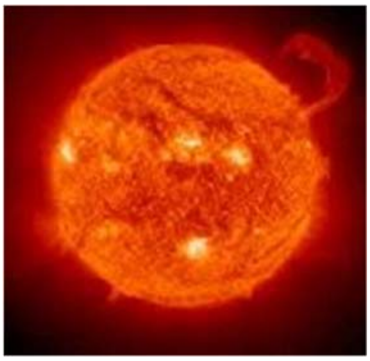
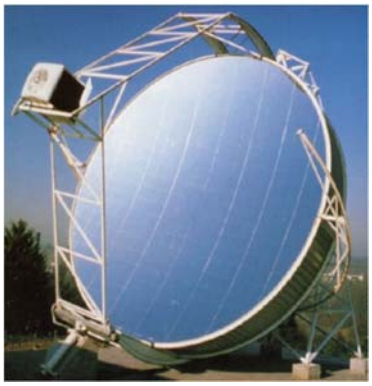


# Fuel and Energy

## Photovoltaic Cells



Dr.-Eng. Zayed Al-Hamamre



## Content

- Basic Concepts
- Common PV Terminology
- PV Arrays
- PV system sizing and design
- Economic Analysis

# Basic Concepts

- **The electric potential**, V, is the energy/charge. Current (I), voltage (V), power (W), and electrical energy (Wh) are key simple electrical concepts needed to understand PV systems.
- **Electrical current** is akin to a flow and is defined as the number of electrons that flow through a material.
- **Current** is measured in Amperes.
- **Electrical voltage** is the work that an external force must do on the electrons within the material to produce current and is measured in volts.



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# Basic Concepts

Electric potential (V) = energy/charge: $V = E/Q$,

where Volt = Joule (J)/coulomb (C), or energy $= V * Q$.

The flow of electrons, current (I), is defined as $I = dq/dt$, the number of charges moving past a point in 1 s, and is measured in Amperes (A), where 1 A = 1 C/s.

The resistance to the flow of electrons in a wire is defined as resistance $(R) = VI$, where Ohm = Volt/Ampere.

Power (P) = $V * I$; Watt = Volt * Ampere. Electrical power (P) is that which is generated or consumed in any given instant and is the product of current and voltage.

Power is measured in Watts, where Watt = Volt * Ampere. The unit of power is the Watt (1 W = 1 V × 1 A). Electrical energy (E) is the power generated or consumed during a period of time (t) and is defined as $E = W \times t$.

The time period of consumption is given in hours; then the unit of energy is the Watt-hour (Wh).

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# Common PV Terminology

- ***Solar cell:*** The PV cell is the component responsible for converting light to electricity.
- ***PV module:*** A PV module is composed of interconnected solar cells that are encapsulated between a glass cover and weatherproof backing.
- The modules are typically framed in aluminum frames suitable for mounting.
- ***PV array:*** PV modules are connected in series and parallel to form an array of modules, thus increasing total available power output to the needed voltage and current for a particular application.
- ***A peak Watt (Wp):*** is the amount of power output a PV module produces at STC of a module operating temperature of 25°C in full noontime sunshine (irradiance) of 1,000 W/m².
- PV modules are rated by their total power output, or peak Watts.



# Common PV Terminology

- Modules often operate at much hotter temperatures than 25°C in all but cold climates, thus reducing crystalline module operating voltage and power by about 0.5% for every 1°C hotter.
- Therefore, a 100 W module operating at 45°C (20° hotter than STC, yielding a 10% power drop) would actually produce about 90 W

**Example Manufacturer's Specifications for a 53-Wp PV Module**

| | Operating point | Model BP VLX-53 |
|---|---|---|
| *Maximum power* | $P_{mp}$ | 53 $W_p$ (peak Watts) |
| *Rated maximum power voltage* | $V_{mp}$ | 17.2 V |
| *Maximum power operating current* | $I_{mp}$ | 3.08 A |
| *Open-circuit voltage* | $V_{oc}$ | 21.5 V |
| *Short-circuit current* | $I_{sc}$ | 3.5 A |
| | Standard test conditions (STCs) | 1,000 W/m², 25°C |

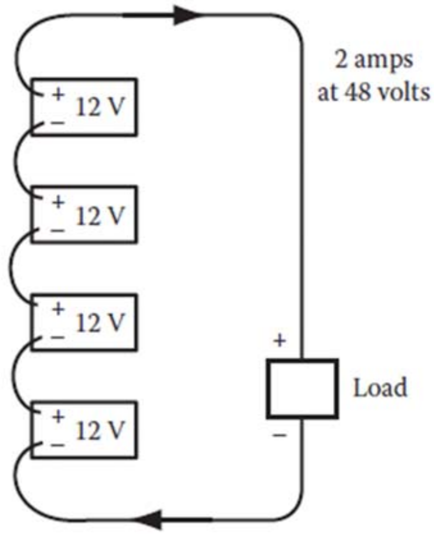
# PV Arrays

- A PV array is a group of modules that are electrically connected either in series or in parallel.
- PV modules are connected in series to obtain higher output voltages

$$\text{Output voltage, } V_o = V_1 + V_2 + V_3 + \ldots$$

- PV modules are connected in parallel to obtain greater current
- The voltage of the parallel-connected modules is the same as the voltage of a single module

$$\text{output current, } I_o = I_1 + I_2 + I_3 + \ldots$$




- Maximum energy is obtained when the Sun's rays strike the receiving surface perpendicularly.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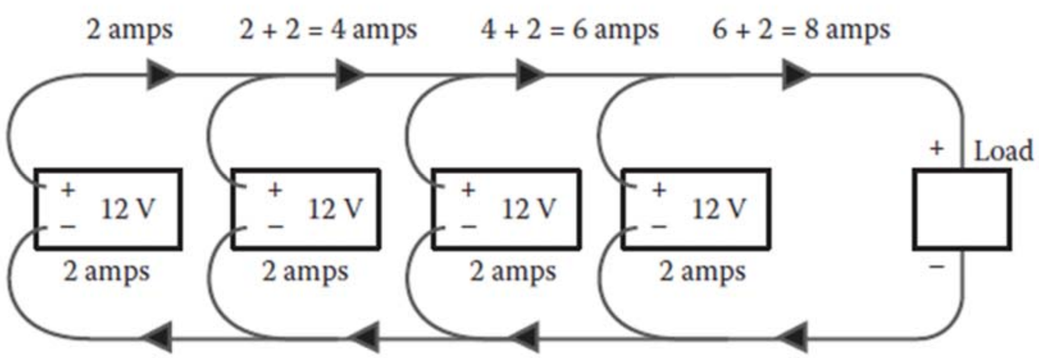
# PV Arrays




## Example

Sixteen PV modules have been interconnected to operate a water pumping system. The array consists of eight modules in series and two strings of these in parallel (8s × 2p).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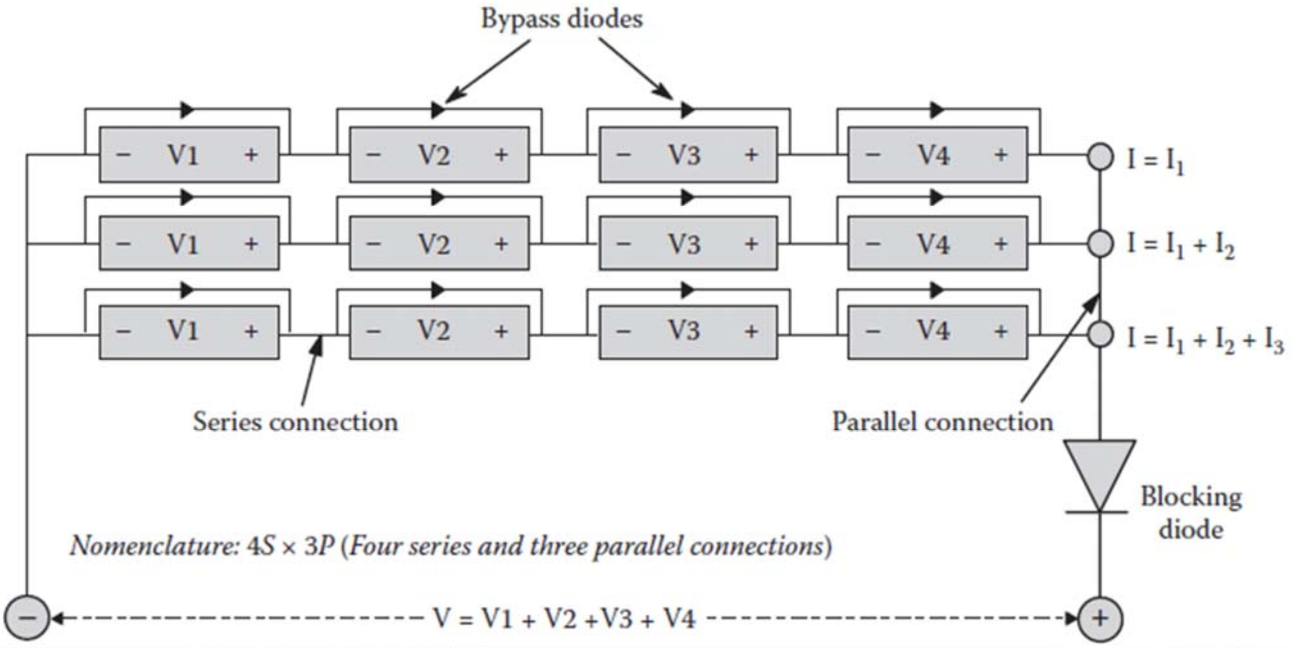
# Example

$I_p = 3.08 \times 2 = 6.16$ A, $V_p = 17.2 \times 8 = 137.6$ V,

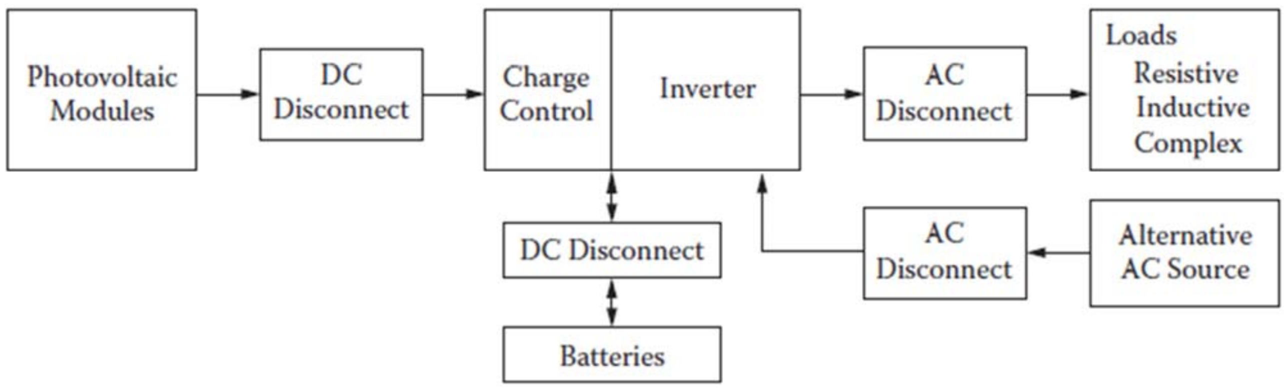
$P_p = 53 \times 16 = 848$ $W_p$; maximum array current ($I_{sc}$) = 3.5 × 2 = 7.0 A;






# PV systems

- PV systems are made up of a variety of components, which may include arrays, wires, fuses, controls, batteries, trackers, and inverters



# PV System Sizing and Design

- In order to size and design a solar energy system,
  - It is necessary to conduct a reasonable assessment of the energy requirements that the system will have to meet.
  - Understanding the local solar resource (depends on location)
  - The system should be designed to fit the need with the seasonal solar resource.
  - Understanding the apparent movement of the Sun throughout the day and throughout the year
  - It must be sized to the critical season for their use.



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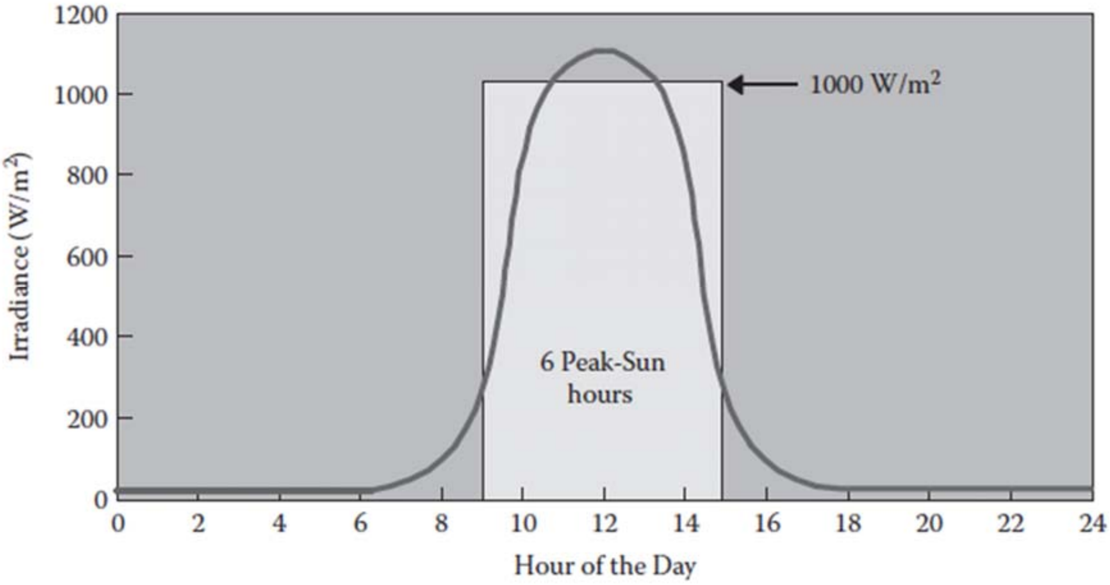
# PV System Sizing and Design




Irradiance and insolation expressed as peak solar hours (i.e., 6 sun-hours = 6 kWh/m$^2$).



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# PV System Sizing and Design

- Insolation is the key parameter for solar energy system design
- The **main factors** affecting the amount of insolation incident upon a solar surface are **orientation**, mounting angle with respect to horizontal, and **climatic conditions**
- Maps and tables are available from various sources that give horizontal-plane insolation values for numerous regions and times of the year



# Example

A 848 Watt PV array has been installed on a family farm near Aldama, Chihuahua, Mexico. The array is pointed true south and has a tilt angle equal to the latitude (30°).

- The real capacity of the array, operating at a cell temperature of 55° C, is 0.85× 0.848 = 0.72 kW.

According to tabulated data, expected insolation is 6.1 kWh/m$^2$ per day in the first third of the year.

- The energy that can be expected from the array is approximately 6.1 × 0.72 = 4.4 kWh per day in the first third of the year and
- 6.6 × 0.72 = 4.8 kWh per day in the last third of the year.

If the array were installed at a tilt angle of 15° (latitude minus 15°),

- The estimated insolation is 5.7 kWh/m$^2$ per day in the first third of the year and 6.9 kWh/m$^2$ per day in the last third of the year.
- In this case, the expected electrical energy for the system is 4.1 kWh and 5.0 kWh per day in the first and last thirds of the year, respectively

# Example Cont.

- PV modules installed on structures anchored to the ground operate at approximately 55°C during the day during the summer; some desert climates may be hotter yet.
- This is 30° above standard test conditions (25°C).
- This means that the real capacity of the array is approximately 15% less than the nominal power rating.
- The effective capacity, then, is 85% of the nominal capacity.



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# Simple PV DC System Sizing

The table assumes some basic loads for a small off-grid residence in Oaxaca, Mexico. The critical design month is assumed to be in winter with 5.4 sun-hours available in December. The battery bank should be designed for 3 days' autonomy, not to exceed 45% depth of discharge.

PV module STC rating: 50 W each — The nominal voltage of 12 V DC

Battery size: 105 Ah (ampere-hours) each, 3 days' storage

| Load | Hours operating/day (hours) | Power (W) | Daily energy (Wh) |
|---|---|---|---|
| Four fluorescent lamps | 4 | 30 | 480 |
| One refrigerator (DC) | 5 | 80 | 400 |
| One laptop | 2 | 50 | 100 |
| One stereo (teenager-free home!) | 2 | 30 | 60 |

- The loads are 1,040 Wh/day



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# Simple PV DC System Sizing



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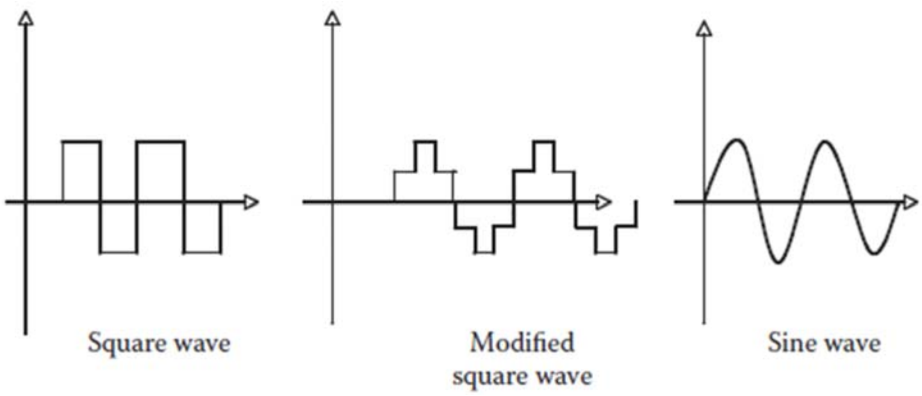
# Sizing Inverters

- Inverters accept an electrical current in one form and output the current in another form.
- An inverter converts DC into AC whereas a rectifier converts AC into DC.




Inverter wave outputs



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# Sizing Inverters

- The inverter for a PV lighting system is an important benefit in running specific AC appliances
- An inverter needs to meet two needs: peak, or surge, power and continuous power:
  - *Surge* is the maximum power that the inverter can supply when a reactive load is turned on (1–5 s)., usually for only a short time.
    - o Some appliances, particularly those with electric motors, need a much higher power level at startup than they do when running
  - *Continuous* is the power that the inverter has to supply on a steady basis. This is usually much lower than surge power
- Inverters are rated by their continuous wattage output. The larger they are, the more they cost
- For sizing inverter for loads where there is a 19-inch TV (**80 W**), blender (350 W), and one fluorescent light at **20 W**, and two fluorescent lights at **11 W** each,

The total load is 472 W. An inverter that can supply a least 472 W continuously will be chosen



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# Sizing Inverters

- The only concern here would be the blender's initial surge requirement.
- Normally, a small motor like the one the blender has will surge for a split second at twice the amount of power it normally uses—in this case, 350 doubled equals about a 700 W surge.
- Some existing loads may need to be turned off to help meet the surge if the inverter is already continuously loaded.
- Suppose that an inverter is selected at 500 W with a surge capacity rating of 1,000 W, which is more than sufficient to handle the blender surge

| | |
|---|---|
| • Nominal system operating voltage (input V): | 12 V DC (10.8–15.5 V) |
| • Output voltage: | 120 V AC, 60 Hz sinewave |
| • Continuous output: | 500 W |
| • Surge capacity power: | 1,000 W |
| • Standby power: | 3 W |
| • Average efficiency: | 90% at full rated power |
| • Recommended input fuse: | 75 A (500 W/10.8 V * 0.8 *1.25) |
| • DC wire size minimum: | 8 AWG |
| • Availability of system status (light indicator): | yes |



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# Load Estimation

| Item: | Watts: | Hours of Use: | Calculated Consumption: |
|---|---|---|---|
| one lamp | 20 | 3/day | |
| two lamps | 11 | 3/day | |
| one 19-in TV (AC) | 80 | 4/day | |
| one blender (AC) | 350 | 0.5/day | |



# Load Estimation

# Load Estimation

- Design month is December at 5.4 h (Oaxaca).
- Assume PV array temperature derate averages 15% of daily requirement.
- Assume inverter losses at 10% of daily requirement.
- Assume fuses/disconnect losses at 1%.
- Assume wiring losses at 3%.
- Assume battery losses at 25%.
- Total system losses are then 0.85 * 0.90 *0.99 * 0.97 * 0.75 = 55%
- Adjusted system load requirement = 63 Ah/day/0.55 = 114 Ah/day.



# Load Estimation

# Battery Requirement

- Battery life is expressed in cycles. The cycle life of a battery is the number of lifetime cycles expected from a battery at a specified temperature, discharge rate, and depth of discharge.
- Typically, the end of battery life is when the battery capacity falls 20% below its rated capacity
- Longer discharge rates will increase available battery capacity, but will also shorten battery life
- Decreased battery life can be caused by several factors: External corrosion increases the interconnect resistance, internal (grid) corrosion reduces.
- Battery capacity may be lost if the electrolyte level falls below the top of the plates, thus preventing active materials from reacting there
- When batteries are purchased for PV systems, the following may be considered for specifying batteries.



# Battery Requirement

- type of battery (e.g., flooded or sealed lead-acid);
- useful Ampere-hour capacity of battery at a specified current;
- operating temperature (e.g., –15 to 65°C);
- maximum allowable depth of discharge (e.g., 20% DOD);
- average daily depth of discharge (e.g., 5% DOD);
- nominal charging current (e.g., 20 A);
- nominal battery subsystem bus voltage (e.g., 12 V);
- maximum number of strings in parallel;
- terminal and interconnect wiring specification (e.g., stud T872);
- battery cap requirements (e.g., Hydrocaps);
- shipping requirements (e.g., dry shipping); and
- recyclability.

# Economic Analysis

- A simple payback calculation can provide a preliminary judgment of economic feasibility

$$SP = \frac{IC}{AKWH \times \$/_{kWh}}$$

where

$SP$ = the simple payback in years
$IC$ = initial cost of installation ($)
$AKWH$ = energy produced annually (kWh/year)
$\$/kWh$ = price of energy displaced

## Example

You purchased a solar hot-water heater to replace an electric hot-water heater (70 gal/day for a family of four). Installed cost = $3,000, and displacing electricity is 6,000 kWh/year at $0.10/kWh. You are assuming that the price of electricity will stay the same over the lifetime for this simple analysis:



# Example Cont.

If your hot-water heater needs replacement anyway, you have an initial cost, $400, and then you pay for the electricity, $50/month for approximately 500 kWh/month. Reducing the IC cost to $2,600 means that now the simple payback on the solar hot-water system would be less:

# Economic Analysis

The next calculation would include the value of money, borrowed or lost interest, and annual operation and maintenance costs:

$$SP = \frac{IC}{AKWH \times {}^{\$}\!/_{kWh} - IC \times FCR - AOM}$$

where

*SP* = the simple payback in years
*IC* = initial cost of installation ($)
*AKWH* = energy produced annually (kWh/year)
*$/kWh* = price of energy displaced or price obtained for energy generated
*FCR* = fixed charge rate per year
*AOM* = annual operation and maintenance cost ($/year)



# Cost of Energy

- The cost of energy (COE) is primarily driven by the installed cost and the annual energy production.
- For PV systems, that cost is determined primarily by the cost of the modules
- The COE (value of the energy produced by the renewable energy system) provides a levelized value over the life of the system (assumed to be 20–30 years):

$$COE = \frac{IC \times FCR + AOM}{AKWH}$$

- The COE is one measure of economic feasibility, and when it is compared to the price of energy from other sources (primarily the utility company) or to the price for which that energy can be sold, it gives an indication of feasibility
- The annual energy production for a PV system can be estimated as

$$AKWH = EF \times AKWH = EF \times Wp \times \overline{PSH} \times 365$$

# Cost of Energy

where

$EF$ = system efficiency factor—typically about 50% off grid and 75% grid tie
$Wp$ = array rating (peak kiloWatts)
$\overline{PSH}$ = average daily solar insolation (sun-hours) (kWh/m²/day)

## Example

Find the COE for a 2-kWp grid-tie PV system for a home in El Paso, Texas, with an average of 6 kWh/m² per day, displacing electricity at an average of $0.12/kWh over 25 years.



# Money Value

- Money value increases or decreases with time, depending on interest rates for borrowing or saving and inflation.
- The discount rate determines how the money increases or decreases with time.
- *Present value* (PV) is the adjusted cost, at present, of future expenses using the real discount rate
- The present value of a single payment made in the future is

$$PV = FV * \underbrace{(1 + i_r)^{-n}}_{\text{present value factor (PVF)}}$$

where

$PV$ is the present value
$FV$ is the future value amount to be paid in the future
$i_r$ is the real discount rate $\quad i_r$ = interest rate – inflation rate
$n$ is the number of years between now and the year of the payment

# Money Value

- The present value of a fixed annual payment is

$$PV = AV \times [(1-1/(1 + I_r)^n)/I_r]$$

where

*PV* is the present value
*AV* is the value amount paid annually
$i_r$ is the real discount rate
*n* is the time period, in years, in which the annual payment is incurred