Photovoltaic Power Plants

Lecture #6

Solar Photovoltaic Power

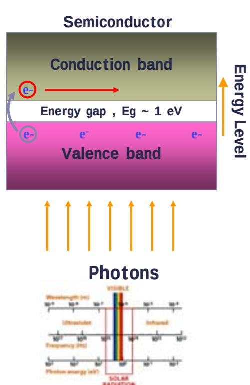
- **6kW from a photovoltaic system instead of a thermal power plant can reduce annual pollution by**
  - 3 lbs. of NO_x (Nitrogen Oxides),
  - 10 lbs. of SO_2 (Sulfur Dioxide), and
  - 10530 lbs. of CO_2 (Carbon Dioxide).

Photoelectric Effect

- Photons strike solar cell, electricity generated via the photoelectric effect
- Electrons flow to front and back contacts. Then, electricity powers devices attached to contacts…

Energy from absorbed photons can excite valence electrons in the atoms of some materials and elevate them into the conduction band.

- The valence and conduction band are determined by electronic energy levels in the bonding between atoms.
- When a photon strikes an electron if it has the amount of energy to break the electron-electron bond a free electron will be released, resulting in a positive "hole" and a negative electron.



Energy of a Photon

Energy (E) in a photon: $$E = h\upsilon = \frac{hc}{\lambda}$$

- h = Planck's constant = 6.63 × 10-34 J/s
- ν = frequency (s-1)
- c = velocity of light in vacuum = 3.0 × 108 m/s
- λ = wavelength (m)

Wavelength of green light: λ = 500 nm = 5 × 108 m)

$$E = \frac{\left(6.63\times10^{-34}\,\frac{J}{s}\right)\left(3.0\times10^{8}\,\frac{m}{s}\right)}{500\times10^{-9}\,m} = 3.978\times10^{-19}\,J$$ of energy in one photon

Sun Light Power Density

- 1 mol = 6.022×10^{23}
- Energy from one mole of photons is:

$$E = \left(\frac{3.978 \times 10^{-19}\, J}{\text{photon}}\right)\left(\frac{6.022 \times 10^{23}\ \text{photons}}{\text{mol of photons}}\right) = 239.6 \frac{\text{kJ}}{\text{mol of photons}}$$

- Amount of photons with 300 nm ≤ λ ≤ 3000 nm that arrives Earth :

$$\approx 3.8 \times 10^{21} \frac{photons}{m^2 \cdot s}$$

- Therefore, a calculation can be made so as to show the power density of sunlight at the stratosphere.

Solar Cells

- Solar light is directly converted into electricity with modules constituted of many photovoltaic solar cells.
- Solar cells are usually manufactured in form of fine films or wafers.
- They are semiconductor devices capable of converting the incident solar energy into dc current, with efficiency varying from 3% to 31%, depending on the technology, the light spectrum, temperature, design and the material of the solar cell

Solar Cells – Three Bullets' History

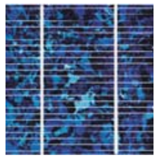
- The effect was first observed in metal selenium in 1877.
- A deeper understanding of the scientific principles, provided by Einstein in 1905 and Schottky in 1930, was required before efficient solar cells could be made.
- A silicon solar cell which converted 6% of sunlight into electricity was developed by Chapin, Pearson and Fuller in 1954, and this kind of cell was used in orbiting space satellites as from 1958.

Solar Cells – Manufacturing Principles

- Semiconductor-grade polysilicon is heated to melting temperature, and trace amounts of boron are added to the melt to create a P-type semiconductor material.
- An ingot is formed by :
  - Growing a pure crystalline silicon ingot from a seed crystal drawn from the molten polysilicon
  - Casting the molten polysilicon in a block, creating a polycrystalline silicon material.
- Individual wafers are sliced from the ingots using wire saws and then subjected to a surface etching process.
- After the wafers are cleaned, they are placed in a phosphorus diffusion furnace, creating a thin N-type semiconductor layer around the entire outer surface of the cell.
- Next, an anti-reflective coating is applied to the top surface of the cell, and electrical contacts are imprinted on the top (negative) surface of the cell.
- An aluminized conductive material is deposited on the back (positive) surface of each cell, restoring the P-type properties of the back surface by displacing the diffused phosphorus layer.
- Each cell is then electrically tested, sorted based on current output, and electrically connected to other cells to form cell circuits for assembly in PV modules.

The Three Most Common Types of Solar Cells

Monocrystalline



Polycrystalline

Amorphous Thin-Film

Monocrystalline and Polycrystalline Cells

- Solar cells that are created from monocrystalline or (single crystal) technology are cut from a silicon ingot that is grown from a single crystal, in other words a crystal that has grown in only one plane or (one direction). Single crystalline are more expensive to manufacture and typically have a slightly higher efficiency than do conventional polycrystalline cells resulting in smaller individual cells and thus typically a slightly smaller module.
- Solar cells that are created from polycrystalline or (multicrystalline) technology are cut from a silicon ingot that is grown from multifaceted crystalline material, or a crystal that grows in multiple directions. Conventional multicrystalline solar cells typically have a slightly lower efficiency resulting in larger individual cells and thus typically a slightly larger module.
- It's important to keep in mind that a 100 watt module is a 100 watt module whether it was made from polycrystalline cells or monocrystalline cells, the area is certainly different.

Thin Films

- Thin film photovoltaic cells use layers of semiconductor materials only a few micrometers thick, attached to an inexpensive backing such as glass, flexible plastic, or stainless steel.
- Semiconductor materials for use in thin films include amorphous silicon (a-Si), copper indium diselenide (CIS), and cadmium telluride (CdTe).
- Amorphous silicon has no crystal structure and is gradually degraded by exposure to light.
- The mechanism of degradation is called the Staebler-Wronski effect. Better stability requires the use of a thinner layers in order to increase the electric field strength across the material. However, this reduces light absorption and hence cell efficiency.

Some Solar Cell Manufacturers

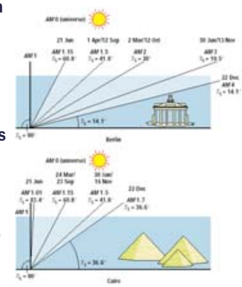
- BP Solar http://www.bpsolar.com
- Sharp http://solar.sharpusa.com
- Matrix http://www.matrixsolar.com
- Kyocera http:// www.kyocerasolar.com
- GE Solar http://www.gepower.com/prod_serv/products/solar/en/index.htm
- Shell Solar http://www.shell.com/shellsolar
- UNI-Solar http://www.uni-solar.com/
- DIY - Do It Yourself http://www.biodesign.org.uk

Solar Irradiance and Irradiation

- Solar irradiance decreases with the square of the distance to the sun. Since the distance of the earth to the sun changes during the year, solar irradiance outside the earth's atmosphere also varies between 1325 W/m² and 1420 W/m².
- On Mars, solar irradiance is below 600 W/m² – a factor to be considered when designing PV-powered satellites.
- The total specific radiant power, or radiant flux, per area that reaches Earth is defined as Spectrum AM (air mass) 0 (extraterrestrial).
- As a worldwide terrestrial average Spectrum AM 1.5 is used.
- Irradiance is measured in W/m² and has the symbol *E*. When integrating the irradiance over a certain time period it becomes solar irradiation.
- Irradiation is measured in either J/m² or Wh/m², and represented by the symbol *H*. For daylighting purposes, only the visible part of the sunlight is considered.

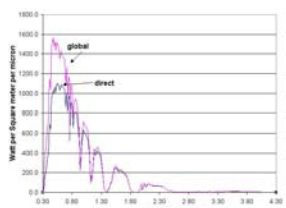
Sun Height vs. Air Mass (AM)

- If the sun is perpendicular to the earth's surface, sunlight only has to pass through the air mass (*AM*) of the atmosphere once. Therefore, this state is called AM 1. In all other cases, the route of the solar radiation through the atmosphere is longer. This way depends on the sun's height. *AM* 2 indicates that the path of the sunlight through the atmosphere is twice *AM* 1. This is the case if the sun is 30° above the horizon (γ_s = 30°). In general, the definition of the air mass is *AM* = 1/sin(γ_s).
- The figure shows the variation of the air mass during the year for Berlin and Cairo at solar noon – that is, the time during a day with the highest sun elevation, which depends on longitude, latitude and date. It is obvious that in Cairo the air mass is always less than in Berlin.



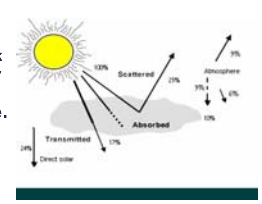
Direct and Global Radiation ASTM E892 and E891

- The photovoltaic (PV) industry, in conjunction with the American Society for Testing and Materials and U.S. government developed and defines two standard terrestrial solar spectral irradiance distributions.
- The two spectra define a standard direct normal spectral irradiance and a standard total (global, hemispherical, within 2-pi steradian field of view of the tilted plane) spectral irradiance.
- The receiving surface is defined in the standards as an inclined plane at 37° tilt toward the equator, facing the sun (i.e., the surface normal points to the sun, at an elevation of 48.81° above the horizon).



Luminous Power at Ground Level

- Gamma rays emitted by the sun reach the terrestrial orbit few minutes after they leave the sun surface, crossing approximately 150 million kilometers.
- Clouds reflect about 18% of sunlight back into space, 9% is scattered backwards by air molecules and 9% is actually directly reflected off the surface back into space. Therefore, the travel through the atmosphere decreases the radiation at Earth surface to less than 40% than the level in the stratosphere.



- In a clear day, at noon, the luminous power at the ground level is considered approximately, 1,000 Watts per square meter.
- Most of the energy has wavelengths in the range 300 nm ≤ λ ≤ 3000 nm (average λ = 556 nm).

Solar Power Density (Formula Based)

$$\rho = \rho_o \cos\xi\left(\alpha_{dt} - \beta_{wa}\right)\alpha_p$$

ρ: solar power density on earth in kW/m^2

ρ_o: extraterrestrial power density ($1.353\ kW/m^2$)

ξ: zenith angle (angle from the outward normal on the earth surface to the center of the sun)

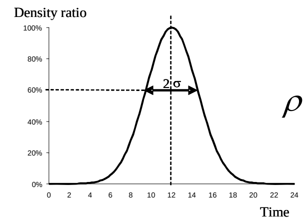
α_{dt}: direct transmittance of gases except for water (the fraction of radiant energy that is not absorbed by gases)

α_p: is the transmittance of aerosol

β_{wa}: water vapor absorptions of radiation.

Solar Power Density (Formula Based) – Cont.

- **Daily Solar Power Density**



$$\rho = \rho_{\max} e^{\frac{-(t-t_o)^2}{2\sigma^2}}$$

t: hour of the day using the 24 hr clock

ρ_{max}: the maximum solar power density

t_o: time at ρ_{max} (noontime in the equator)

σ: standard deviation

Solar Efficiency (η)

$$\eta = \frac{\rho}{\rho_0} \qquad \eta = \cos\xi\left(\alpha_{dt} - \beta_{wa}\right)\alpha_p = 5-70\%$$

An area located near the equator has the following parameters:

$$\alpha_{dt} = 80\%,\ \alpha_p = 95\%,\ \beta_{wa} = 2\%$$

Assume that the standard deviation of the solar distribution function is 3.5hr. Compute the solar power density and solar efficiency at 3:00 PM.

Solution

At noon

$$\rho_{max} = \rho_o \cos\xi\left(\alpha_{dt} - \beta_{wa}\right)\alpha_p$$

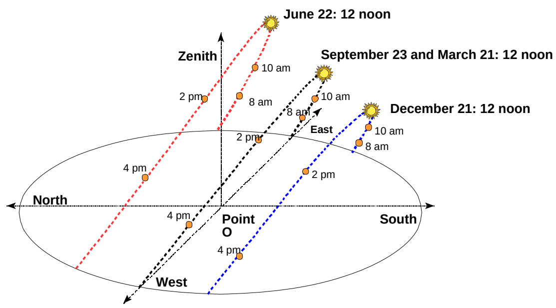
$$= 1353 * \cos(0) * (0.8-0.02) * 0.95 = 1.0\ \ kW/m^2$$

At 3:00PM

$$\rho = \rho_{max}\, e^{\frac{-(t-t_o)^2}{2\sigma^2}} = 1.0 * e^{\frac{-(15-12)^2}{2*(3.5)^2}} = 0.693\ kw/m^2$$

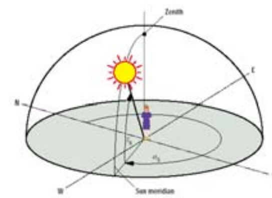
$$\eta = \cos(0) * (0.8-0.02) * 0.95 = 74\%$$

Sun Path



Angles for Description of the Position of the Sun

- **Sun height, height angle, solar altitude angle or elevation γ_S**
  This is the angle between a line that points from the site towards the center of the sun, and the horizon. Zenith angle is the opposite angle to the sun height (90° – γ_S).
- **Sun azimuth α_S**
  The sun azimuth α_S is the angle, measured clockwise, between geographical North and the point on the horizon directly below the sun (at the end of a line running from the center of the sun to the horizon).

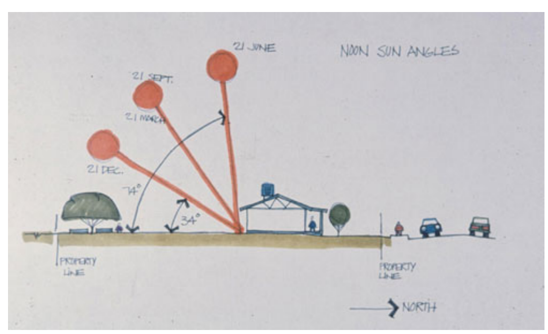


- **Another definition used in Architecture the sun azimuth is counted as zero when the sun is in the South and measured anticlockwise.**

Array Orientation

- **For the installation site we have to evaluate the surroundings for best orientation.**
- **A North-South cross section cut, may help in evaluate the incidence angle and any possible block of sunlight.**
- **A East-West cross section, is an open wide view in how the sun will travel from sunrise to sunset and possible shading along that path.**

A N-S Sketch Would Help in Defining Possible Shading Throughout the Year

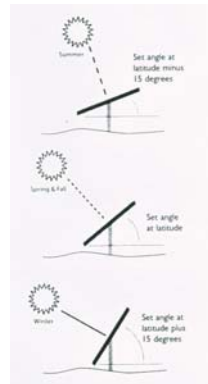


Basic Array Angle Optimization

- **Azimuth Angle**
  A PV array generates the most energy when it faces due South. The azimuth angle determines the direction the array faces with respect to due South.
- **Array Tilt**
  The tilt of the array will determine how much energy the PV array will generate as well.
- **Array Face**
  - An array will generate the most energy annually when it **faces South** and has an **array tilt equal to the latitude of that location.**
  - For the **southern hemisphere** the array will have to **face North.**

Tilt to Meet the Sun

- **The angle at which sunlight hits the solar array changes every day.**
- **March 20 and September 22 are the vernal and autumnal equinoxes, where the array angle should be equal to the latitude.**
- **If you have a ground mounted array, you may be able to adjust +15º for Winter or -15º for Summer correction.**



Tilt Adjustable Solar Array

Tilt Adjustable, Roof Mounted

Power for Fossil Fuel :>)

Roof Installation, no tilt, but large area…

Implications of Shading

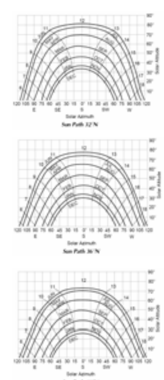
- Sun height
- Sun azimuth
- Surrounding objects

- To asses the shading resulting from the location the **shadow outline of the surroundings should be recorded at the center of the PV panel**. A diagram of the sunpath with **sun elevation angle plotted againts azimuth** should be used, and the **geometric features of objects height and their distances should be marked** along the times of the year they would block the sunshine.

E-W Wide View : Sun Path Diagram

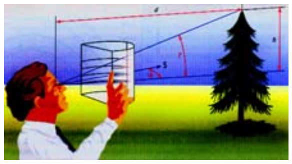
- 32° for Southern California
- 36° for Central California
- 40° for Northern California

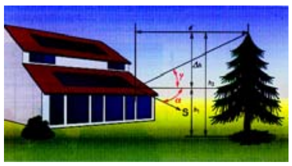
- Find the **intersection** of the two curves corresponding to the **month and hour of interest**.
- From this point, read **solar altitude** from scale at right and read **solar azimuth** from scale at the bottom. This is the **sun's position at that month and hour**.



Shading Analysis

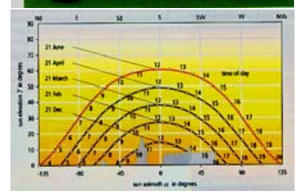
- Record elevation angles for all obstacles surrounding the solar system.
- The elevation angles could be determined by a shading analyser (camera with digital software).
- However, a transparency arranged in a semi-circle will help in recording the elevation and azimuth angles
- Trees have a transmission factor that can be evaluated with some simulation programs, such as PV-Sol or PV-DesignPro





Shading Analysis – Cont.

- The outcome of the shading analysis is the silhouette of the shading caused by the surrounding in a wide-angle view.
- The geometric features should be transferred to the sun path diagram.
- For example, the figure on the left shows that the location is 50% shaded on December 21st, in the morning and afternoon the sun penetrates for one hour or so.
- From February 21st onwards no more shading occurs and the solar system has clear sunlight from March to October.



Solar Pathfinder Device

- The equipment has a compass for magnetic north and corrections for magnetic deviation based on your latitude.
- By using suncharts for the latitude the user is able to trace the reflection of the skyline onto the sunchart.
- **Information Provided by this Equipment:**
  - Actual sunrise and sunset times, for each month, at a specific location.
  - Times of the day when objects will shade the site, for each month of the year.
  - Percent of solar radiation available for the average day each month.
  - Percent of solar radiation lost to obstacles due to shadows for each hour and month.
  - Output info is available from the Solar Pathfinder in a variety of units.

http://www.solarpathfinder.com

Equivalent Model of A Solar Cell

- The equivalent electrical circuit of a single cell is represented below from where it can be derived the following equation:

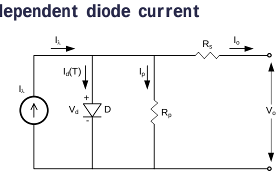
$$I_o = I_\lambda - I_d - I_p$$

where:

I_λ is the photon current, which depends on the light intensity and its wavelength

I_d is the Shockley temperature dependent diode current

I_p is the PV cell leakage current



$k = 1.38047 \cdot 10^{-23} Joule/K$

Solar Cell Modeling

- if the photon current is known for certain standard illumination intensity, then it is possible to approximately obtain the photon current for every other levels through the following expression:

$$I_\lambda = \frac{L}{L_s} I_{\lambda o}$$

- The diode current is given by:

$$I_d = I_s(e^{qV_d/\eta kT} - 1)$$

where

I_s is the reverse saturated current of the diode, typically $100pA$ for the silicon cell

$k = 1.38047 \cdot 10^{-23} Joule/K$ is the constant of Boltzman

$q = 1.60210 \cdot 10^{-19} Coulomb$ is the electron charge

V_d is the diode voltage in Volts

η is an empirical constant

$T = 273.2 + t_C$ is the absolute temperature in function of the temperature Celsius

- A parallel resistance can represent the internal losses, or leakage current, across the Shockley diode. These values usually range between 200 and 300Ω. Also, there is a series resistance between the photon current source and the load across the photovoltaic cell terminals. The usual value of this resistance is very small (0.05 to 0.10Ω) directly reflecting on the manufacturing quality of the PV cells.
- The equation becomes:

$$I_o = I_\lambda - I_s(e^{qV_d/\eta kT} - 1) - \frac{V_d}{R_p}$$

- The diode voltage as function of load is :

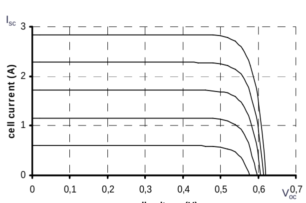
$$V_d = I_o(R_s + R_L) = V_o(1 + \frac{R_s}{R_L})$$

- Therefore, the output current becomes:

$$I_o = \frac{R_p}{R_p + R_s + R_L}[I_\lambda - I_s(e^{qV_d/\eta kT} - 1)]$$

Current vs. Voltage

- And a family of curves may define the operating range :



Output Power and Efficiency

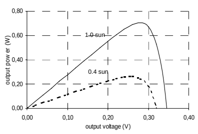
- The output power of the cell is the product of voltage by the output current given by previous equation, which gives:

$$P_m = \frac{V_{om}(I_s + I_\lambda)}{1 + \eta kT / qV_{om}((1 + R_s / R_L)}$$

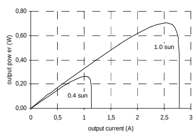
- If the incident flux power, P_i , on the cell is known, the conversion efficiency for the maximum power becomes:

$$\eta_m = \frac{P_m}{P_i} = \frac{V_{om}(I_s + I_\lambda)}{P_i(1 + kT / \eta qV_{om})((1 + R_s / R_L)}$$

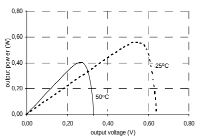
Effects of Sun Illumination and Temperature on the Output Power



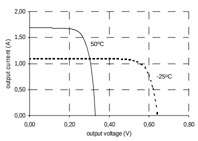
(a) effects of the illumination level on the power versus voltage characteristic



(b) effects of the illumination level on the power versus current characteristic



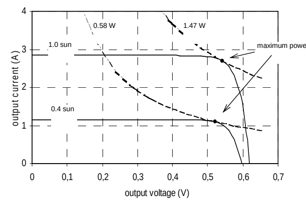
(c) effects of the temperature on the power versus voltage characteristic



(d) effects of the temperature on the voltage versus current characteristic

Peak Power Tracking

- As the current vs. voltage curve changes, the maximum power at the knee of the curve will move !



Solar Panels and Arrays

- Solar cells are connected in series and usually sold in solar panels.
- Solar panels can be connected in series / parallel in order to provide the required voltage or current as necessary for the installation.
- Estimate the maximum power, current, and voltage ratings of the panel and array in the figure. Assume that each PV cell produce a maximum power of 2.5 W at the best solar conditions.

Solution

The panel has 9 series cells. Assume that the voltage of each cell is 0.5 V, the total voltage of the panel is

$$V_{panel} = 0.5 * 9 = 4.5$$

The panel has a total of 36 cells, the power of the panel is

$$P_{panel} = 2.5 * 36 = 90\text{W}$$

Total current of panel

$$I_{panel} = \frac{P_{panel}}{V_{panel}} = \frac{90}{4.5} = 20 \quad A$$

The array consists of 2 columns of 4 series modules. The total voltage of the array is

$$V_{array} = V_{panel} * 4 = 4.5 * 4 = 18 \quad V$$

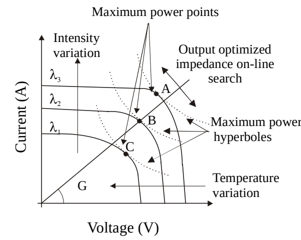
Total power of the array is

$$P_{array} = P_{panel} * 8 = 90 * 8 = 720 \quad W$$

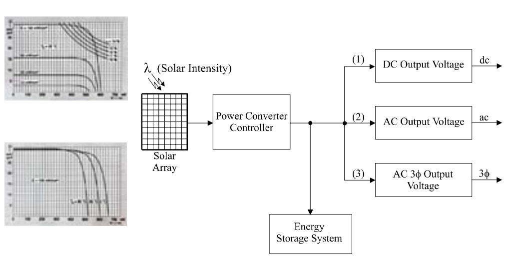
$$I_{array} = \frac{P_{array}}{V_{array}} = \frac{720}{18} = 40 \quad A$$

MPPT – Maximum Peak Power Tracking Controller

- The peak power point moves as temperature or sunlight changes
- A controller must be inserted between the solar cell and the load, in order to optimize the operating point, i.e. to match the best load impedance that the cell needs to deliver maximum power`.



MPPT Controller



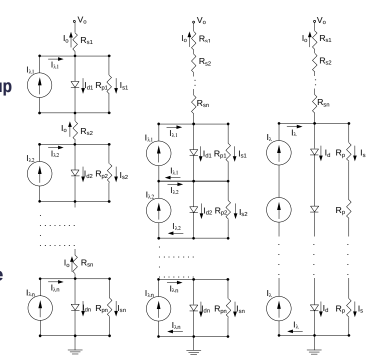
Series Connection

- The respective output voltage and current of the group are :

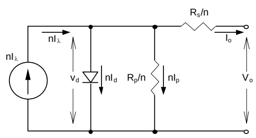
$$V_o = nV_{oi}$$

$$I_o = I_{oi}$$

where V_{oi} and I_{oi} are, respectively, the voltage and the current in the individual cell.



Parallel Connection

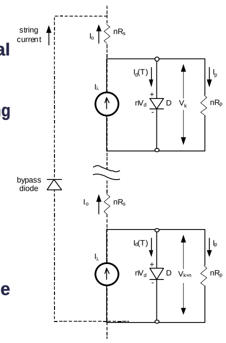


- The cells are supposed to be identical.
- The current will be n x each cell current.

$$V_o = V_{oi}$$
$$I_o = nI_{oi}$$

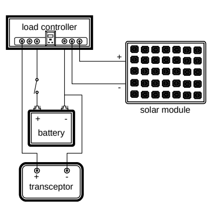
By-Pass Diode, Improving Partial Shadow

- Under no light, the photocurrent is zero.and it remains only the internal diode
- Voltage of the healthy cells will supply current to the shadowy string cells, dissipating internally valuable energy.
- In a series group of these cells under shadow, these internal resistances will act like a heat source, so decreasing the overall efficiency of the solar panel.
- Divide the strings in several sub-strings with bypass diodes under the total string current.
- The diode will by-pass current through the shadowed cells.



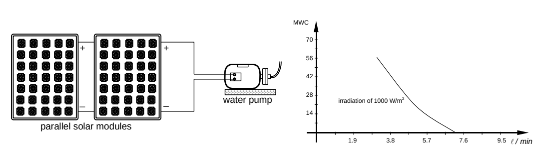
Telecommunication Systems Fed by Solar Module

- Photovoltaic systems for telecommunication applications must supply energy with long autonomy to overcome long absences of sunlight. In many countries, telephone booths along highways use solar panels to avoid long passages of the feeding electric lines. The telephone signals are transmitted via radio transceptors, whose modules are fed through load controllers.



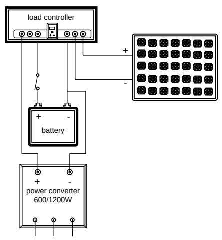
Solar Pumping Systems

- Solar pumping systems are specially designed for water supply and irrigation in remote areas where no reliable electricity supply is available. Rural applications of solar energy are very valuable despite of its high cost.
- Small villages and towns far from the electric grid may invest in irrigation systems or potable water supply powered by water pump and solar modules.
- The flow characteristic is inversely proportional to the pumping head, as in any conventional system of water pumping.



Stand Alone Electric Power Supply

- Solar energy can supply electric power in alternating current of 110 V, 127 V or 220 V at 60 Hz or 50 Hz (depending on the inverter) or, directly in direct current at 12 V, 24 V or 48 V. That energy can be used for small electro domestic equipments.
- The available energy is obtained from a battery that is constantly recharged by solar modules.



Solar Car – made by faculty and students, University of São Paulo, Brazil, 1996