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# CSP Training Module 2: Fuel

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Sponsored by College of the Desert

BrightSource Ivanpah, CA

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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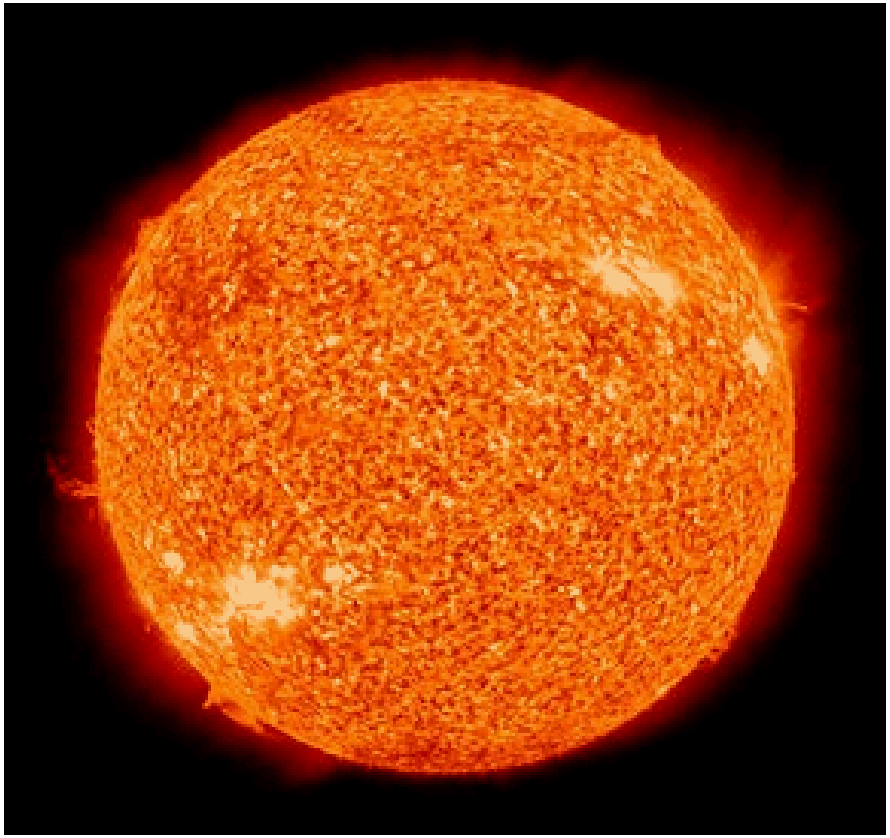
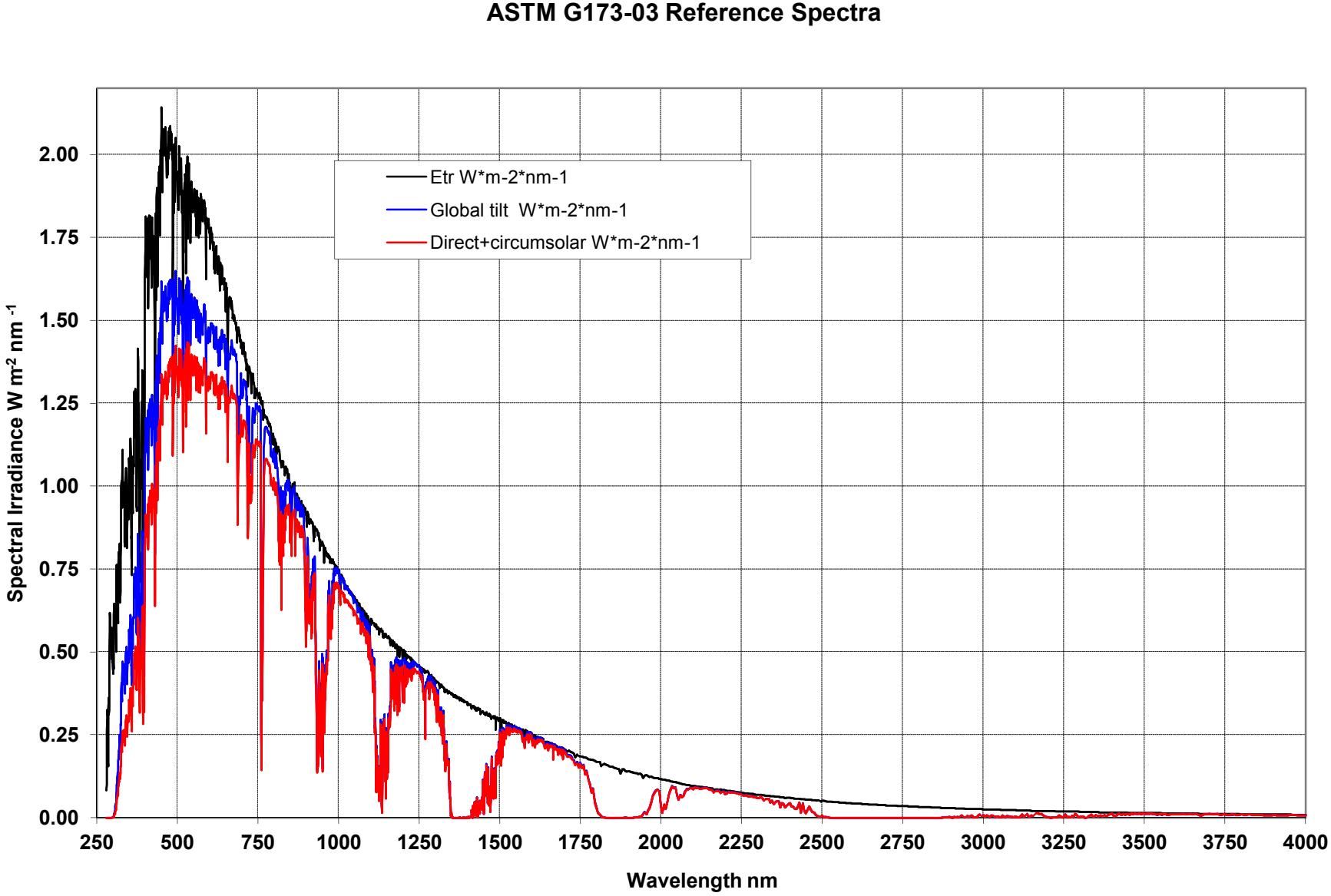
# 2. FUEL

# Gravitational-Containment Nuclear-Fusion Reactor

- Our sun – the nearest star.
- 92.9 million miles away
- 866,000 miles diameter (109 times earth's diameter)
- Blackbody emission at 5780 K
- Core temperature 15,600,000 K
- Irradiance outside earth's atmosphere:  1323 W/m2



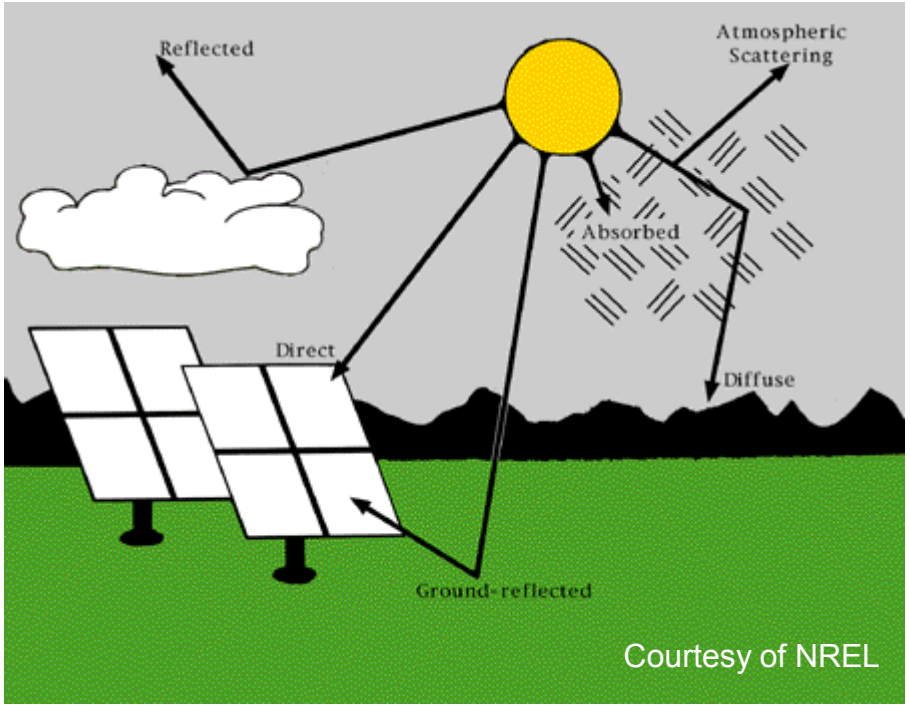
# Terrestrial Spectral Irradiance




Reference: http://rredc.nrel.gov/solar/spectra/am1.5/

# Definitions

- Direct normal irradiance (DNI):
  - Amount of solar radiation incident on a plane perpendicular to radiation. Typically measured in $W/m^2$.
- Global horizontal irradiance (GHI):
  - Total solar radiation on a horizontal plane. It is the sum of the direct normal irradiance and diffuse horizontal irradiance on a horizontal surface. Typically measured in $W/m^2$.
- Diffuse horizontal irradiance (DHI):
  - The radiation component that strikes a point from the sky, excluding circumsolar radiation. Typically measured in $W/m^2$.
- Insolation:
  - A measure of solar radiation **energy** received on a given surface area and recorded during a given time. Integrated irradiance over time. Typical units of $kWh/m^2$.




$$GHI = DHI + DNI * \cos(Z)$$

where:

Z is the solar zenith angle.

# Typical Meteorological Year Data

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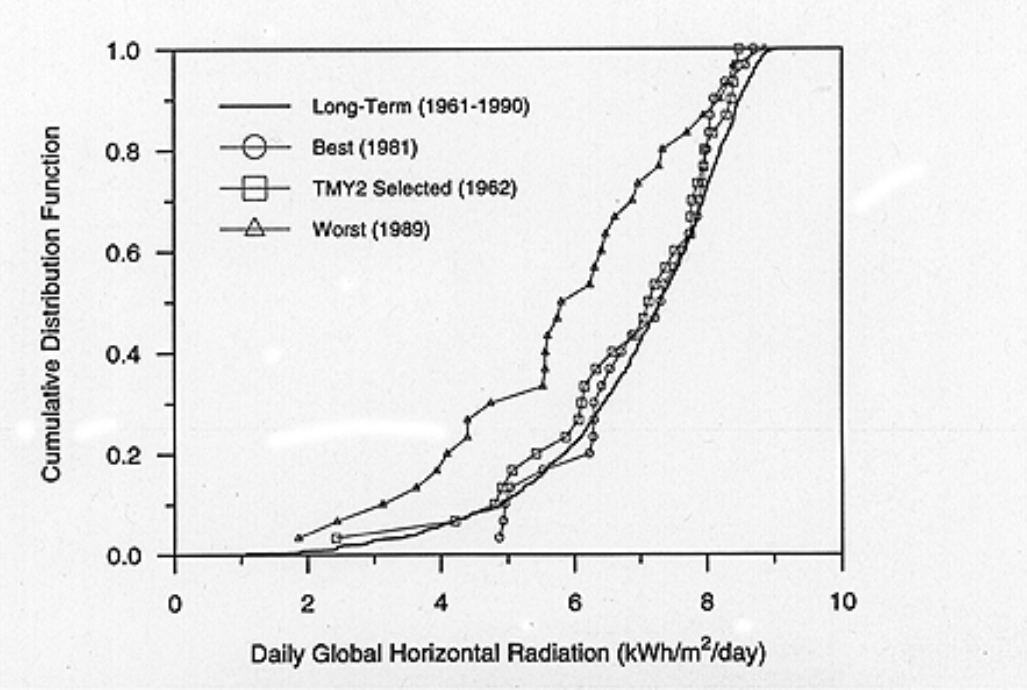
- Data set contains typical meteorological values for specific locations.
- Used for modeling solar power plants and other renewable energy conversion systems.
- Data sets contain hourly values of solar radiation and meteorological elements for a one-year period that typify climate based on a much longer period of time.
- Three versions of data sets:  TMY (original), TMY2 and TMY3.
- 8760 lines of data
- 68 data fields

# TMY Data (Continued)

- Composed of 12 typical meteorological months concatenated to form a single year
- Date set is chosen using the Sandia empirical approach.
  - Selects a typical month using cumulative distribution functions (CDF) and Finkelstein-Schafer statistics based on nine daily indices consisting of the maximum, minimum, and mean dry bulb and dew point temperatures; the maximum and mean wind velocity; and the total global horizontal solar radiation.
  - Final selection of a month includes consideration of the monthly mean and median and the persistence of weather patterns.
- TMY3 data sets contain 1020 locations and are based on more recent and accurate data.

# What's Typical?

- Cumulative Distribution Function for June GHI for Boulder, CO




Source: S. Wilcox and W. Marion, *Users Manual for TMY3 Data Sets*, NREL/TP-581-43156, May 2008

# TMY3 Stations

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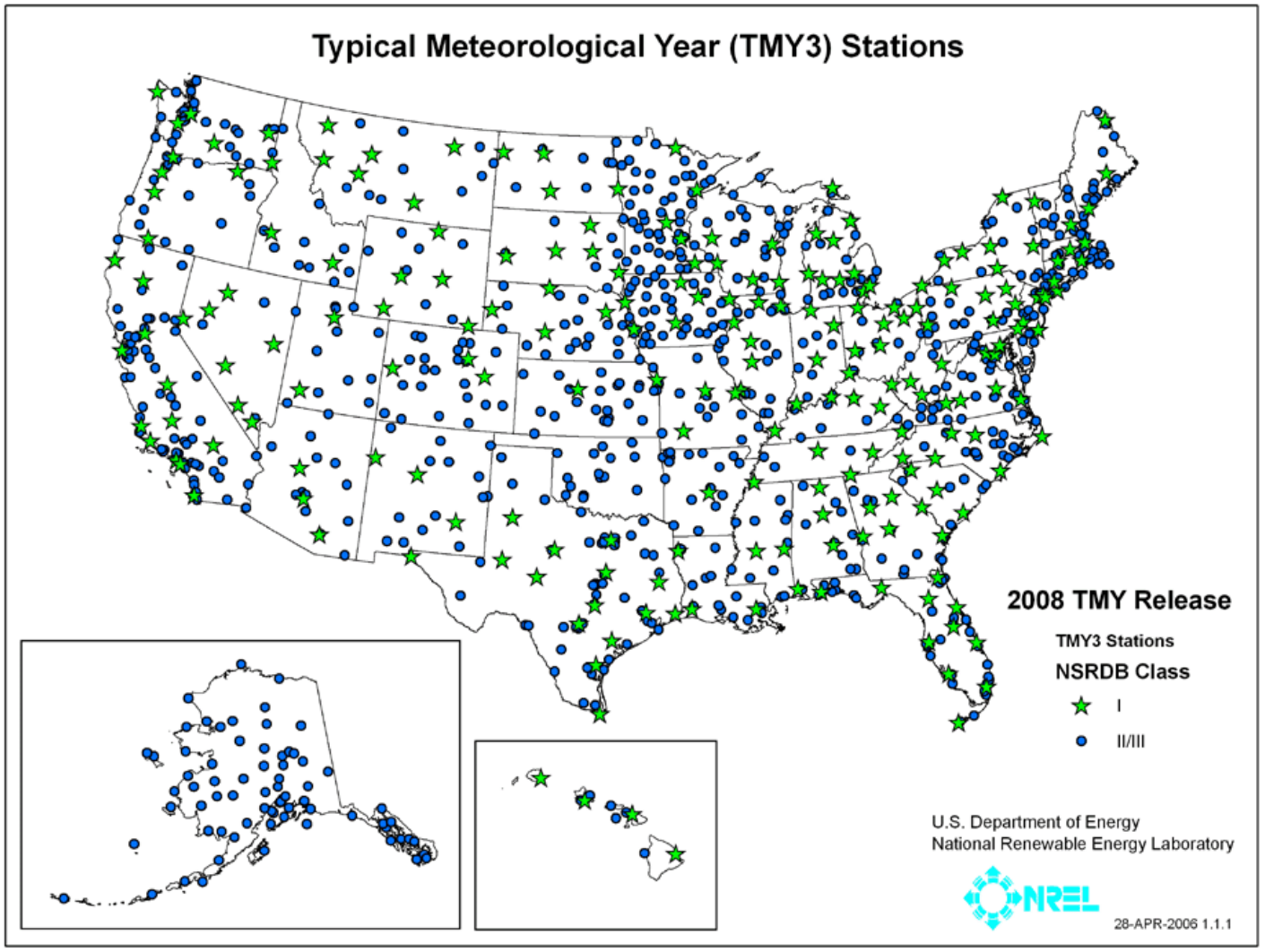

# Example TMY File (Partial)

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| | | | | | | |
|---|---|---|---|---|---|---|
| 723860 | LAS VEGAS MCCARRAN INTL AP | NV | -8 | 36.083 | -115.15 | 648 |

| Date (MM/DD/YYYY) | Time (HH:MM) | ETR (W/m^2) | ETRN (W/m^2) | GHI (W/m^2) | GHI source | GHI uncert (%) | DNI (W/m^2) | DNI source | DNI uncert (%) | DHI (W/m^2) | DHI source | DHI uncert (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/1/2001 | 1:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 2:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 3:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 4:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 5:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 6:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 7:00 | 1 | 153 | 0 | 2 | 9 | 0 | 2 | 21 | 0 | 2 | 9 |
| 1/1/2001 | 8:00 | 146 | 1415 | 65 | 2 | 9 | 485 | 2 | 21 | 15 | 2 | 9 |
| 1/1/2001 | 9:00 | 371 | 1415 | 237 | 2 | 9 | 760 | 2 | 21 | 37 | 2 | 9 |
| 1/1/2001 | 10:00 | 551 | 1415 | 374 | 2 | 9 | 784 | 2 | 21 | 68 | 2 | 9 |
| 1/1/2001 | 11:00 | 671 | 1415 | 466 | 2 | 9 | 809 | 2 | 21 | 81 | 2 | 9 |
| 1/1/2001 | 12:00 | 724 | 1415 | 522 | 2 | 9 | 828 | 2 | 21 | 97 | 2 | 9 |
| 1/1/2001 | 13:00 | 705 | 1415 | 488 | 2 | 9 | 793 | 2 | 21 | 91 | 2 | 9 |
| 1/1/2001 | 14:00 | 617 | 1415 | 450 | 2 | 9 | 894 | 2 | 21 | 59 | 2 | 9 |
| 1/1/2001 | 15:00 | 464 | 1415 | 327 | 2 | 9 | 777 | 2 | 21 | 71 | 2 | 9 |
| 1/1/2001 | 16:00 | 259 | 1415 | 191 | 2 | 9 | 513 | 2 | 21 | 96 | 2 | 9 |
| 1/1/2001 | 17:00 | 42 | 837 | 4 | 2 | 9 | 120 | 2 | 21 | 2 | 2 | 9 |
| 1/1/2001 | 18:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 19:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 20:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 21:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 22:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 23:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |
| 1/1/2001 | 24:00:00 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 |

# Satellite Data

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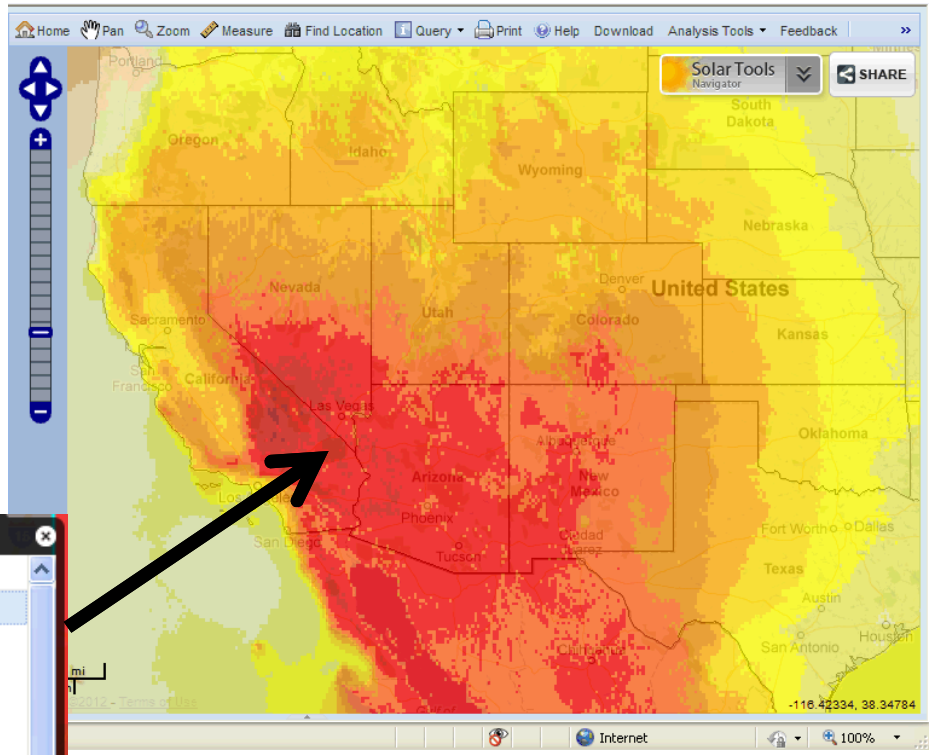
- Satellite data is used to prediction solar radiation
- An example is the SUNY Satellite Solar Radiation Model
  - Data are averaged from hourly model output over 8 years (1998-2005).
  - Uses hourly radiance images from geostationary weather satellites, daily snow cover data, and monthly averages of atmospheric water vapor, trace gases, and the amount of aerosols in the atmosphere to calculate the hourly total insolation falling on a horizontal surface.
  - The direct beam radiation is then calculated using the atmospheric water vapor, trace gases, and aerosols.
  - Where possible, existing ground measurement stations are used to validate the data.

# Solar Prospector

- Obtain monthly and annual solar radiation data (DNI, GHI, Global Tilt)
- Also obtain slope data, infrastructure, land ownership, borders, location of power plants (CSP, and fossil), etc.




http://maps.nrel.gov/prospector

**Query Results**

| | |
|---|---|
| Avg. Annual DNI | *1 nearby result* |
| Result 1 of 1 | |
| Annual Avg. (Wh/m2/day): | 7390 |
| January: | 5436 |
| February: | 5724 |
| March: | 7245 |
| April: | 7803 |
| May: | 9090 |
| June: | 9855 |
| July: | 8568 |
| August: | 7866 |
| September: | 8271 |
| October: | 6966 |
| November: | 6282 |
| December: | 5508 |
| State Borders | *1 nearby result* |

Annual and monthly DNI at Ivanpah, CA
35.55 N lat, 115.45 W long

# Measurement Solar Radiation

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- A solar plant needs to have reliable and accurate measurements of solar radiation for the operation of the plant
- Measurements are also needed for performance assessments and could be required for performance guarantees
- The primary solar irradiance measurements required are :
  - Direct Normal Irradiance
  - Global Horizontal Irradiance
  - Diffuse Horizontal Irradiance
- All three are required to conduct quality assurance of the data.
- Other meteorological data are required:
  - Wind speed and direction
  - Ambient temperature
  - Relative humidity
  - Atmospheric pressure
- Require a location that provides good daily solar access throughout the year
  - Should be an area with a clear horizon without any obstructions (no shading or reflections)
  - A building roof is often a good location.
  - Location should have safe and secure access (allow for regular inspections)

# Instruments to Measure Solar Radiation

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- Less cost, less accurate, less maintenance (e.g., for site resource monitoring):
  - Silicon photodiode radimeters with rotating shadow band for GHI and DHI. DNI is computed
- For higher accuracy, more cost, higher maintenance measurement (e.g., plant operation and performance monitoring):
  - Thermopile Pyrheliometer (with tracker) for DNI
  - Thermopile ventilated pyrheliometer for GHI and DHI
- Reference: *Solar Resource and Meteorological Assessment Project (SOLRMAP) Solar and Meteorological Station Options: Configurations and Specifications*, Steve Wilcox and Tom Stoffel, NREL, July 1, 2009.

# Lower cost, lower maintenance, less accurate system

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| | Instrument | Data Parameter(s) | Purchase Price | Installation (Person-Hrs) | Data Uncertainty* | |
|---|---|---|---|---|---|---|
| | | | | | Bias (mean deviation) | Random (std deviation) |
| Baseline Configuration | Rotating Shadowband Radiometer System (Irradiance, Inc Model RSR2 | Measured GH and DIFF irradiances. Computed DNI. Includes secondary sensor, CR800 data logger with air temperature and gill shield. | $9,100 | 4 | -3.5 to -7.5% DNI<br>+1.0 to -1.2% GH<br>+3.0 to -0.2% DIF | 16 to 19%†<br>4 to 6%<br>5 to 6% |
| | Mounting Method | • Simple pipe for flat surface (e.g. concrete pile)<br>• Ballast plate for flat surface (e.g., roof)<br>• Tripod for ground mounting (e.g., desert floor) | $95<br>$185<br>$575 | 4 | N/A | N/A |
| | Choose Power Supply (as needed) | 10-watt module, charge controller and battery for high insolation (>3 kWh/m^2 day average during minimum month)<br>20-watt module, charge controller and battery (>2 kWh/m^2/day minimum) | $500<br>$700 | N/A | N/A | N/A |
| | Temperature and Relative Humidity | Campbell CS 215 | $535 | 1 | ±0.2° temp<br>±2% RH | Not evaluated |
| | Barometric Pressure | CS106 | $885 | 1 | ±1 mbar | Not evaluated |
| | Wind | 03001-L RM Young WS/WD set with supporting 10 ft mast | $1050 | 2 | ±5° WD<br>±1.5% WS | Not evaluated |
| | Communications | Telephone wired modem | $550 | N/A | N/A | N/A |
| Optional Upgrades | Licor LI-200 pyranometer (optional) | POA for fixed tilt collector | $270 | 2 | +2.8 to -2.0% | 3 to 8% |
| | Texas Electronics Tipping Bucket (Campbell p/n TE525-20) | PRECIP | $615 | 3 | ± 0.01" | Not evaluated |
| | Communications Upgrades | Ethernet (hard wired)<br>Ethernet (cellular gprs/edge) | $640<br>$1125 | N/A | N/A | N/A |
| | Data logger upgrade to Campbell CR-1000 | Required for meteorological instruments and optional solar instruments | $700 | N/A | N./A | N/A |
| | **Total** | Minimal configuration<br>With all options | $12,620<br>$15,555 | 12<br>17 | | |

# Higher cost, higher maintenance, more accurate

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| | Instrument | Data Parameter(s) / comments | Purchase Price | Installation (Person-Hrs) | Data Uncertainty* Bias (mean deviation) | Data Uncertainty* Random (std deviation) |
|---|---|---|---|---|---|---|
| Baseline Configuration | **Pyrheliometer**<br>Eppley Model NIP<br>Kipp & Zonen Model CH1 or CHP1 | DNI | $2,350[1]<br>$3,500[2] | 2 | +0.46 to -0.53%<br>+0.23 to +0.1% | 0.4 to 0.6%<br>0.4 to 0.5% |
| | **Ventilated Pyranometer**<br>Eppley Model PSP w/VEN ventilator<br>Kipp & Zonen Model CMP22 w/CVF-3 Ventilator and CVP-2 Power supply | GH | $3,200[1]<br>$9,016[2] | 6 | +1.6 to -11.3%<br>+0.6 to +0.4% | 2 to 8%<br>2 to 3% |
| | **Ventilated Pyranometer**<br>Eppley Model 8-48 w/VEN ventilator<br>Kipp & Zonen Model CMP22 w/CVF-3 ventilator and CVP-2 Power supply | DIFF | $2,475[1]<br>$9,016[2] | 6 | ±5% of reading or 10 W/m²<br>±2% of reading or 5 W/m² + | ±3W/m²<br>±3W/m² |
| | **Automatic Solar Tracker**<br>Eppley SMT-3<br>Kipp & Zonen Model 2AP-GD | (Radiometers and ventilators installed on solar tracker. Includes tripod or mount†, shade mechanism, and other accessories.) | $18,975[1]†<br>$29,350[2] | 4 | <0.1° (1/50 5°FOV)<br><0.05° (1/100 5°FOV) | ±0.02° (1/250 5°FOV)<br>±0.01° (1/500 5°FOV) |
| | **Meteorological Tower** Campbell Scientific<br>CM10 10 ft steel tripod tower<br>ENC12/14 Enclosure for logger | (Tripod 10 ft tower supports data logger and meteorological instruments: | $450<br>$205 | 4 | N/A | N/A |
| | **Meteorological Instruments**<br>Vaisala HMP-50C Temp & RH<br>Campbel 41003-5 Radiation Shield<br>03001-L RM Young WS/WD set | Co-located meteorological measurements of air temperature, relative humidity, wind speed, and wind direction | $400<br>$120<br>$650 | 2 | N/A | N/A |
| | **Data Logger** Campbell Scientific, Inc. Model CR1000 | Programmable control and data acquisition system. Includes extended temperature range and 4MB memory | $1,640 | 6 | (OFFSET) 22µV (~2-3 W/m² at 7 µV/W) | 4.2 µV (~ 0.5 W/m² at 7 µV/W) |
| | **Telephone Modem** Campbell Scientific, Inc. Model COMM220 | (Access data logger recordings by land line) | $400 | 2 | N/A | N/A |
| | **Miscellaneous** | Cabling, connectors, conduit, hardware, etc. | $400 | 3 | N/A | N/A |
| Optional Upgrades | **Network Link Interface** Campbell Scientific, Inc. Model NL100 | (Access data logger recordings by internet connection to NREL/MIDC) | $500 | 2 | N/A | N/A |
| | **Ventilated Pyranometer**<br>Eppley Model PSP w/VEN ventilator<br>Kipp & Zonen Model CMP22 w/CVF-3 Ventilator and CVP-2 Power supply | POA for tracking flat plate collector | $3,200[1]<br>$9,016[2] | 2 | ±1.6% ‡<br>±0.6%‡ | 2 to 3%<br>2 to 3% |
| | **Ventilated Pyranometer**<br>Eppley Model PSP w/VEN ventilator<br>Kipp & Zonen Model CMP22 w/CVF-3 Ventilator and CVP-2 Power supply | POA for fixed tilt collector | $3,200[1]<br>$9,016[2] | 2 | +1.6 to -11.3%<br>+0.6 to +0.4% | 2 to 8%<br>2 to 3% |
| | **Barometer**<br>Vaisala CS106 | BP | $590 | 1 | ±1 mbar | Not evaluated |
| Total | **Base system**<br>**With all options** | | $31,265[1] $55,147[2]<br>$38,355[1] $73,869[2] | 45<br>52 | N/A | |