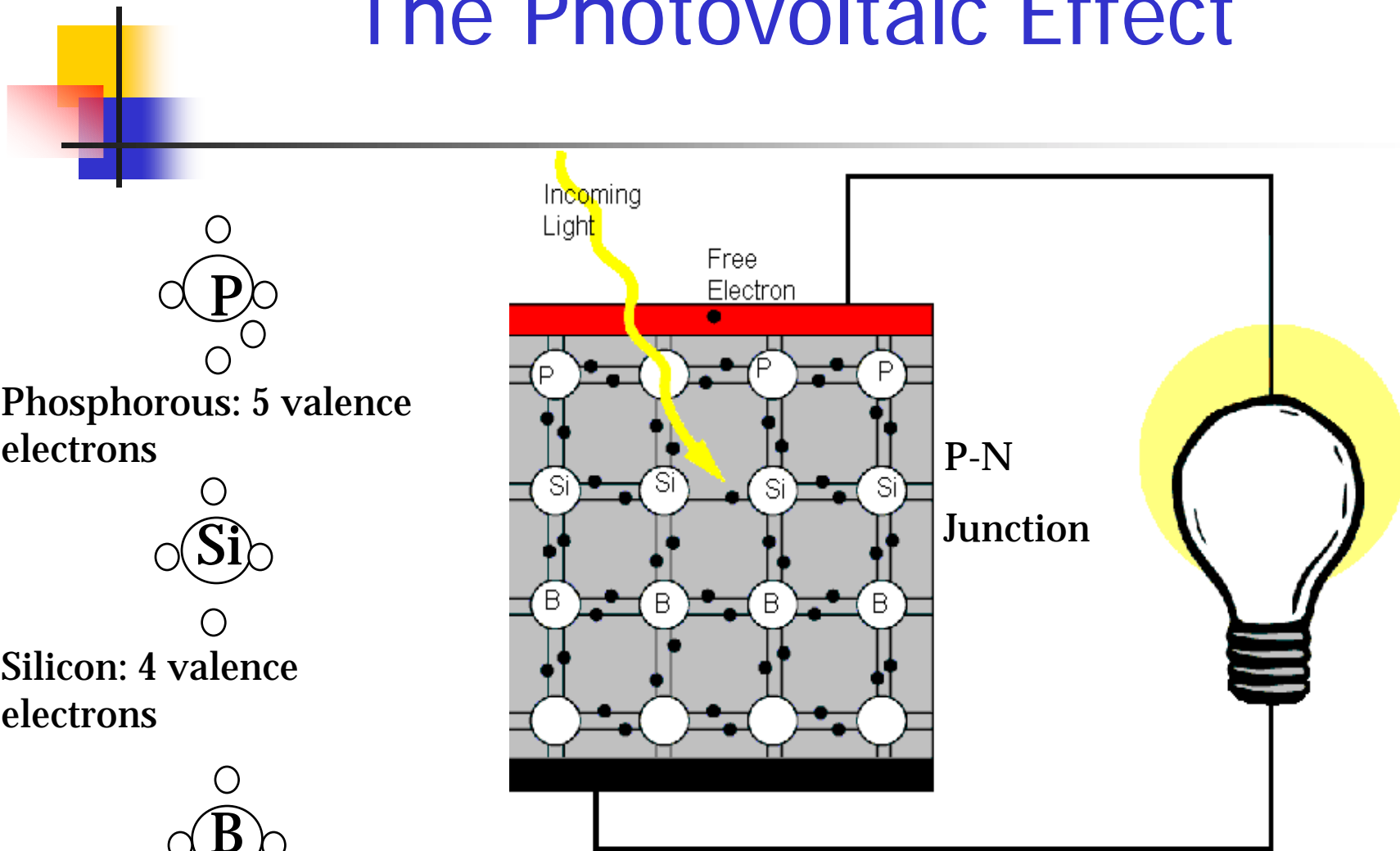


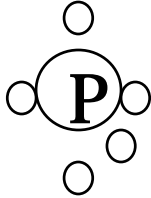


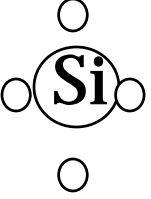
Photovoltaic Technology

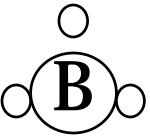
Andy Walker PhD PE

The Photovoltaic Effect




Phosphorous: 5 valence electrons

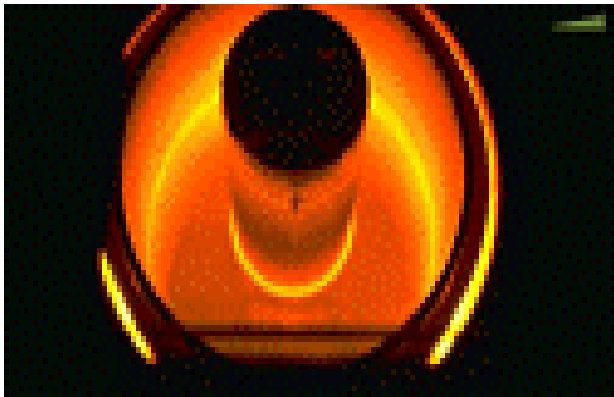

Silicon: 4 valence electrons


Boron: 3 valence electrons

No material is consumed and the process could continue indefinitely

PV Manufacturing

Single Crystal



- 10 to 16 % efficiency
- 51.9 MW sold for \$155 million in 2000.
- \$3.48/Watt

Multi-Crystal



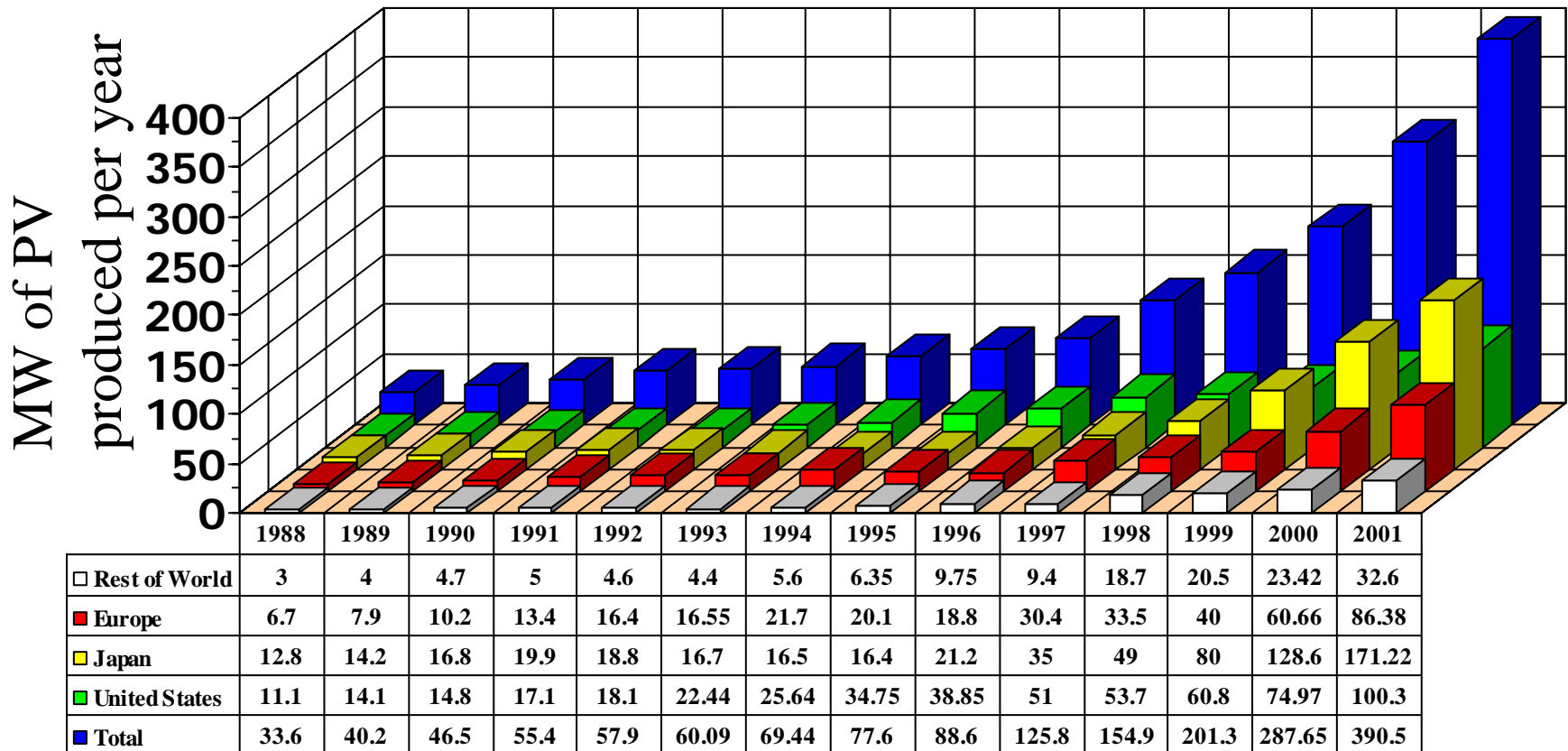
- 10 to 12 % efficiency
- 33.2 MW sold for \$103 million in 2000.
- \$3.41/Watt

Amorphous Thin Film



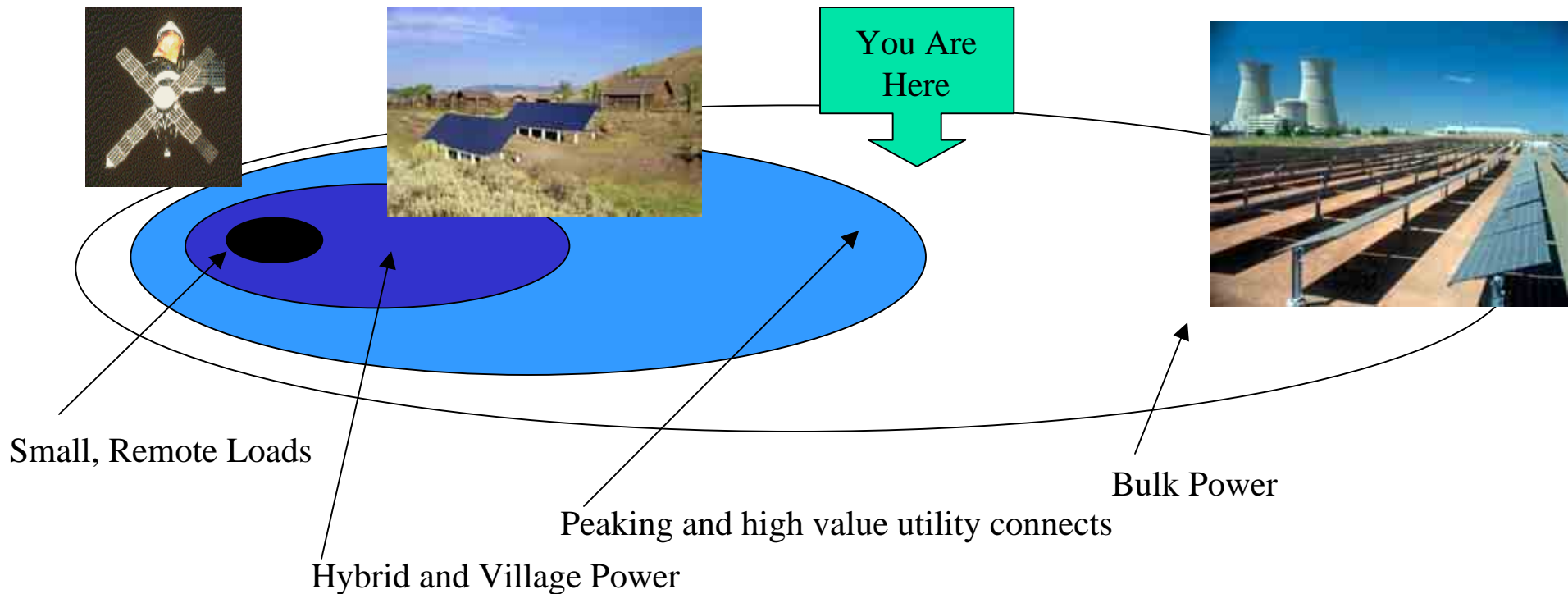
- 4 to 9.5 % efficiency
- 2.7 MW sold for \$11.2 million in 2000.
- \$4.15/Watt
- Promise of low cost

World PV Cell/Module Production

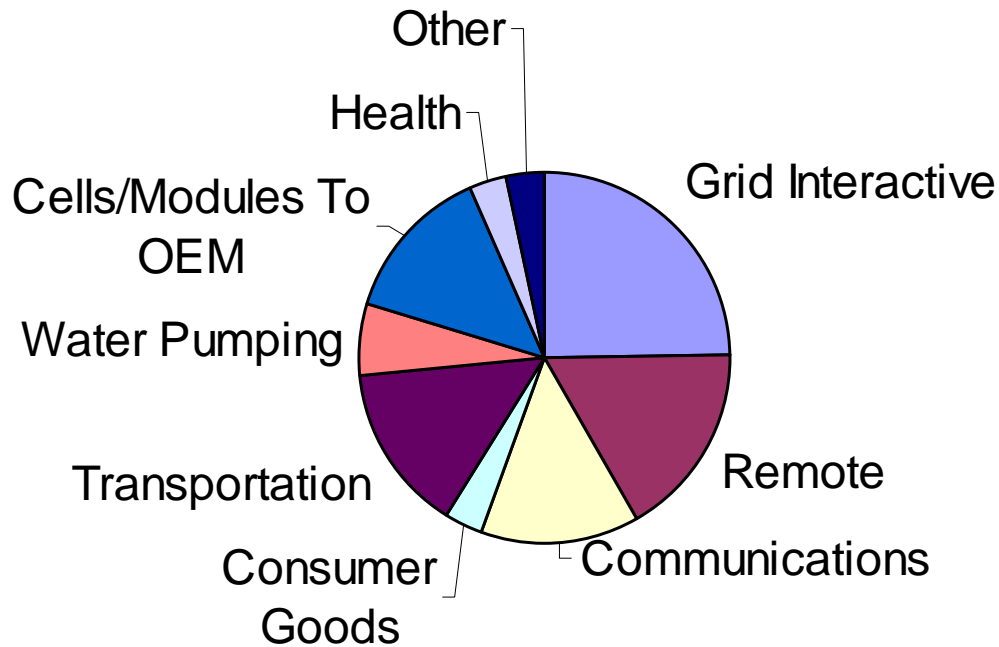
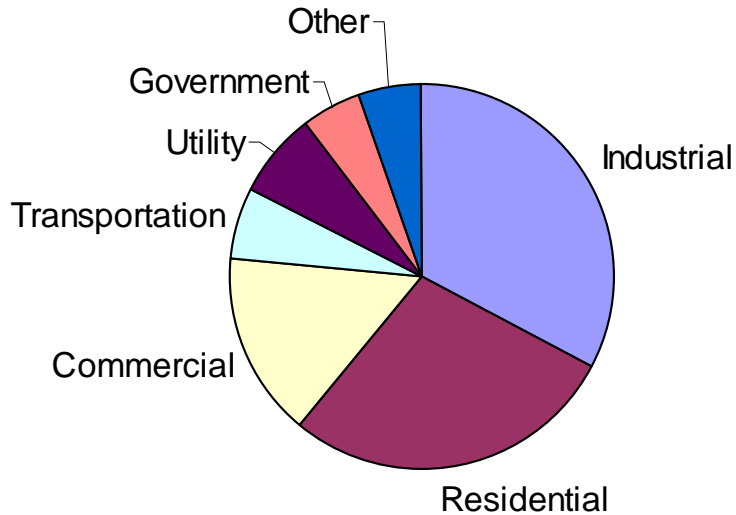


Cost Effective PV Applications

Diffusion Model: As the cost of PV comes down, and the cost of alternatives go up, PV applications grow from high-value niche applications to widespread use.

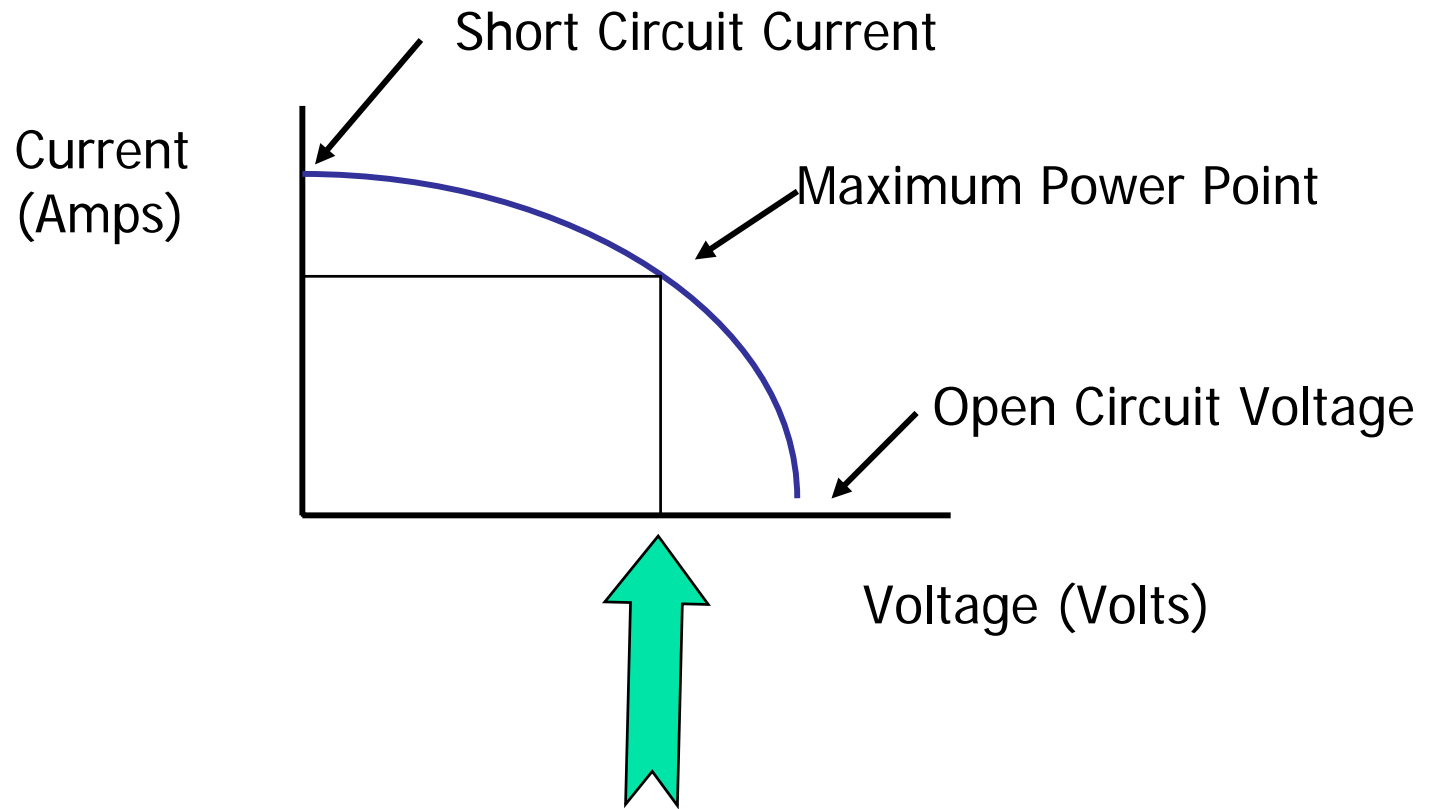


PV Markets



- Most Cost Effective:
 - Small Loads
 - Emergency Call Boxes
 - Irrigation Controls
 - Sign lighting
 - Avoided Line Extensions (\$20k to \$100k/mile)
 - Water Pumping
 - Residential
 - Remote Diesel Generators (\$0.19 to \$1.68/kWh)

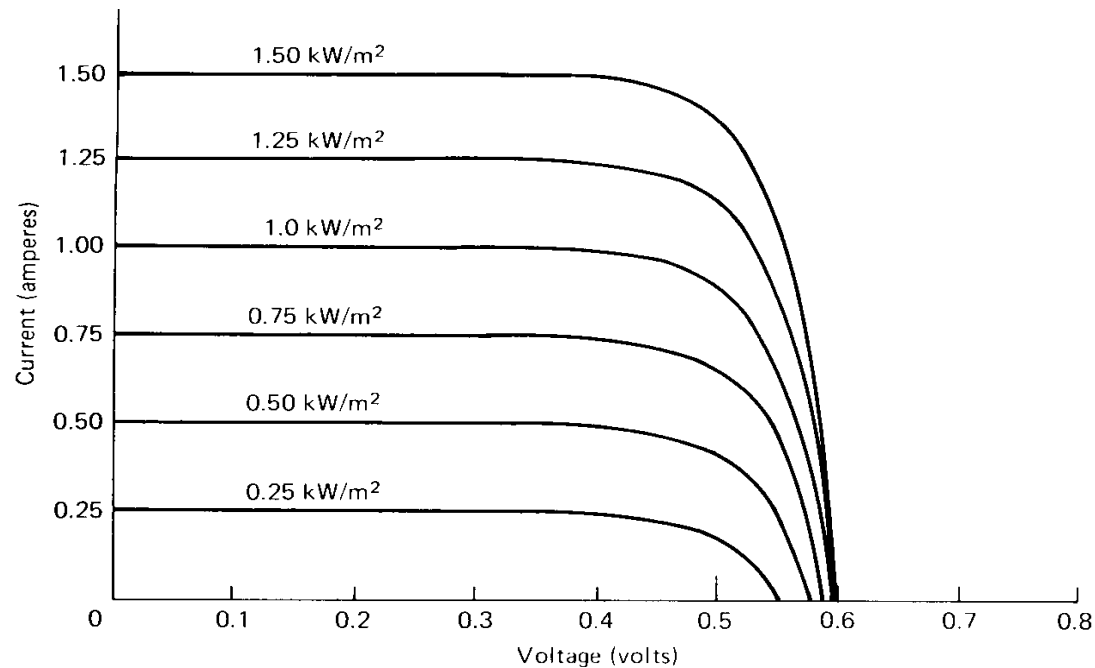
PV Cells "I-V Curve"



Optimal voltage changes with sunlight and temperature

I-V Curve: Sunlight and Current

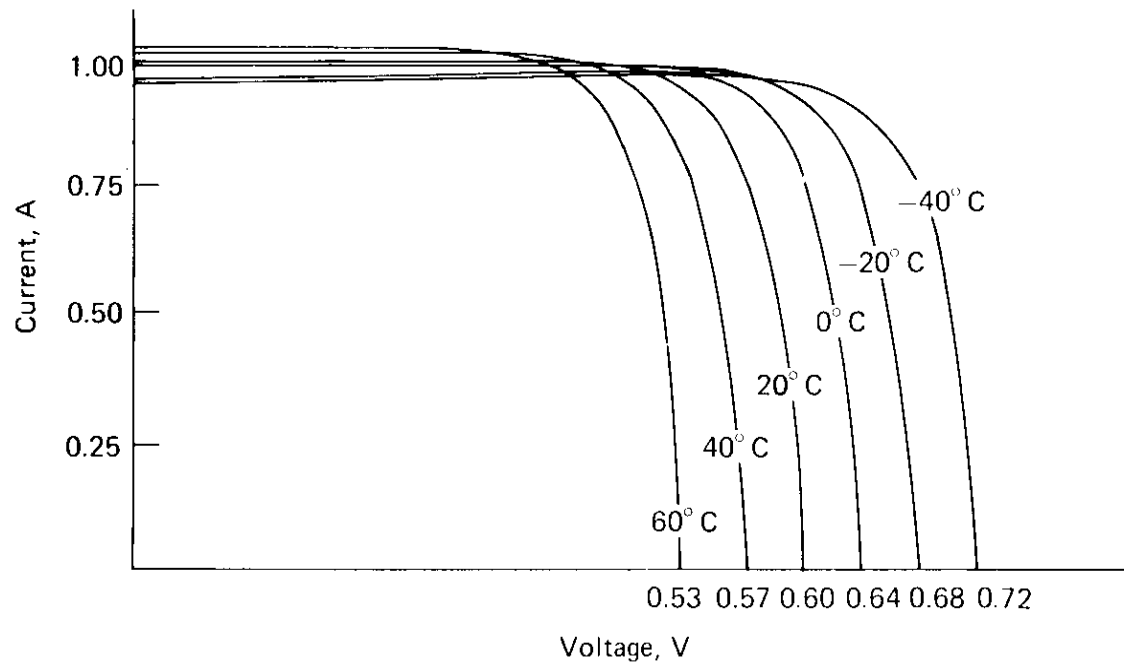
- Current (Amps) of each cell depends on
 - surface area
 - intensity of incident sunlight (kW/m^2)



Changing current with changing insolation.

IV Curve: Voltage and Temperature

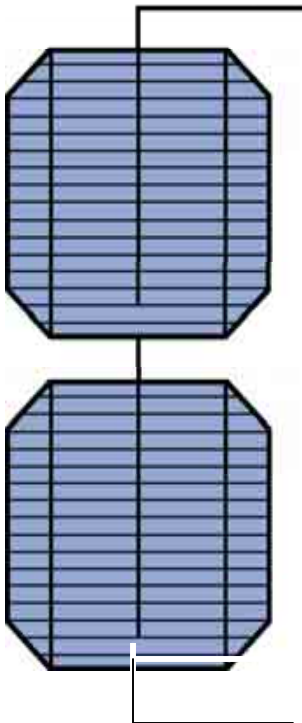
- Voltage (Volts) of each cell depends on
 - the material's band gap (eV),
 - goes down slightly with increasing temperature



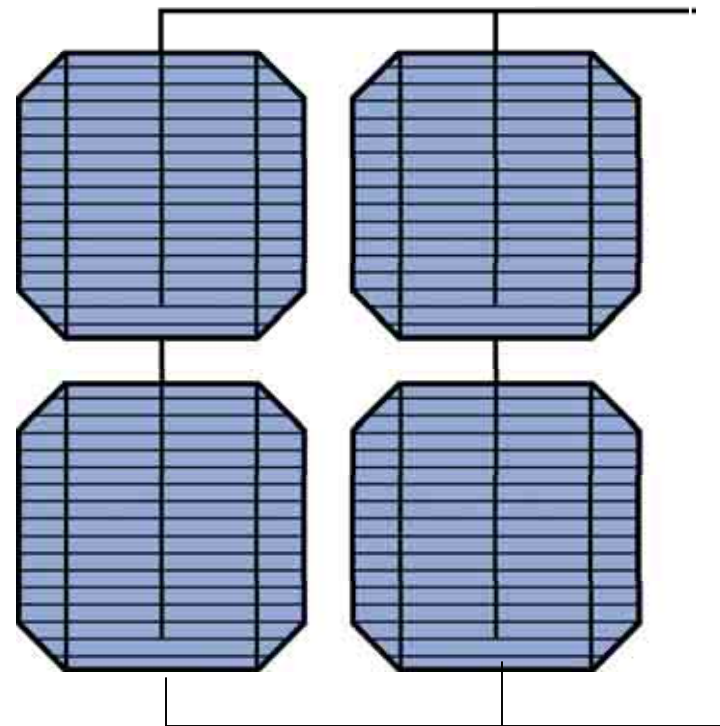
Changing voltage with changing temperature.

PV Cells

PV Cells are wired in series to increase voltage...

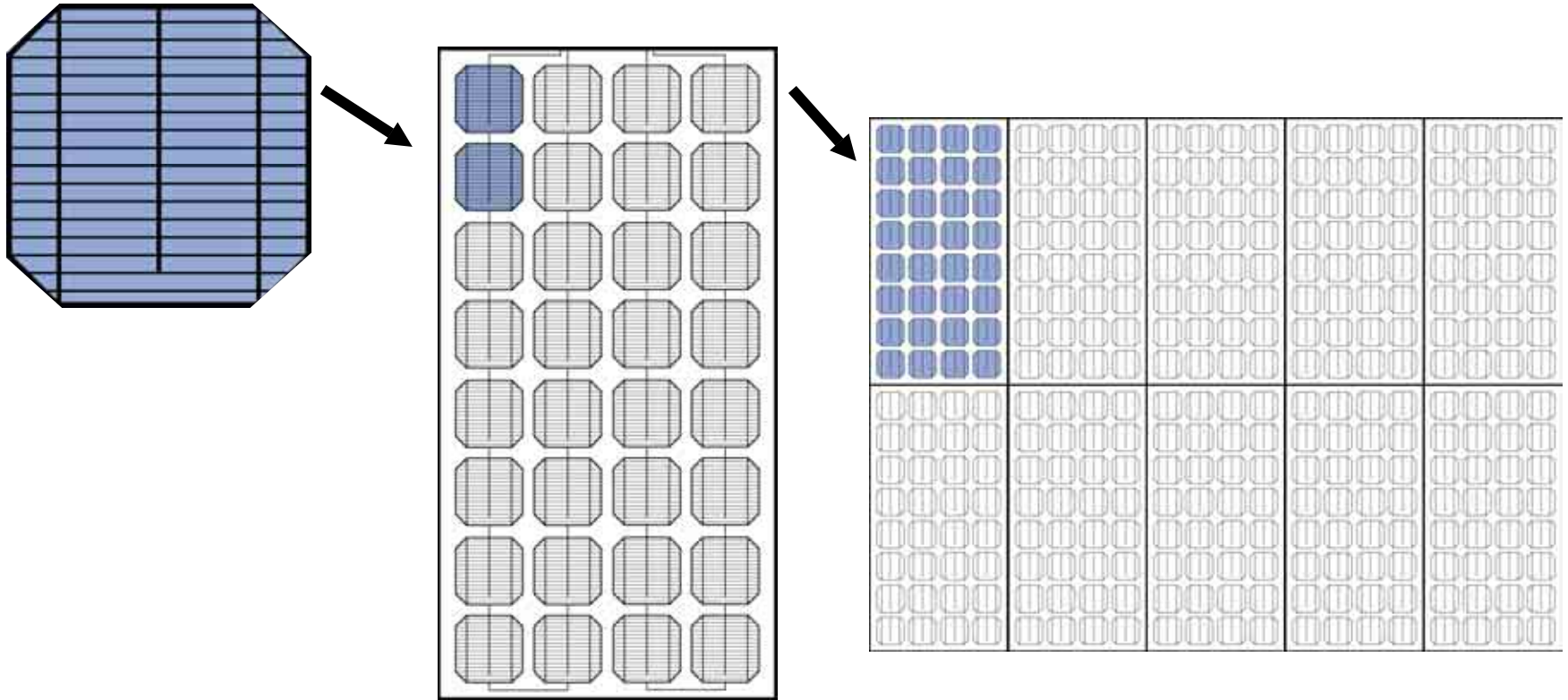


and in parallel to increase current





PV is *Modular*



Cells are assembled into *Modules*.. and modules into arrays.

PV Module Nameplate Rating

- “Rated Power” is the output of a PV module under standard reference conditions
 - 1 kW/m² sunlight,
 - 25 C ambient temperature
 - 1 m/s wind speed.



ASTM E1036-96, Standard Test Method for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells

Module Nameplate

SIEMENS

MODEL SP18
PHOTOVOLTAIC MODULE

CE 
3088 LISTED

SPECIFICATIONS AT 1000 W/M² SOLAR IRRADIANCE, 25°C CELL TEMPERATURE

NON-INCENDIVE CLASS 1 DIVISION 2
GROUP A, B, C, D HAZARDOUS LOCATION

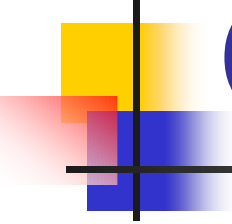

APPROVED

MAX. POWER	SHORT CKT. CURRENT	RATED
18 WATTS	1.2 A	1.05 A
MAX. SYST. OPEN CKT. VOLTAGE	VOLTAGE RATED	
600 V	21.7 V	17.0 V
FIRE RATING	SERIES FUSE	
CLASS C	2 A	
FIELD WIRING	BYPASS DIODE	
COPPER ONLY, 14 AWG MIN INSULATED FOR 90°C MIN	INSTALLATION GUIDE 019831	
SERIAL NUMBER		



Efficiency versus Size

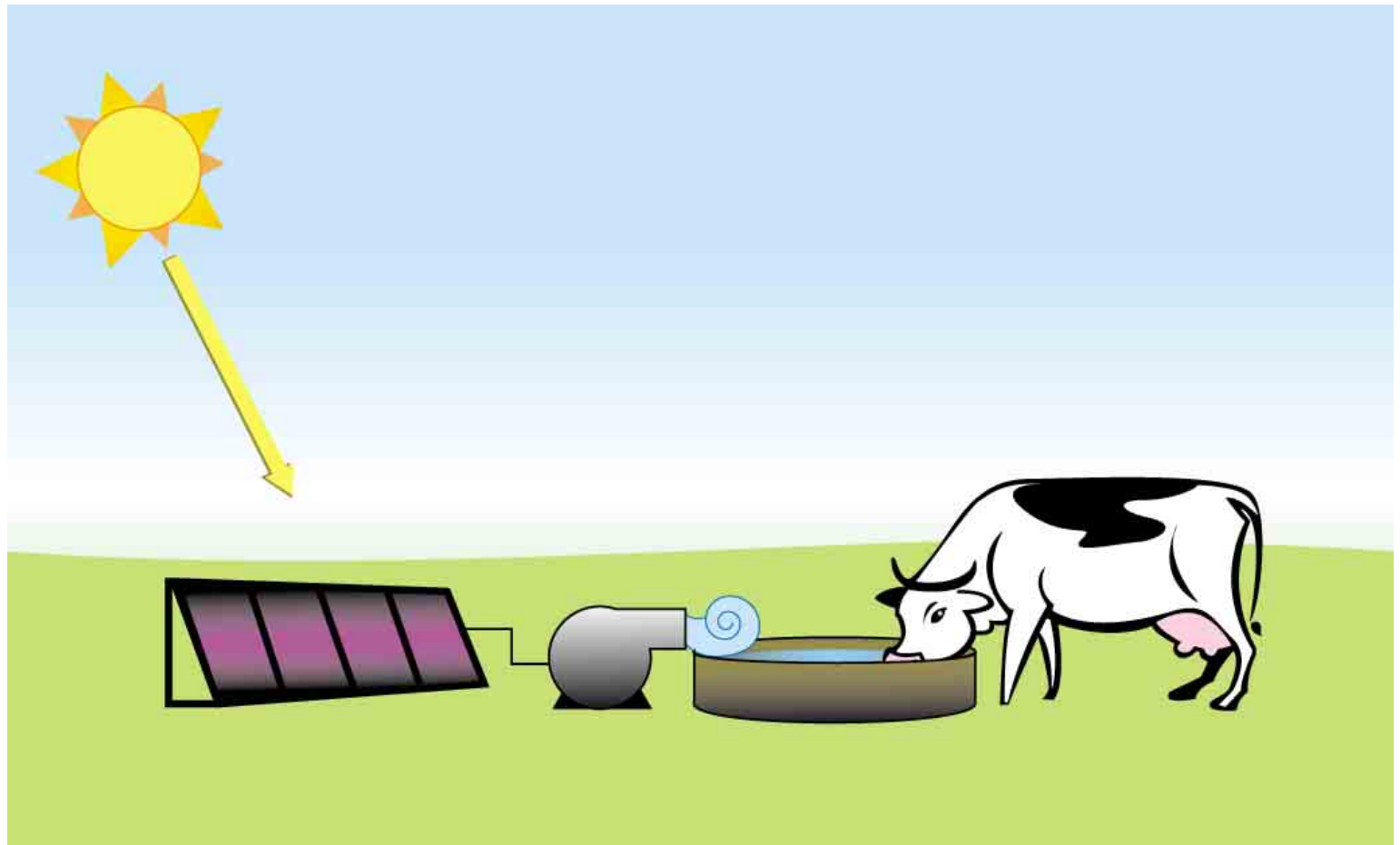
- Efficiency = power out/power in
- Power in = Area (m²) * 1 kW/m²
- For Example:
 - 1 kW of 11.2% efficient crystalline 84ft²
 - 1 kW of 9.5 % efficient amorphous 99ft²



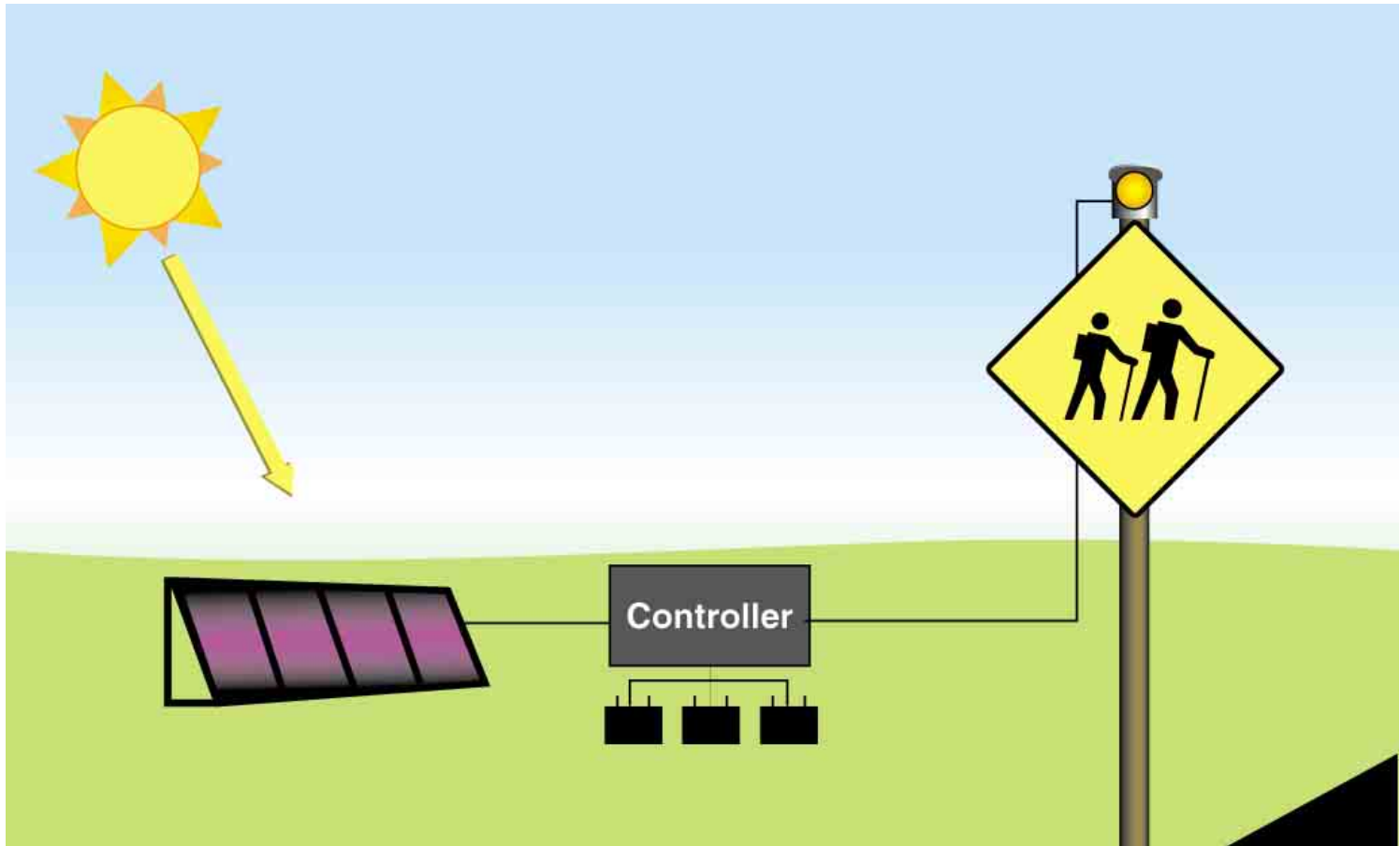
PV System Components (depending on type of system)

- ***PV Array*** to convert sunlight to electricity
- **Array Support Structure** and **Enclosure** to protect other equipment
- ***Maximum Power Point Tracker*** to match load to optimal array voltage
- ***Batteries*** to store charge for when it is needed
- ***Charge Controller*** to protect battery from over-charging
- ***Low Voltage Disconnect*** to protect battery from over-discharging
- ***Inverter*** to convert direct current (DC) to alternating current (AC)
- Wiring, combiner boxes, fuses and disconnects
- Automatic generator starter/stopper to start a generator when battery is too low

Simple Direct Drive PV System



Simple DC PV System with Battery Storage

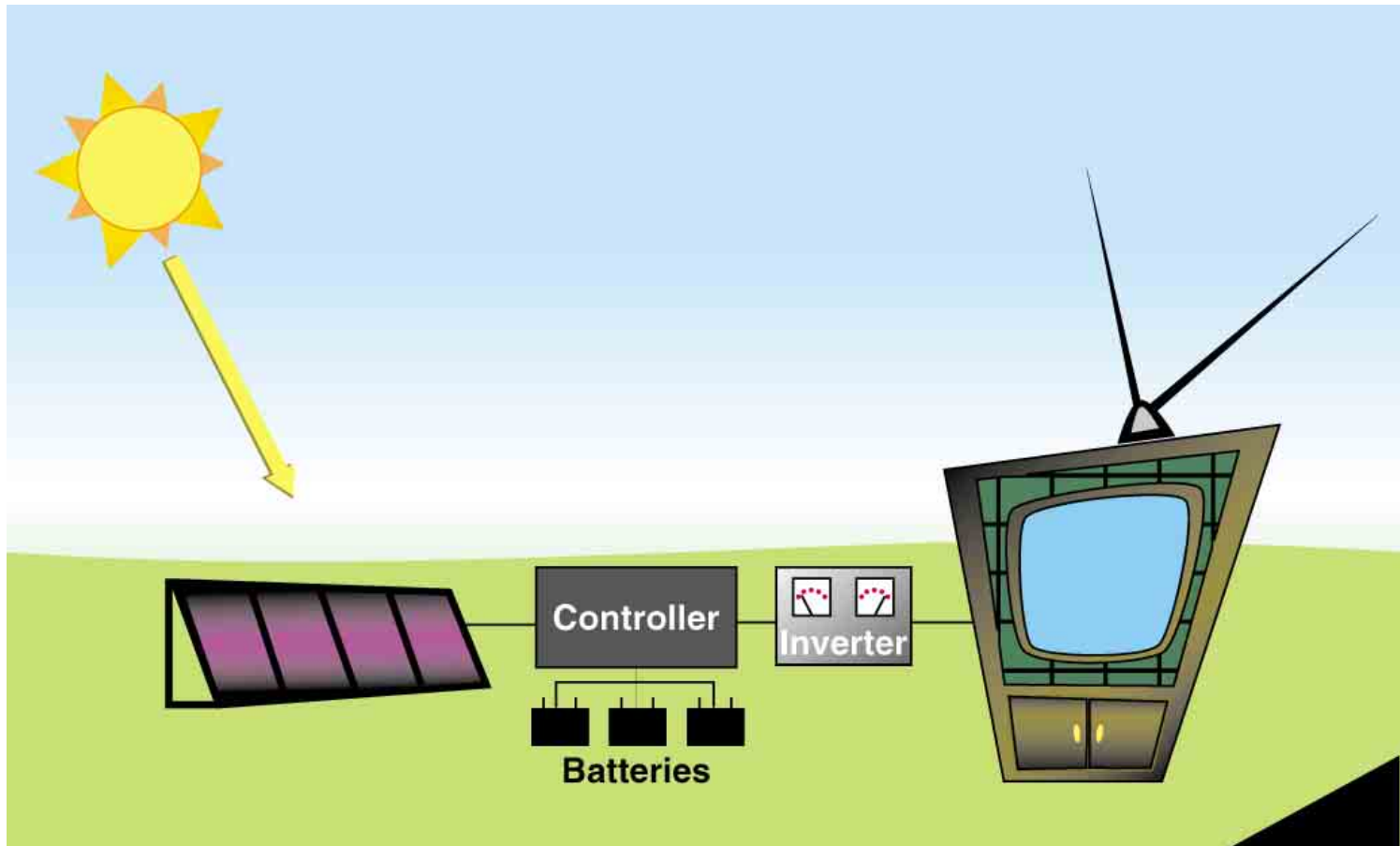


DC PV System Example: PJKK Federal Building, HI



- 2 solar panels per lamp with peak output of 96 watts
- 39 Watt fluorescent lamps, 2500 lumens
- 90 amp-hour battery powers 12 hours per night
- ~\$2500 per light

AC PV System with Inverter



Inverter



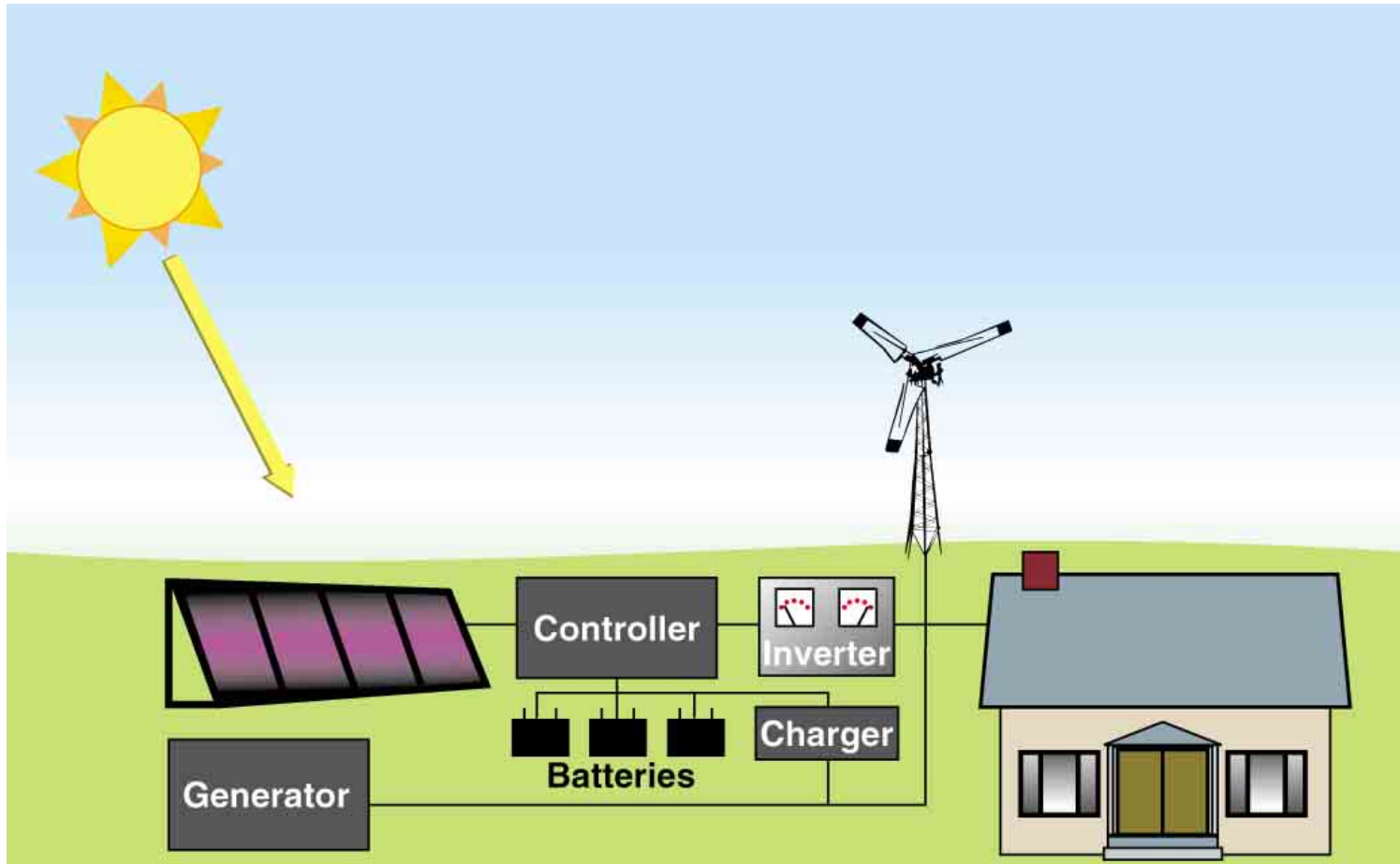
Converts Direct Current (DC) to Alternating Current (AC)



Inverter Technology

- Various DC and AC voltages, number of phases
- **MODIFIED SINE WAVE**
 - low cost, slightly more efficient
 - Bad for some computers, photocopier machines, laser printers, and cordless tool rechargers.
 - Trace UX, Trace DR, Powerstar, Portawattz
- **TRUE SINE WAVE**
 - power of better quality than utility
 - Trace SW, Prosine, Exeltech
- **SIZE** from under 100 watts to 10 kW, larger are custom
- **EFFICIENCY** 85 to 95%.
- **FEATURES:** meters, alarms, battery charger, automatic shut down, start/stop other devices.

Hybrid PV/Generator System



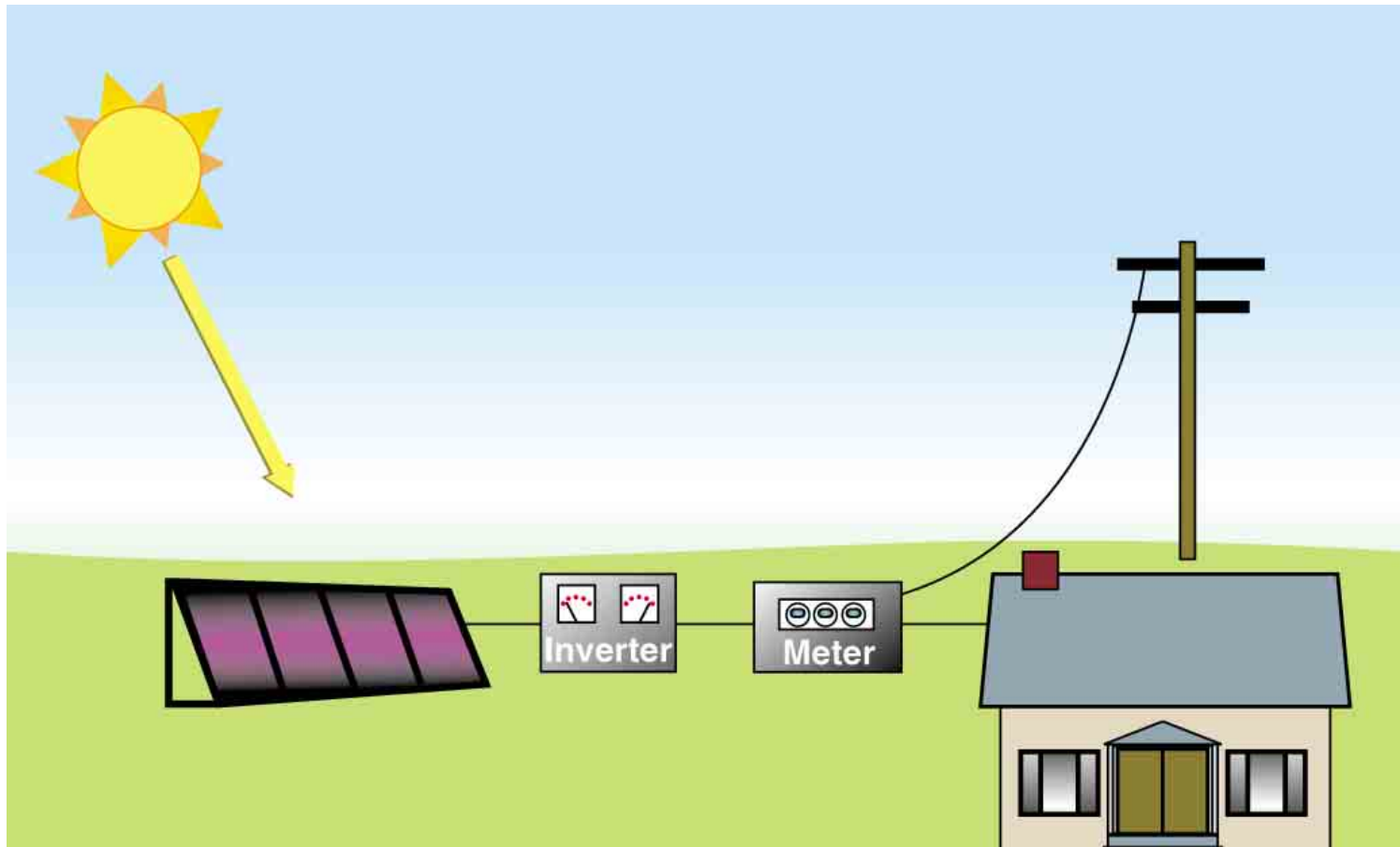
PV/Propane Hybrid Example: Joshua Tree National Park



- 20.5 kW PV Array
- 613 kWh battery bank
- 35 kW propane generator
- \$273,000 cost financed by Southern California Edison under 15 year tariff



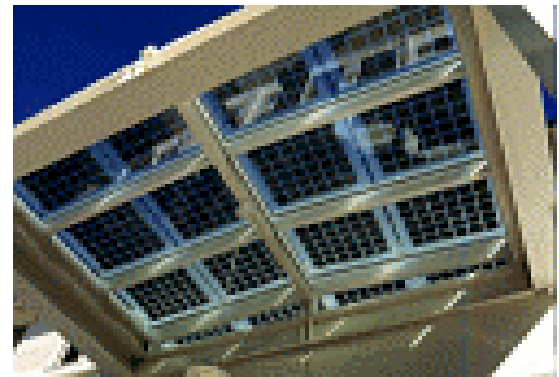
Utility-Connected (Line-Tie) PV System



Utility-Connected PV Example: Presidio Thoreau Center



- Building-Integrated Photovoltaics
- 1.25 kW PV Array
- Spacing between cells admits daylight into entry atrium below



Building-Integrated PV (BIPV)

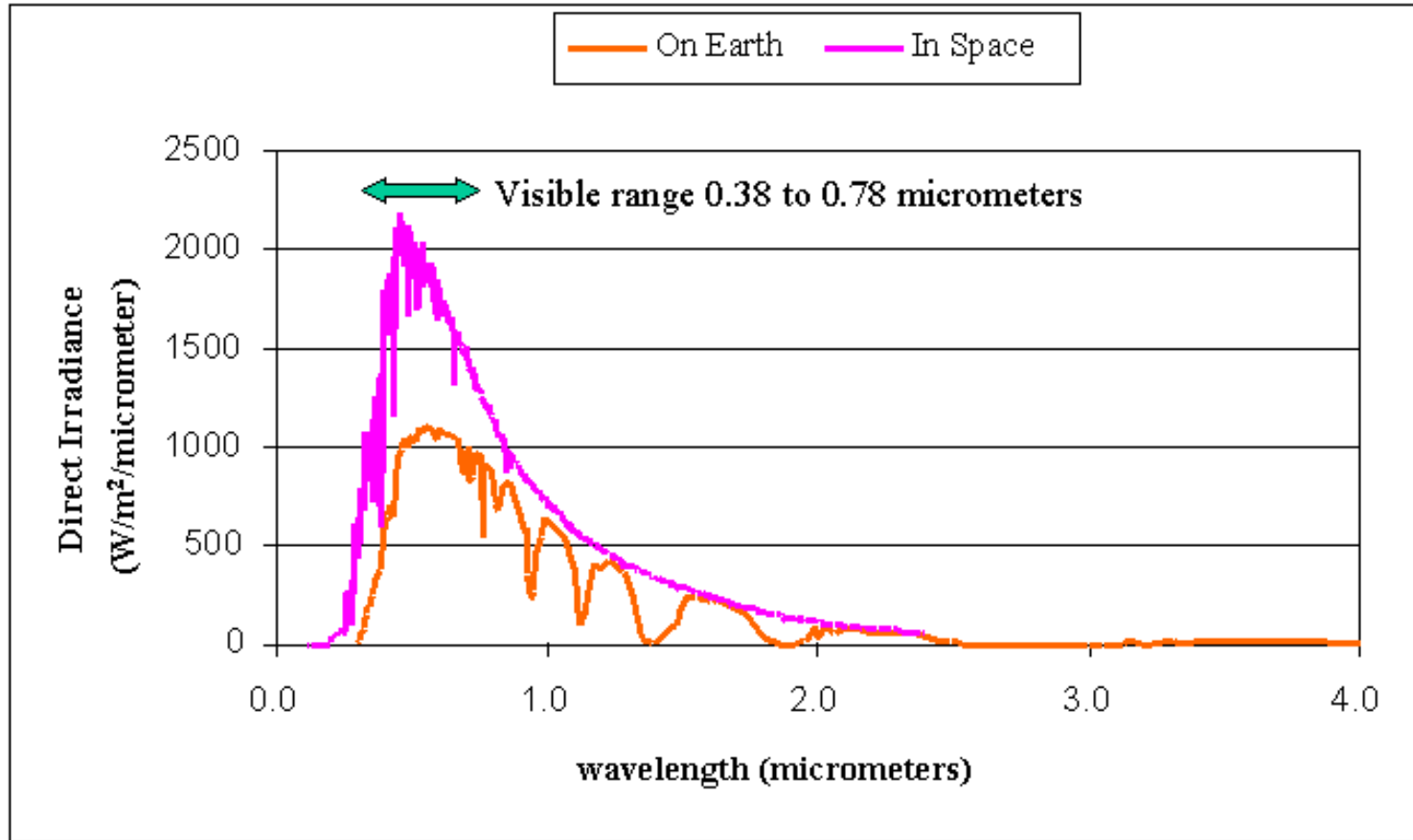




Design Procedure

- Collect solar resource (weather) data
- Determine power requirements
 - Power (kW) and Run times (kWh)
- Inverter capacity (kW)
- Battery capacity (kWh)
- Photovoltaic capacity (kW rated or m²)
- Conductors (wiring)
- Conduit
- Switches, disconnects, fuses.

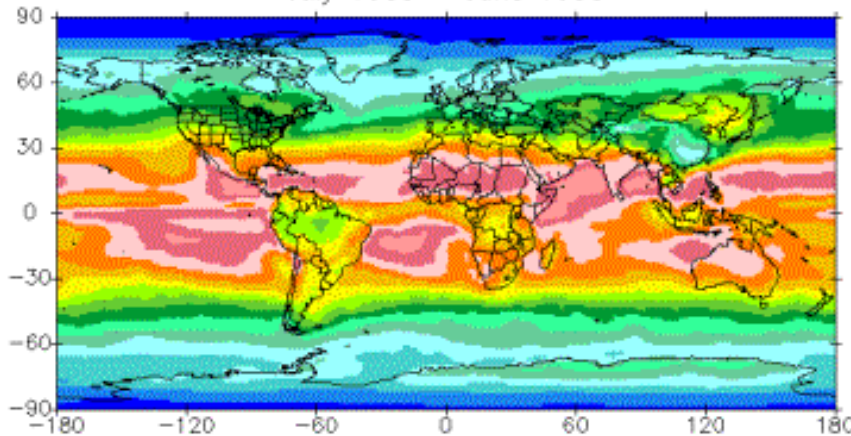
Solar Spectrum



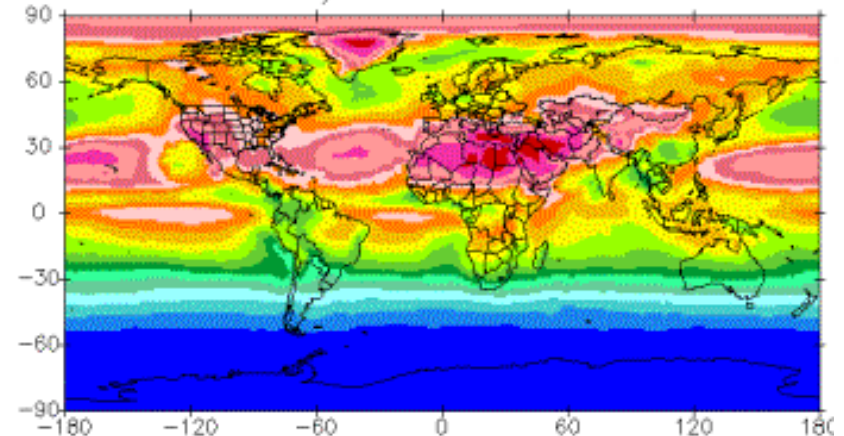
- 6% ultraviolet, 48% visible, and 46% infrared light
- annual average radiation 1,366 W/m² in space,
- typically less than 1000 W/m² on Earth.

Daily Average Solar Resource

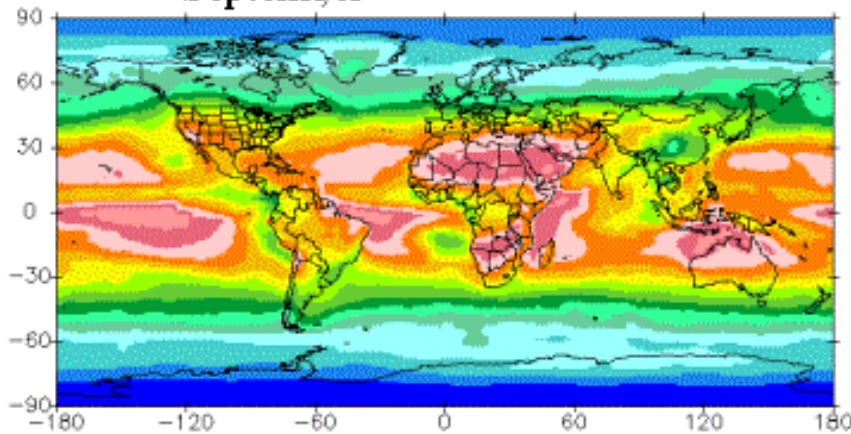
March



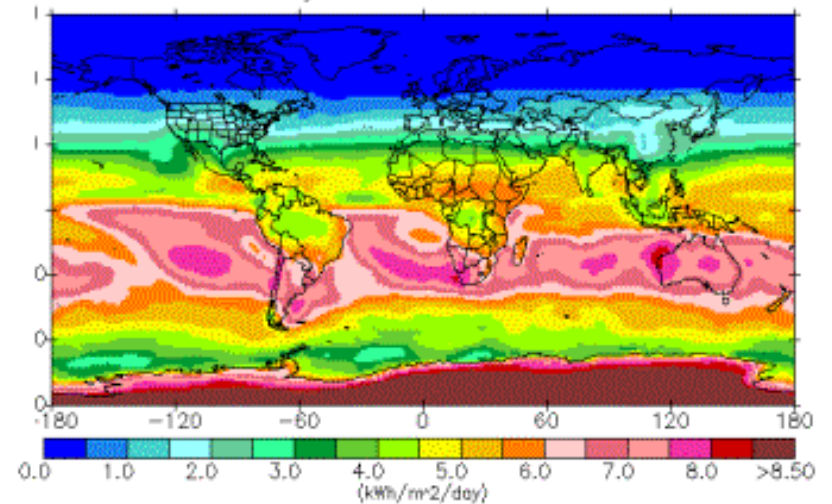
June



September



December



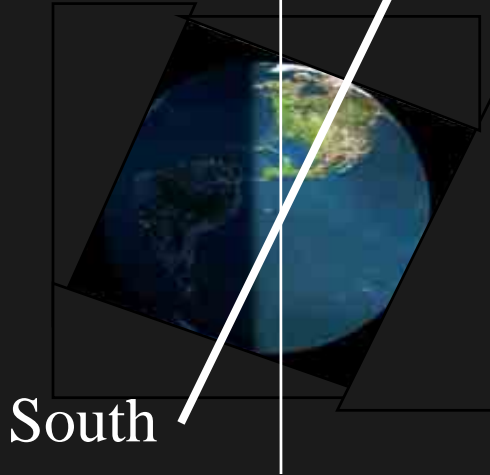
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 >8.50
(kWh/m²/day)

Declination, d , and the Seasons

Summer Solstice,

$d=23.45$ degrees

North



Spring
Equinox,

$d=0$



Sun

Winter Solstice,
 $d= -23.45$ deg



Fall Equinox,

$d=0$



Varies like a sin wave throughout the year.

Hour angle, h, and time of day

Earth rotates 360 deg in 24 hours, $h = 15 \text{ degrees/hour} \times \text{hours from noon}$

Solar Time	6 am	12 noon	6 pm
Hour angle, h	+90 deg	0 deg	-90 deg

Summer
Solstice
(June 22)



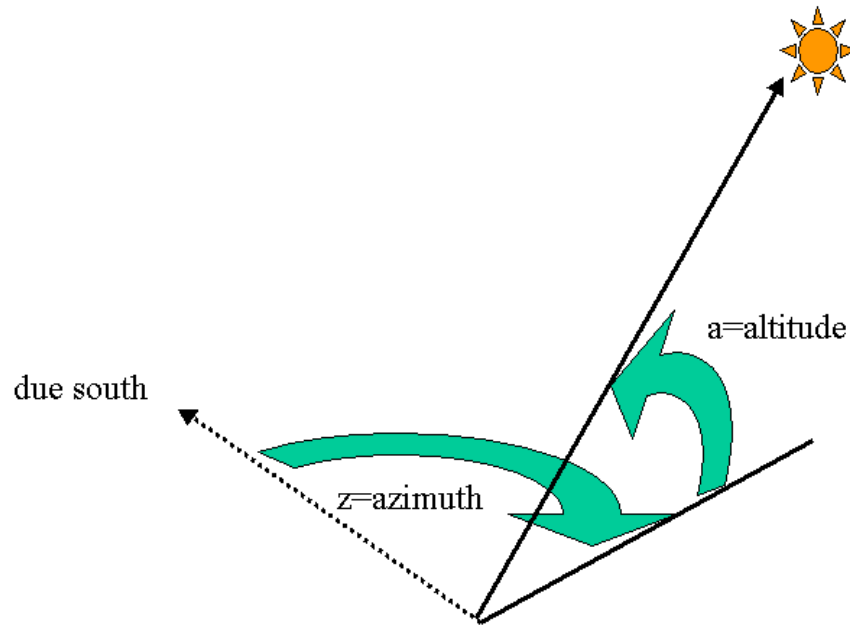
Spring & Fall
Equinox
(March 23)



Winter
Solstice
(Dec 23)



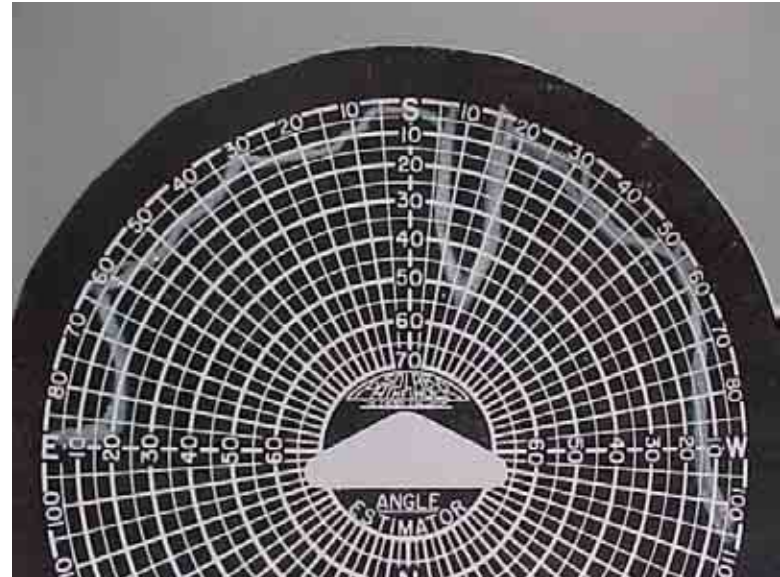
Position of the Sun in Sky



- Altitude angle, a , angle from the horizon up to the sun
 $\sin a = \cos l \cos d \cos h + \sin l \sin d$
- Azimuth angle, z , horizontal from due south to the sun,
 $\sin z = \sin h \cos d / \cos a$
- l =latitude (deg), h =hour angle (deg), d =declination (deg)
Warning: azimuth is more complicated if sun north of east-west line

Shading: horizon profile

Altitude angle of horizon at each azimuth angle



Solar Pathfinder

Software: Maui Solar Shading Effects

PV-DesignPro-S v5.0 Standalone Photovoltaic Energy System Design and Analysis Tool

PV System Files... Help... Window

Climate Shading Load PV Array Wind Wiring Battery Backup Inverter Calculate

PV System Shading Effects

Use Shading Effects?

Enter Shading Altitude and % Beam Blocked

Azimuth (S=0)	Altitude	% Beam
-180 to -170	0	0
-170 to -160	0	0
-160 to -150	0	0
-150 to -140	0	0
-140 to -130	0	0
-130 to -120	0	0
-120 to -110	0	0
-110 to -100	0	0
-100 to -90	0	0
-90 to -80	0	0
-80 to -70	20	0
-70 to -60	10	0
-60 to -50	0	0
-50 to -40	10	0
-40 to -30	5	0
-30 to -20	10	0
-20 to -10	5	0
-10 to 0	0	0
0 to 10	0	0
10 to 20	55	0
20 to 30	5	0
30 to 40	5	0
40 to 50	10	0
50 to 60	10	0
60 to 70	0	0
70 to 80	5	0
80 to 90	10	0
90 to 100	10	0
100 to 110	15	0
110 to 120	0	0
120 to 130	5	0
130 to 140	5	0
140 to 150	5	0
150 to 160	5	0
160 to 170	5	0
170 to 180	5	0

Daily Solar Position Plot: Yellow (Left Axis: Solar Altitude in Degrees, Bottom Axis: Solar Azimuth in Degrees)

Shading Altitude Angle from Horizon (Left Axis: Degrees), Shading Azimuth Angle (Bottom Axis: Degrees; 0=S, E=+, W=-)

Month: 12 Day: 12

OK Print <<-30 Days <-1 Day 1 Day--> 30 Days-->

nycsmoke.pvs No Calculation 0.000% 0.000% 0 Seconds

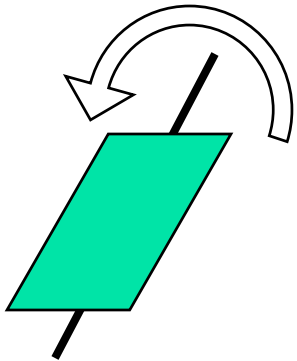
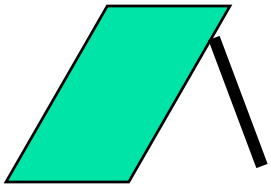
Fixed Tilt and Tracking

Fixed Tilt Facing Equator

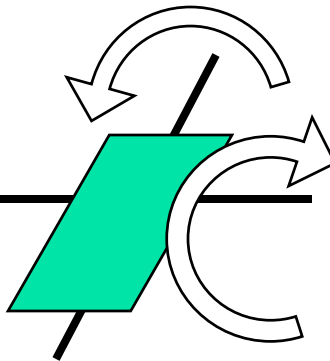
tilt = latitude

tilt < latitude for summer gain

tilt > latitude for winter gain



One Axis Tracking around axis tilted or flat

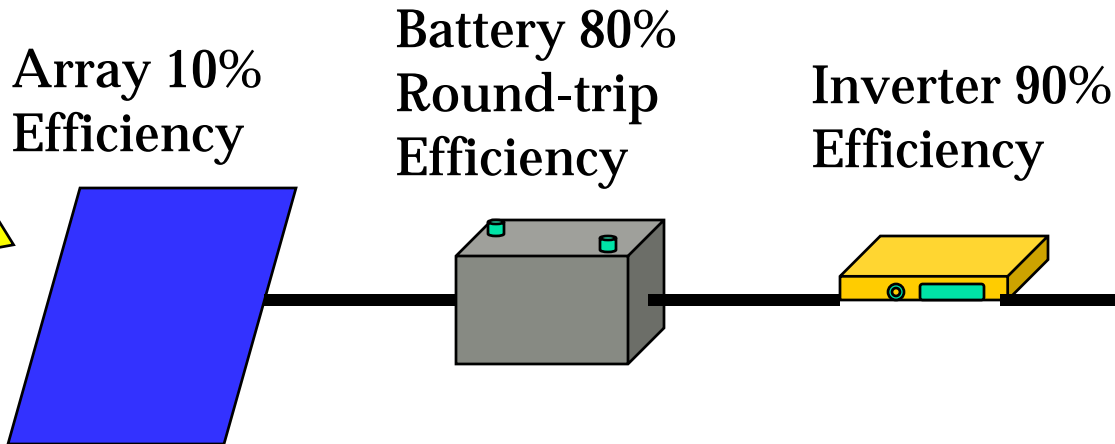


Two Axis Tracking both azimuth and altitude of sun around two axes



System Efficiency

Efficiency = power out / power in



100 Watts from sun > 10 Watts > 8 Watts > 7.2 AC Watts to load

Overall system efficiency is product of component efficiencies. Example
 $0.10 \times 0.80 \times 0.90 = 0.072$

...exacerbated by mismatch losses, typical system efficiency = 0.06

PV System Sizing: Stand-Alone Applications

PV System Size

$$P_{\text{rated}} = \frac{L}{I_{\text{min}}}$$

P_{rated} = rated PV power (kW)

L = Daily Load on PV = electricity required/inverter efficiency/battery efficiency (kWh/day)

I_{min} = minimum daily solar radiation (sun hours/day)

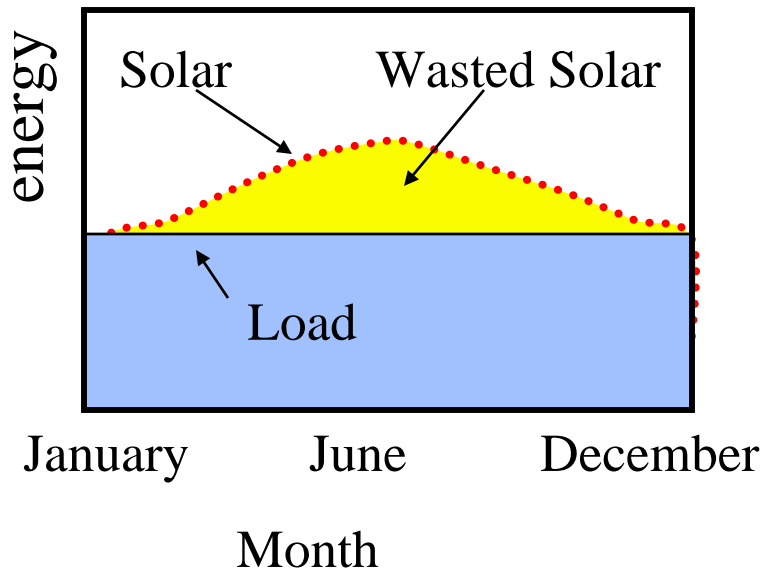
if you want to know how big in m^2 , divide P_{rated} by about 100 W/m^2

Annual Energy Delivery

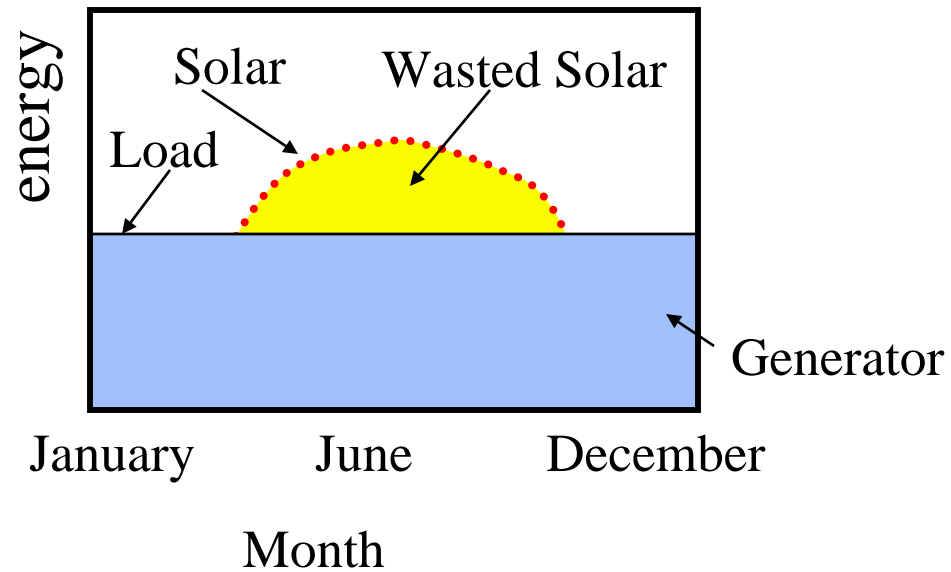
$$E_s = L * 365 \text{ (days/year)}$$

$$\text{Wasted solar} = (P_{\text{rated}} I_{\text{ave}} - L) * 365 \text{ (d/y)}$$

I_{ave} = average solar radiation (sun hours/day)



Hybrid Applications



Example: Small Load in Anchorage AK

- **Daily Electric Load**

Lights 120 Watts * 4 hours/day = 480 Wh/day

Fan 250 Watts * 2 hours/day = 500 Wh/day

Clock 20 Watts * 24 hours/day = 480 Wh/day

Peak Load 390 W Total Daily Load = 1.460 kWh/day

- **Inverter sizing:** at least 390 W, say 500W.

- **Battery Sizing:** 3 days storage * 1.46 kWh/day = 4.38 kWh
4.38 kWh/0.5 max depth of discharge= 8.76 kWh





Example: Small Load in Anchorage

- **Array Sizing**

- Add system inefficiency to Load

1.46 kWh/day/0.80 battery efficiency/0.90 inverter efficiency = 2.027 kWh/day

- For Anchorage, tilt equal to 61 degrees (local latitude)

$I_{max} = 4.6$, $I_{ave} = 3.0$, and $I_{min} = 0.6$ (kWh/m²/day = sunhours/day)

- If PV stands alone to meet the load, size for minimum sun

$$\begin{aligned} P_{rated} &= L / I_{min} = 2.027 \text{ kWh/day} / 0.6 \text{ sunhours/day} \\ &= 3.378 \text{ kW} \end{aligned}$$

PV Energy Delivery = 2.027 kWh/day * 365 days/year = 740 kWh/year



American Society for Testing and Materials (ASTM)

- nearly 100 standards regarding solar energy systems
- American Society for Testing and Materials (ASTM)
100 Barr Harbor Drive
West Conshohocken, PA 19428
Phone: (610) 832-9585; Fax: (610) 832-9555
Email: service@astm.org
World Wide Web: <http://www.astm.org/>
- *Annual Book of ASTM Standards, Volume 12:02:
Nuclear, Solar and Geothermal Energy*



ASTM E44.09 Standards

- **E 927-91** Specification for Solar Simulation for Terrestrial PV Testing
- **E 948-95** Test Method for Electrical Performance of PV Cells using Reference Cells under Simulated Sunlight
- **E 973-91** Test Method for Determination of the Spectral Mismatch Parameter Between a PV Device and a PV Reference Cell
- **E 1021-95** Test Methods for Measuring Spectral Response of PV Cells
- **E 1036-96** Test Methods Electrical Performance of Nonconcentrator Terrestrial PV Modules and Arrays using Reference Cells
- E 1038-93 Test Method for Determining Resistance of PV Modules to Hail by Impact with Propelled Ice Balls
- **E 1039-94** Test Method for Calibration of Silicon Non-Concentrator PV Primary Reference Cells Under Global Irradiation
- **E 1040-93** Specification for Physical Characteristics of Non-Concentrator Terrestrial PV Reference Cells
- **E 1125-94** Test Method for Calibration of Primary Non-Concentrator Terrestrial PV Reference Cells using a Tabular Spectrum
- **E 1143-94** Test Method for Determining the Linearity of a PV Device Parameter with Respect to a Test Parameter
- E 1171-93 Test Method for PV Modules in Cyclic Temperature and Humidity Environments
- **E 1328-94** Terminology Relating to PV Solar Energy Conversion
- **E 1362-95** Test Method for the Calibration of Non-Concentrator Terrestrial PV Secondary Reference Cells
- **E 1462-95** Test Methods for Insulation Integrity and Ground Path Continuity of PV Modules
- E 1524-93 Test Methods for Saltwater Immersion and Corrosion Testing of PV Modules for Marine Environments
- **E 1596-94** Test Methods for Solar Radiation Weathering of PV Modules
- E 1597-94 Test Method for Saltwater Pressure Immersion and Temperature Testing of PV Modules for Marine Environments
- **E 1799-96** Practice for Visual Inspection of PV Modules
- **E 1802-96** Test Methods for Wet Insulation Integrity Testing of PV Modules

Institute of Electrical and Electronic Engineers (IEEE)



- Standards for electrical and electronic equipment
- relates to industry experts.
- Institute of Electrical and Electronic Engineers, Inc
345 East 47th Street
New York, NY 10017, USA
- **P929 Recommended Practice for Utility Interface of Photovoltaic (PV) Systems**
 - display “Utility-Interactive” on the listing label
 - frequency and voltage limits, power quality, non-islanding inverter testing



IEEE PV Standards

- **928** IEEE Recommended Criteria for Terrestrial PV Power Systems
- **929** IEEE Recommended Practice for Utility Interface of Residential and Intermediate PV Systems
- **937** IEEE Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for PV Systems
- **1013** IEEE Recommended Practice for Sizing Lead-Acid Batteries for PV Systems
- **1144** Sizing of Industrial Nickel-Cadmium Batteries for PV Systems
- **1145** IEEE Recommended Practice for Installation and Maintenance of Nickel-Cadmium Batteries for PV Systems
- **P1262** Recommended Practice for Qualification of PV Modules
- **P1361** Recommended Practice for Determining Performance Characteristics and Suitability of Batteries in PV Systems
- **P1373** Recommended Practice for Field Test Methods and Procedures for Grid-Connected PV Systems
- **P1374** Guide for Terrestrial PV Power System Safety



Underwriters Laboratory (UL)

- Standards for Electrical Equipment Safety
- relates mainly to manufacturers.
- 333 Pfingsten Road Northbrook, IL 60062
- **UL Standard 1703, Flat-plate Photovoltaic Modules and Panels**
- **UL Standard 1741, Standard for Static Inverters and Charge Controllers for Use in Photovoltaic Power Systems**
 - incorporates the testing required by IEEE 929
 - includes design (type) testing and production testing.

National Fire Protection Association (NFPA)



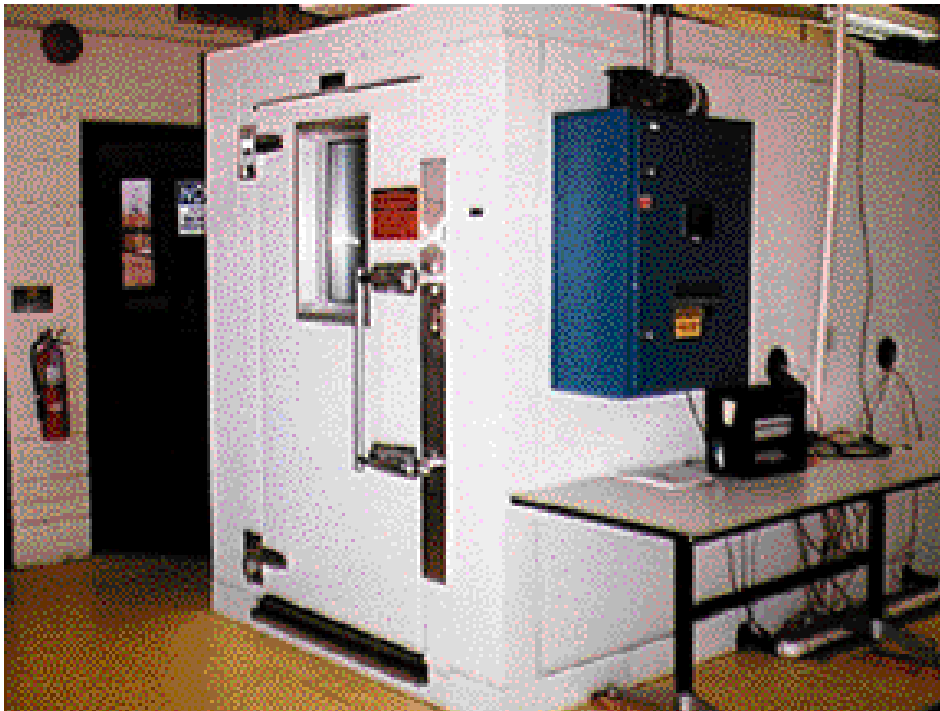
- National Electrical Code (NEC)
- Electrical Power System Installation
- relates to electrical trade and industry experts.
- Article 690: Solar Photovoltaic Systems
 - requires listing for utility interface inverters
 - Underwriters Laboratory (UL)
 - Edison Testing Laboratories (ETL)
 - Factory Mutual Research (FM)
- Article 230: Disconnect Means
- Article 240: Overcurrent Protection
- Article 250: Grounding
- Article 300 to 384: Wiring Methods
- Check out <http://www.nmsu.edu/~tdi/codes&.htm>



IEC PV Standards

- **IEC-891** Procedures for Temperature and Irradiance Corrections to Measured I-V Characteristics of Crystalline Silicon PV Devices
- **IEC-904-1** Measurement of PV I-V Characteristics
- **IEC-904-2** Requirements for Reference Solar Cells
- **IEC-904-3** Measurement Principles for Terrestrial PV Solar Devices with Reference Spectral Irradiance Data
- **IEC-904-4** On-Site Measurements of Crystalline Silicon PV Array I-V Characteristics
- **IEC-904-5** Determination of the Equivalent Cell Temperature (ECT) of PV Devices by the Open-Circuit Voltage Method
- **IEC-904-6** Requirements for Reference Solar Modules
- **IEC-904-7** Computation of Spectral Measurement of a PV Device
- **IEC-904-8** Guidance for Spectral Measurement of a PV Device
- **IEC-904-9** Solar Simulator Performance Requirements
- **IEC-1173** Overvoltage Protection for PV Power Generating Systems
- **IEC-1194** Characteristic Parameters of Stand-Alone PV Systems
- **IEC-1215** Design and Type Approval of Crystalline Silicon Terrestrial PV Modules
- **IEC-1277** Guide-General Description of PV Power Generating System
- **IEC-1701** Salt Mist Corrosion Testing of PV Modules
- **IEC-1702** Rating of Direct-Coupled PV Pumping Systems
- **IEC-1721** Susceptibility of a Module to Accidental Impact Damage (Resistance to Impact Test)
- **IEC-1727** PV-Characteristics of the Utility Interface
- **IEC-1829** Crystalline Silicon PV Array - On-Site Measurement of I-V Characteristics

Environmental Testing



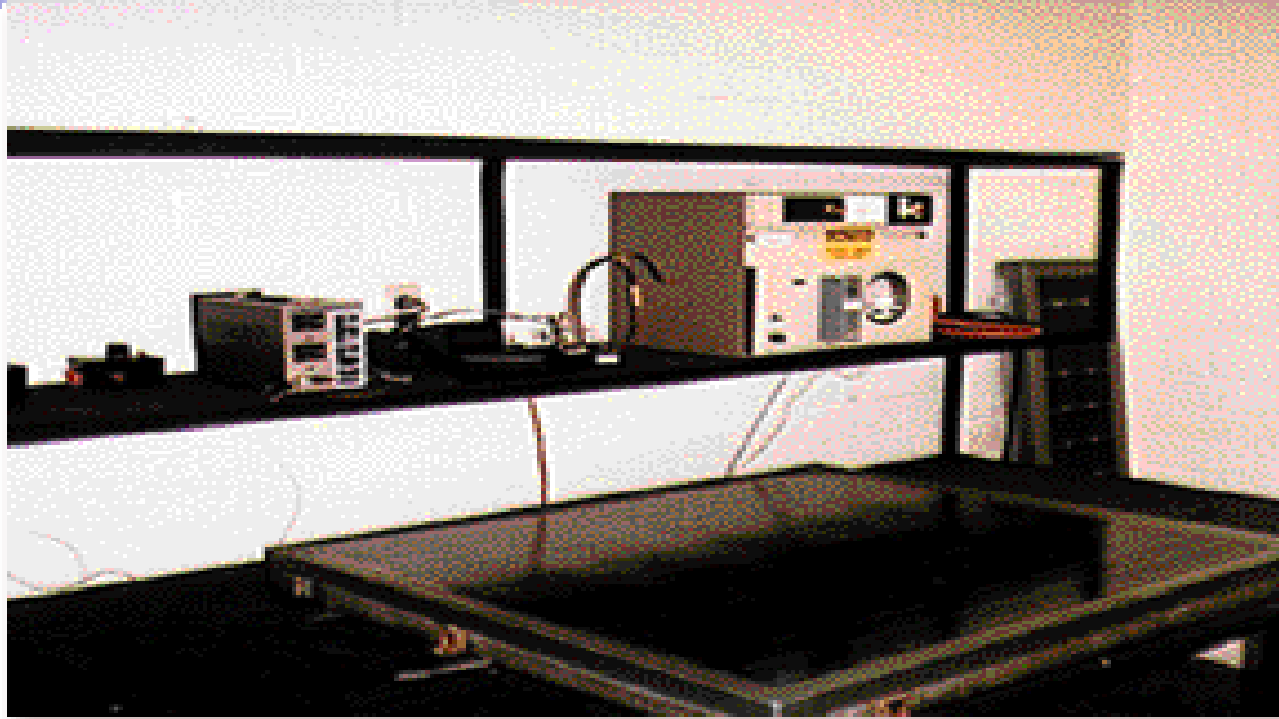
- **ASTM E 1171-93** Test Method for PV Modules in Cyclic Temperature and Humidity Environments
- Temperature -40 to +85 C
- Damp heat 85 C, 85%RH
- Humidity freeze 85%RH, -40 C
- Thermal Shock -40 to 110 C in 20 min

Hail Impact Testing



- **ASTM E 1038-93** Test Method for Determining Resistance of PV Modules to Hail by Impact with Propelled Ice Balls
- 1" simulated hailstones
- 55 mph
- Corner, edge and middle of module

Cyclic Load Testing



- ASTM E 1830M-96, Standard Test Method for Determining the Mechanical Integrity of Photovoltaic Modules. (30 lb/ft² cyclic load)



Other Requirements

- Building codes - UBC, SBC, BOCA, local codes
- ASTM
 - Standard Glass specifications
 - structural
- Consumer Product Safety Council
 - Structural Requirements , section 16
 - tempered, laminated
- Local covenants regarding appearance
- National Historic Preservation Act, SHPO

PV Design Tools

[http:// www.eren.doe.gov/buildings/tools_directory](http://www.eren.doe.gov/buildings/tools_directory)

▪ **Capabilities:**

- Sunpath Geometry
- System Sizing
- System Configuration
- On grid vs. Off grid
- Est. Power Output
- Building Simulations
- Shading
- Temperature & Thermal Performance
- Economic Analysis
- Avoided Emissions
- Building Energy Load Analysis
- Meteorological Data

Available Software:

- PVSYST
- MAUI SOLAR
 - PV DESIGN PRO
- WATSUN PV
- PV CAD
- PV FORM
- BLCC
- HOMER
- ENERGY-10
- AWNSHADE



Requirements for Success

- Conservation First
- Verify Load Estimates
- Appropriate Application
- Proven Design
- Operational Indicators or Monitoring
- Operations and Maintenance Training and Manual
- Properly Sized
- Require No Manual Intervention
- Performance Guarantee