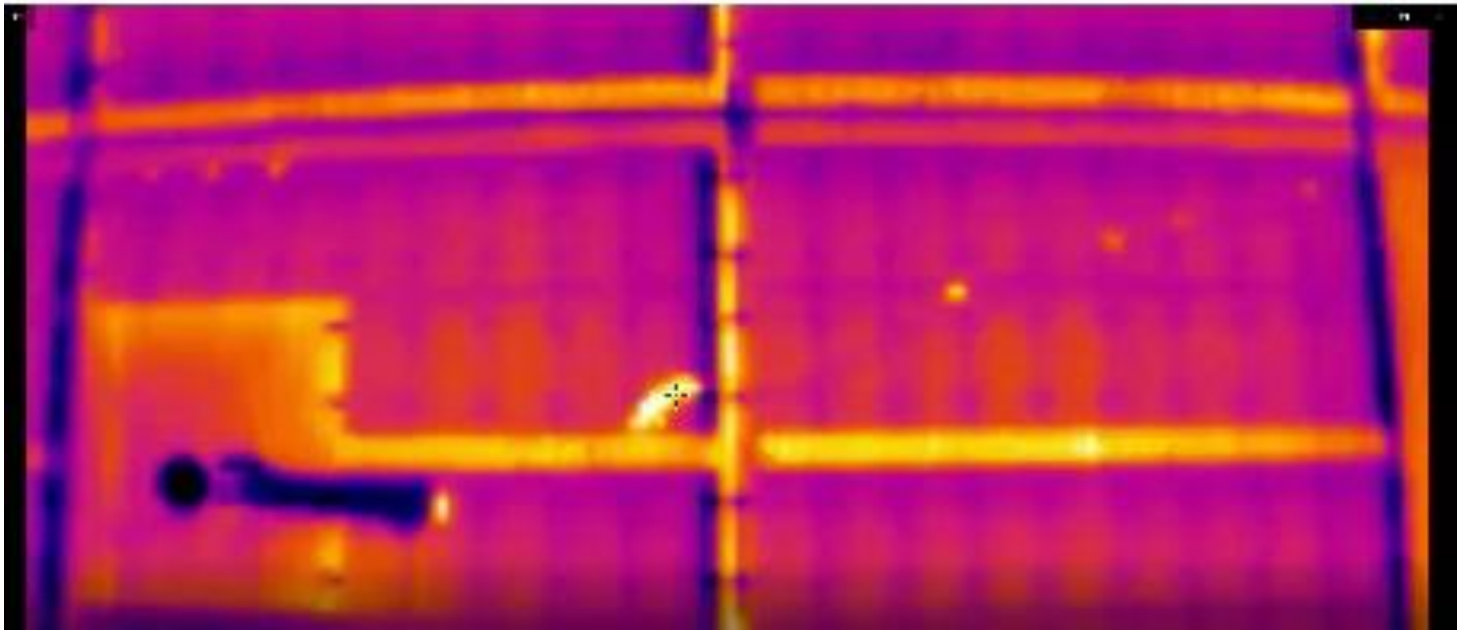
SUN2000-100KTL-M1

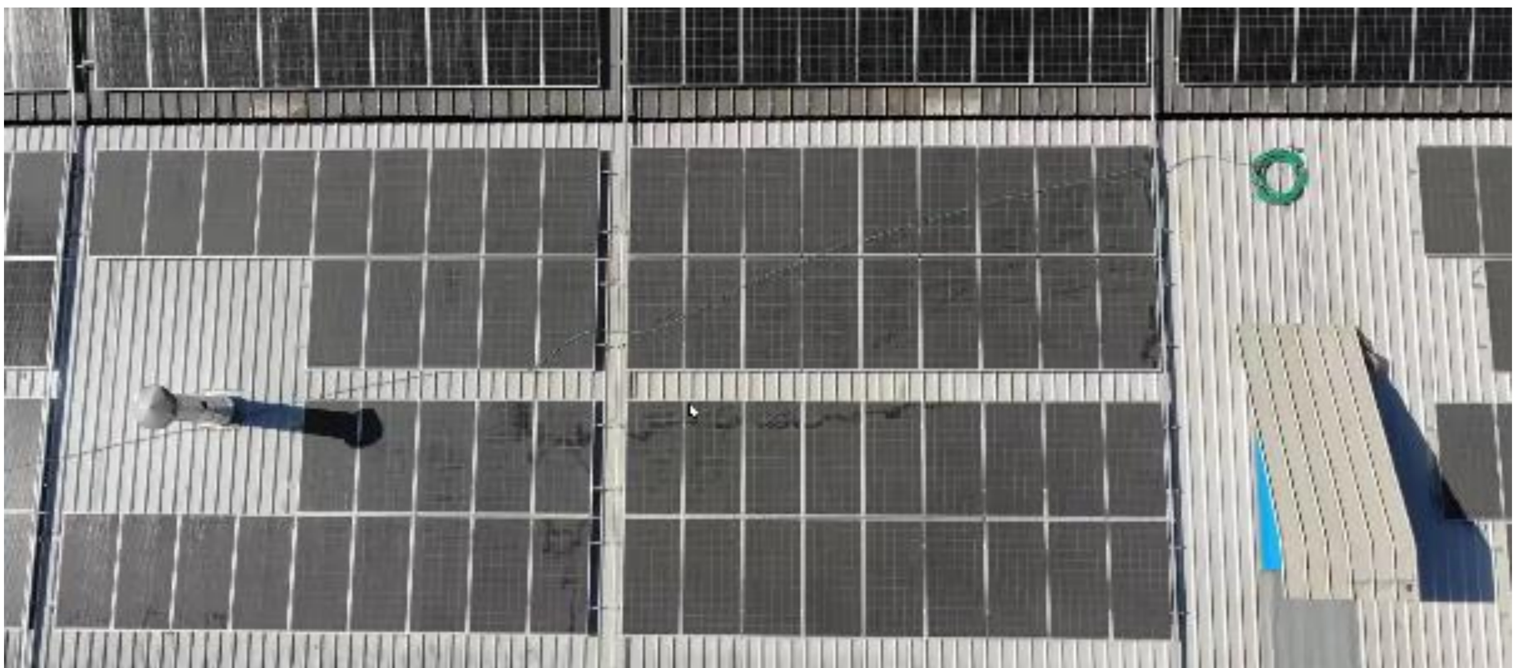
Technical Specification

Technical Specification	SUN2000-100KTL-M1
Efficiency	
Max. efficiency	98.8% @480 V, 98.6% @380 V / 400 V
European efficiency	98.6% @480 V, 98.4% @380 V / 400 V
Input	
Max. Input Voltage [1]	1,100 V
Max. Current per MPPT	26 A
Max. Short Circuit Current per MPPT	40 A
Start Voltage	200 V
MPPT Operating Voltage Range [2]	200 V ~ 1,000 V
Nominal Input Voltage	720 V @480 Vac, 600 V @400 Vac, 570 V @380 Vac
Number of MPP trackers	10
Max. input number per MPP tracker	2
Output	
Nominal AC Active Power	100,000 W
Max. AC Apparent Power	110,000 VA
Max. AC Active Power (cosφ=1)	110,000 W
Nominal Output Voltage	480 V/ 400 V/ 380 V, 3W+(N)+PE
Rated AC Grid Frequency	50 Hz / 60 Hz
Nominal Output Current	120.3 A @480 V, 144.4 A @400 V, 152.0 A @380 V
Max. Output Current	133.7 A @480 V, 160.4 A @400 V, 168.8 A @380 V
Adjustable Power Factor Range	0.8 leading ... 0.8 lagging
Max. Total Harmonic Distortion	< 3%
Protection	
Input-side Disconnection Device	Yes
Anti-islanding Protection	Yes
AC Overcurrent Protection	Yes
DC Reverse-polarity Protection	Yes
PV-array String Fault Monitoring	Yes
DC Surge Arrester	Type II
AC Surge Arrester	Type II
DC Insulation Resistance Detection	Yes
Residual Current Monitoring Unit	Yes
Arc Fault Protection	Optional
Communication	
Display	LED Indicators; WLAN adaptor + FusionSolar APP
RS485	Yes
USB	Yes
Smart Dongle-4G	4G / 3G / 2G via Smart Dongle – 4G (Optional)
Monitoring BUS (MBUS)	Yes (isolation transformer required)
General Data	
Dimensions (W x H x D)	1,035 x 700 x 365 mm
Weight (with mounting plate)	90 kg
Operating Temperature Range	-25°C ~ 60°C
Cooling Method	Smart Air Cooling
Max. Operating Altitude	4,000 m (13,123 ft.)
Relative Humidity	0 ~ 100%
DC Connector	Staubli MC4
AC Connector	Waterproof Connector + OT/DT Terminal
Protection Degree	IP66
Topology	Transformerless
Nighttime Power Consumption	< 3.5 W

Standard Compliance (more available upon request)





THANK YOU…