Sunlight and its Properties III

EE 446/646

Y. Baghzouz

Hourly Clear Sky Insolation

- The previous insolation equations are instantaneous values (at a given specific time).
- These can be tabulated into hourly, daily, monthly, and annual values for different tracking and fixed tilt angles: The Table below is one example of hourly insolation.

Solar Time	Tracking		Tilt Angles, Latitude 40°						
	One-Axis	Two-Axis	0	20	30	40	50	60	90
			June 21					(W/m^2)	
6, 6	471	524	188	128	93	57	53	48	32
7, 5	668	742	386	330	289	240	185	126	45
8, 4	772	855	572	538	498	445	380	305	51
9, 3	835	921	731	722	686	632	560	473	147
10, 2	875	961	853	865	834	780	703	607	233
11, 1	898	982	929	956	928	874	795	693	288
12	906	989	955	987	960	906	826	723	308
kWh/d:	9.94	10.96	8.27	8.06	7.62	6.96	6.18	5.23	1.90

Note: Similar tables for other months and latitudes are given in Appendix C

Reflected light is not included in the above table

Daily and Annual Clear-Sky Insolation

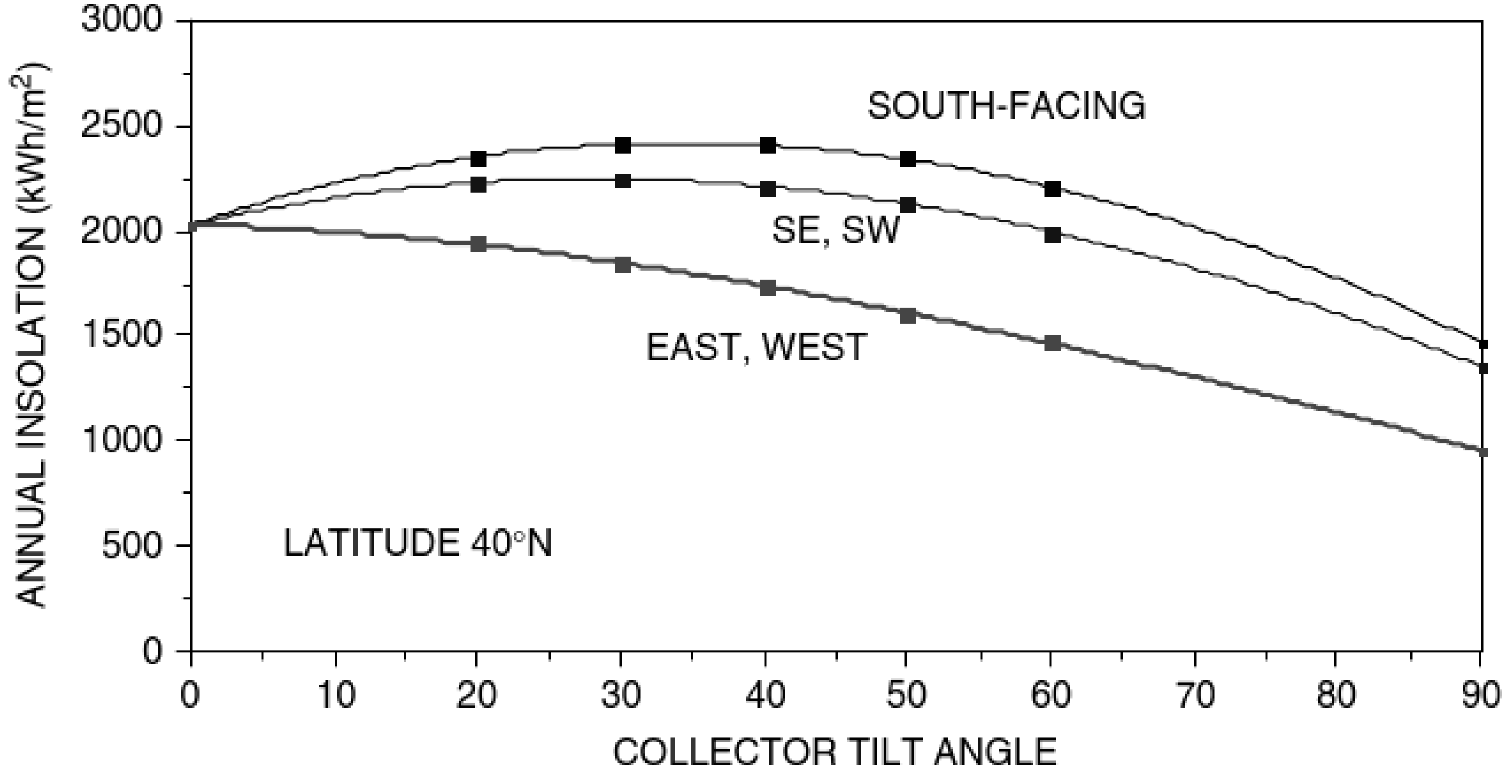
Daily Clear-Sky Insolation (kWh/m^2) Latitude 40°N

Azim:		S						SE/SW						E, W						Tracking	
Tilt:	0	20	30	40	50	60	90	20	30	40	50	60	90	20	30	40	50	60	90	One-Axis	Two-Axis
Jan	3.0	4.6	5.2	5.7	6.0	6.2	5.5	4.1	4.5	4.7	4.9	4.9	4.0	2.9	2.8	2.7	2.6	2.4	1.7	6.8	7.2
Feb	4.2	5.8	6.3	6.6	6.8	6.7	5.4	5.3	5.6	5.7	5.7	5.5	4.2	4.1	3.9	3.7	3.5	3.3	2.2	8.2	8.3
Mar	5.8	6.9	7.2	7.3	7.1	6.8	4.7	6.5	6.6	6.6	6.4	6.0	4.1	5.5	5.3	5.0	4.6	4.3	2.8	9.5	9.5
Apr	7.2	7.7	7.7	7.4	6.9	6.2	3.3	7.5	7.4	7.1	6.6	6.1	3.7	6.9	6.6	6.2	5.7	5.2	3.3	10.3	10.6
May	8.1	8.0	7.7	7.1	6.4	5.5	2.3	8.0	7.6	7.2	6.5	5.8	3.2	7.7	7.3	6.8	6.2	5.5	3.5	10.2	11.0
Jun	8.3	8.1	7.6	7.0	6.2	5.2	1.9	8.0	7.6	7.1	6.4	5.6	3.0	7.8	7.4	6.9	6.3	5.6	3.4	9.9	11.0
July	8.0	7.9	7.6	7.0	6.3	5.5	2.2	7.9	7.5	7.1	6.4	5.7	3.2	7.6	7.2	6.7	6.1	5.5	3.4	10.0	10.7
Aug	7.1	7.5	7.5	7.2	6.7	6.0	3.2	7.3	7.2	6.9	6.5	5.9	3.6	6.7	6.4	6.0	5.5	5.0	3.2	9.8	10.1
Sept	5.6	6.7	6.9	7.0	6.9	6.5	4.5	6.3	6.4	6.3	6.1	5.8	4.0	5.4	5.2	4.9	4.5	4.1	2.7	9.0	9.0
Oct	4.1	5.5	6.0	6.3	6.4	6.4	5.1	5.0	5.3	5.4	5.4	5.2	4.0	3.9	3.7	3.6	3.3	3.1	2.1	7.7	7.8
Nov	2.9	4.5	5.1	5.5	5.8	5.9	5.3	3.9	4.3	4.6	4.7	4.7	3.9	2.8	2.7	2.6	2.5	2.3	1.6	6.5	6.9
Dec	2.5	4.1	4.7	5.2	5.5	5.7	5.2	3.6	3.9	4.2	4.4	4.4	3.8	2.4	2.3	2.2	2.1	2.0	1.4	6.0	6.5
Total	2029	2352	2415	2410	2342	2208	1471	2231	2249	2216	2130	1997	1357	1938	1848	1738	1612	1467	960	3167	3305

Tables for other latitudes are in Appendix D

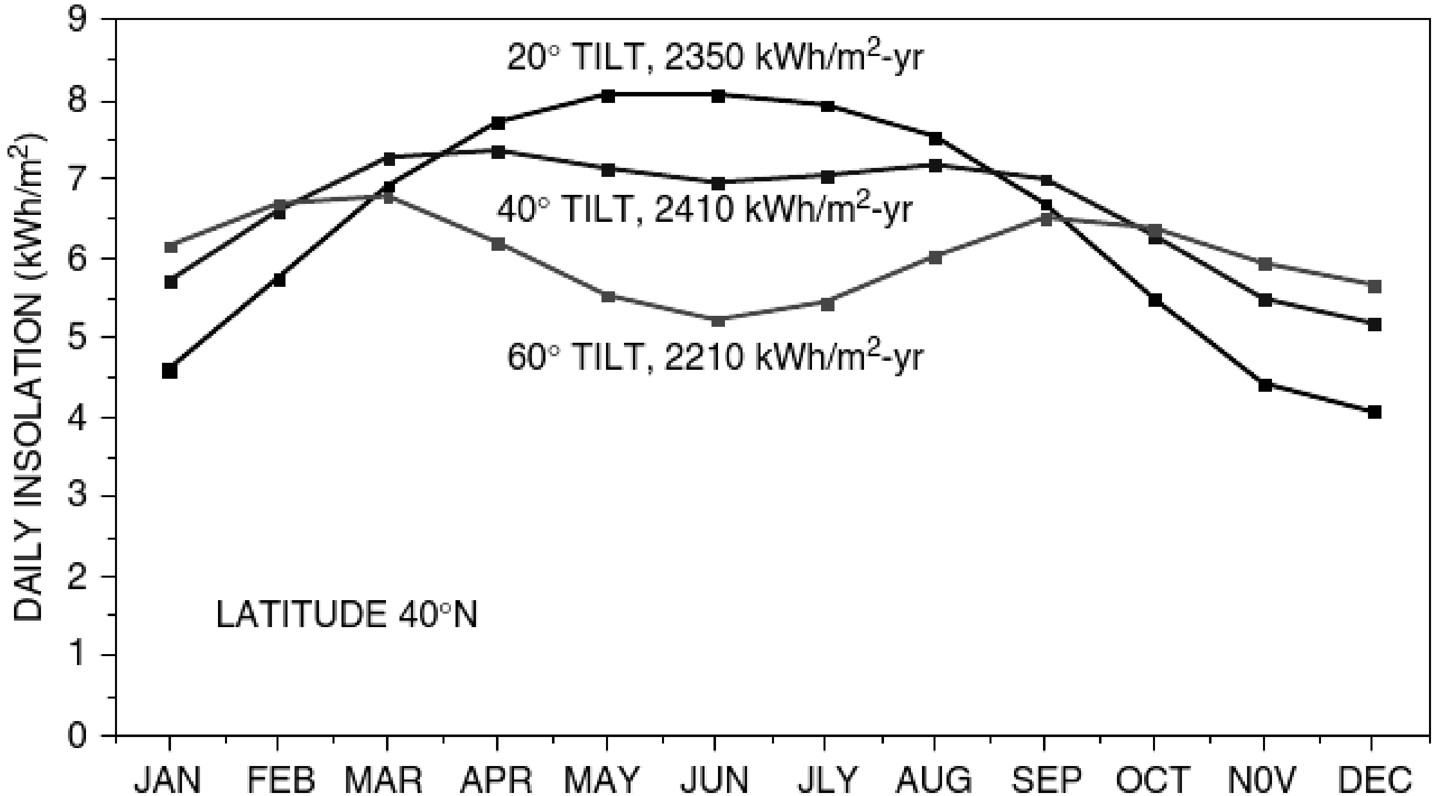
Annual Insolation for Fixed Collectors

- **Remark:** Annual amounts vary only slightly over a wide range of collector tilt and azimuth angles.



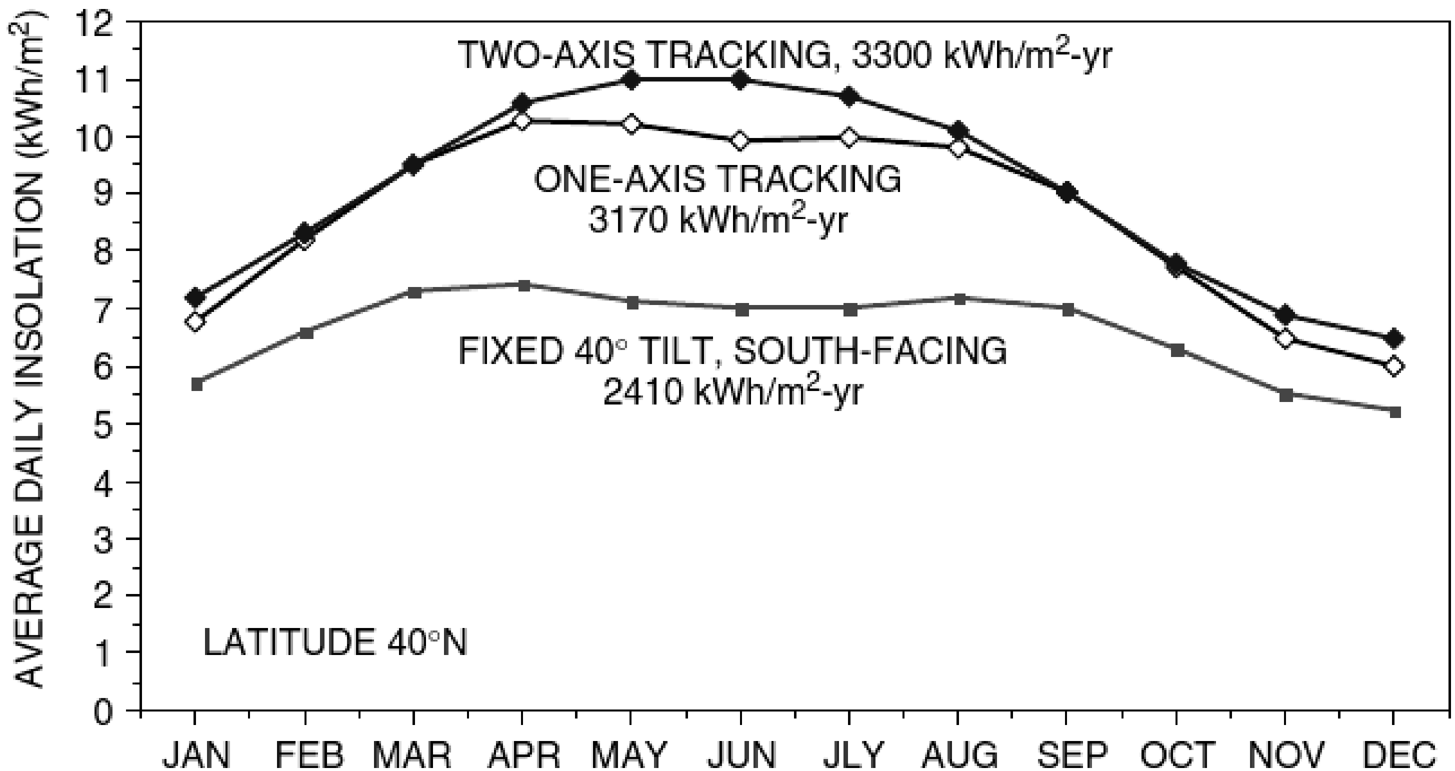
Daily Clear-Sky Insolation of South-Facing Collectors

- **Note:** while the annual insolation is nearly the same, the monthly distribution is quite different.



Daily Clear-Sky Insolation of Fixed and Tracking Collectors

- **Note:** Performance boost of the tracking systems is apparent.



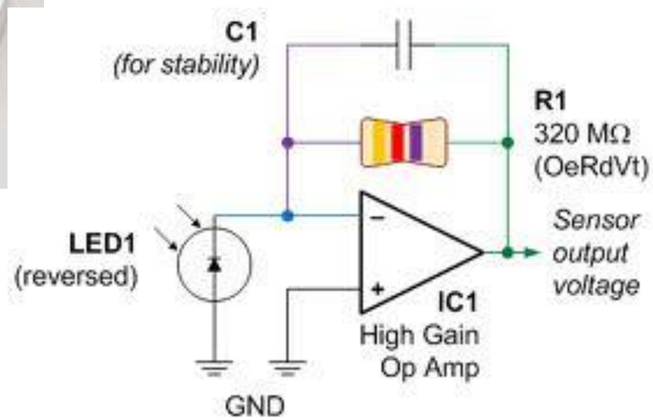
Measuring Sunlight

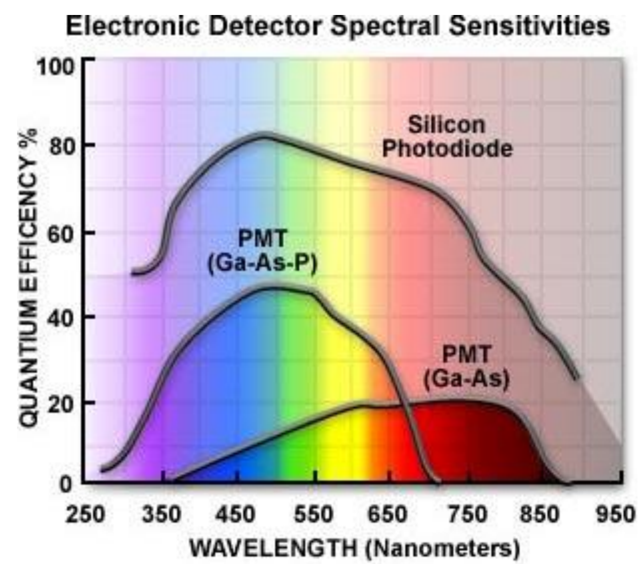
- **Pyranometers** are designed to accurately measure the global solar irradiance (they respond to all wavelengths).
  - By a placing a shade ring to block the direct beam, a pyranometer can be used to measure diffuse radiation.

- **Pyrheliometers** - shaped like long narrow tubes - are designed to measure the direct (or normal incident) irradiance.
- Both Pyranometers and pyrheliometers use a stack of thermocouples (thermopile) to detect how much hotter a black surface becomes when exposed to sunlight – then produces a voltage that is proportional to insolation.
- Both of the above devices respond to all wavelengths.

Measuring sunlight

- **Other instruments** which are less expensive (but less accurate) are available. The most common is the silicon photodiode.
- A photodiode sends a current through a calibrated resistance to produce a voltage that is proportional to insolation.
- These photoelectric sensors respond only to a limited portion of the solar spectrum, and not accurately to artificial light.



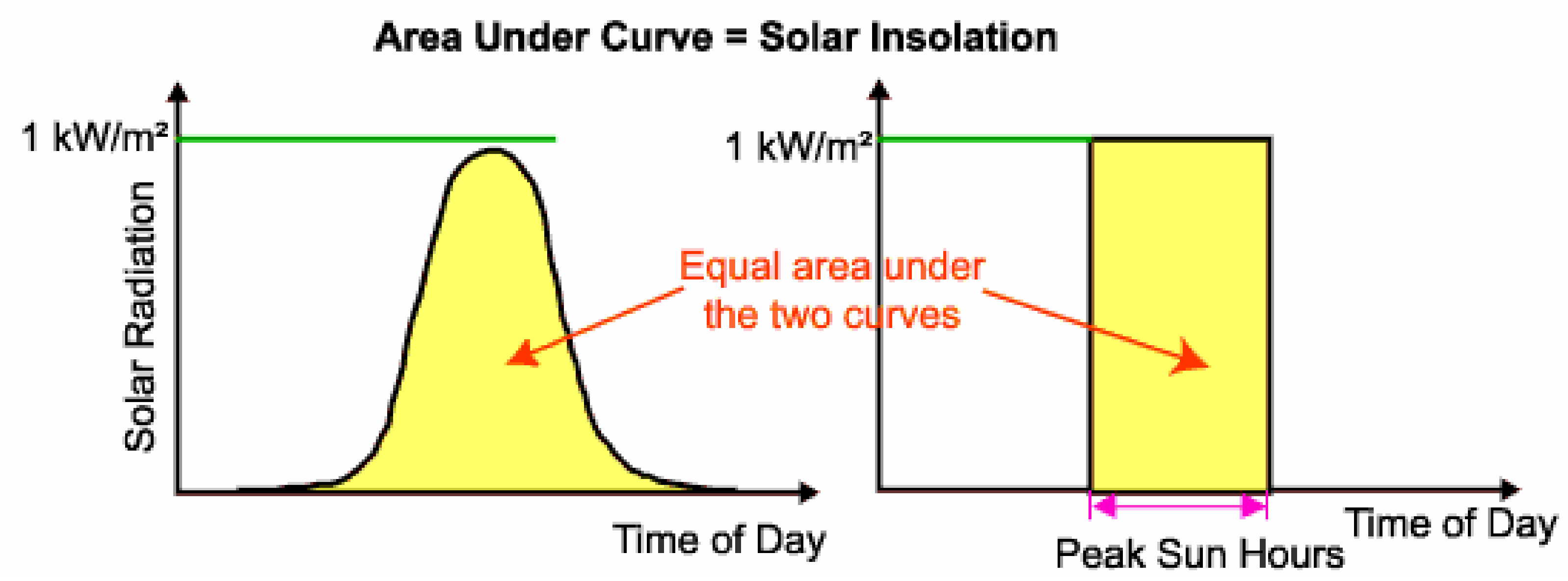


Solar Insolation Under Normal Skies: Refer to National Solar Radiation Database

- Refer to the "*solar radiation manual for flat-plate and concentration collectors*" published by NREL (1994).
- Resource website; http://rredc.nrel.gov/solar/pubs/redbook/
- The book contains displays data in the form of tables, graphs, maps, etc…
- Refer to the book appendix for a sample of the data that is available in the above manual.
- Refer to next slide for useful local data.

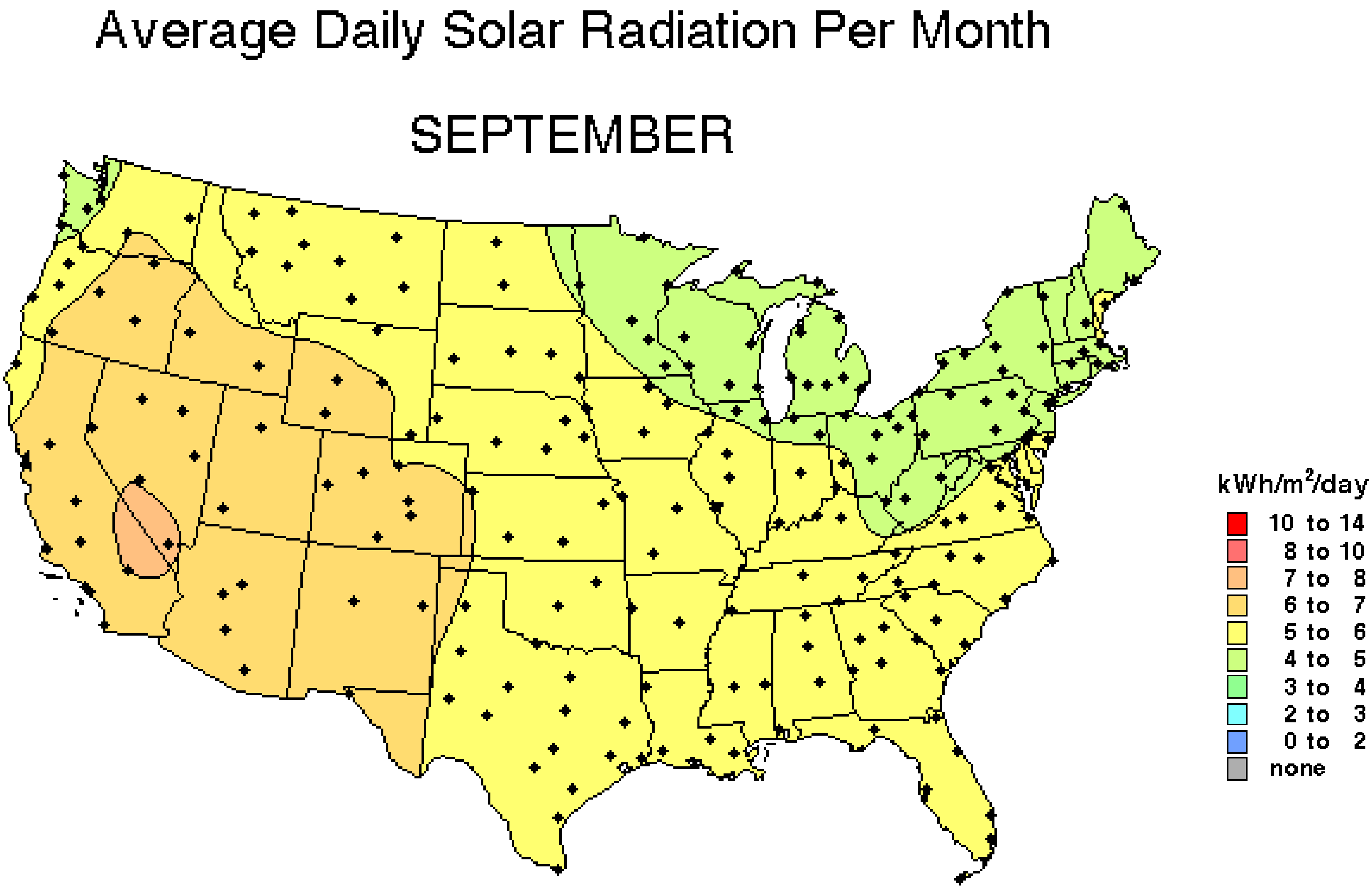
Peak Sun Hours (psh)

- The average daily solar insolation in units of kWh/m^2/ day is sometimes referred to as "peak sun hours".
- The term "peak sun hours" refers to the solar insolation which a particular location would receive if the sun were shining at its maximum value for a certain number of hours.
- Since the peak solar radiation is 1 kW/m^2, the number of peak sun hours is numerically identical to the average daily solar insolation.



US Solar Radiation Solar Resource Maps

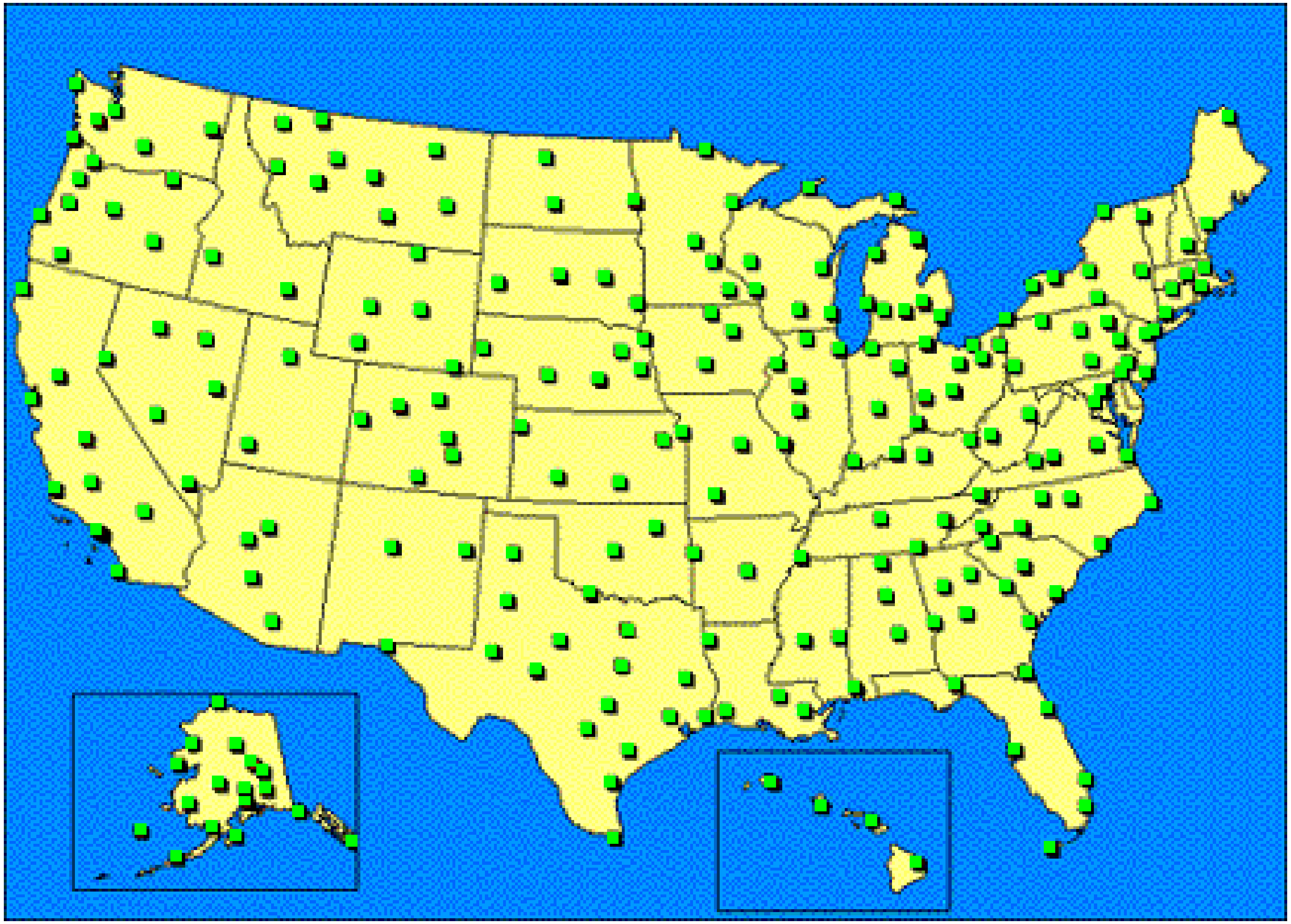
Source: http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/



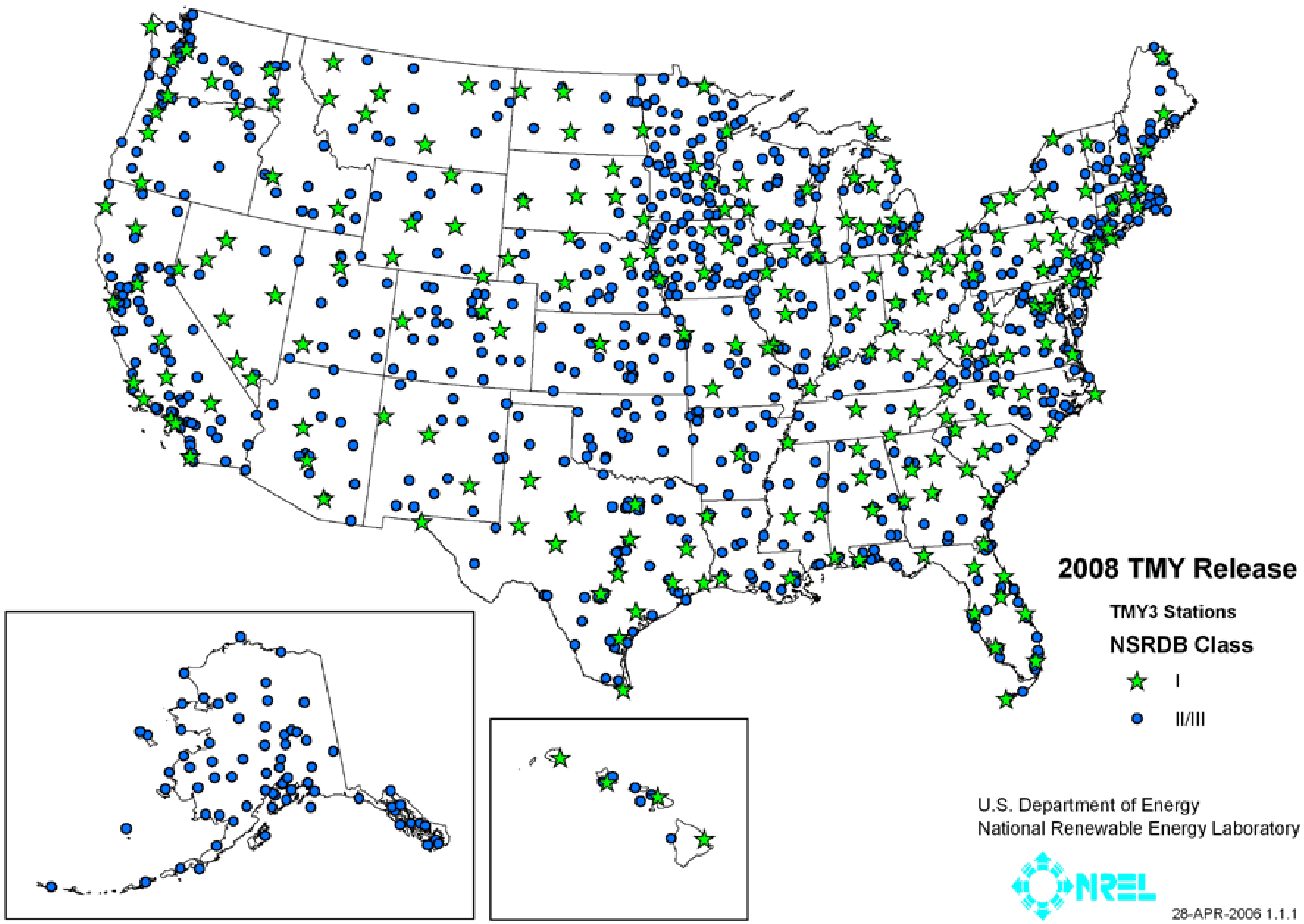
Typical Metrological Data (TMY)

- The most common data for describing the local solar climate is through Typical Meteorological Year data (TMY).
  - Various meteorological measurements are made at hourly intervals over a number of years to build up a picture of the local climate.
  - Of the parameters given, usually only the time and irradiation figures are used. However, more advanced models also use the temperature and wind speed.
  - TMY2 – average over 30 years (1961-1990)
  - TMY3 – average over 15 years (1991-2005)

TMY2 data sets for 239 stations



TMY3 data sets for 1020 stations

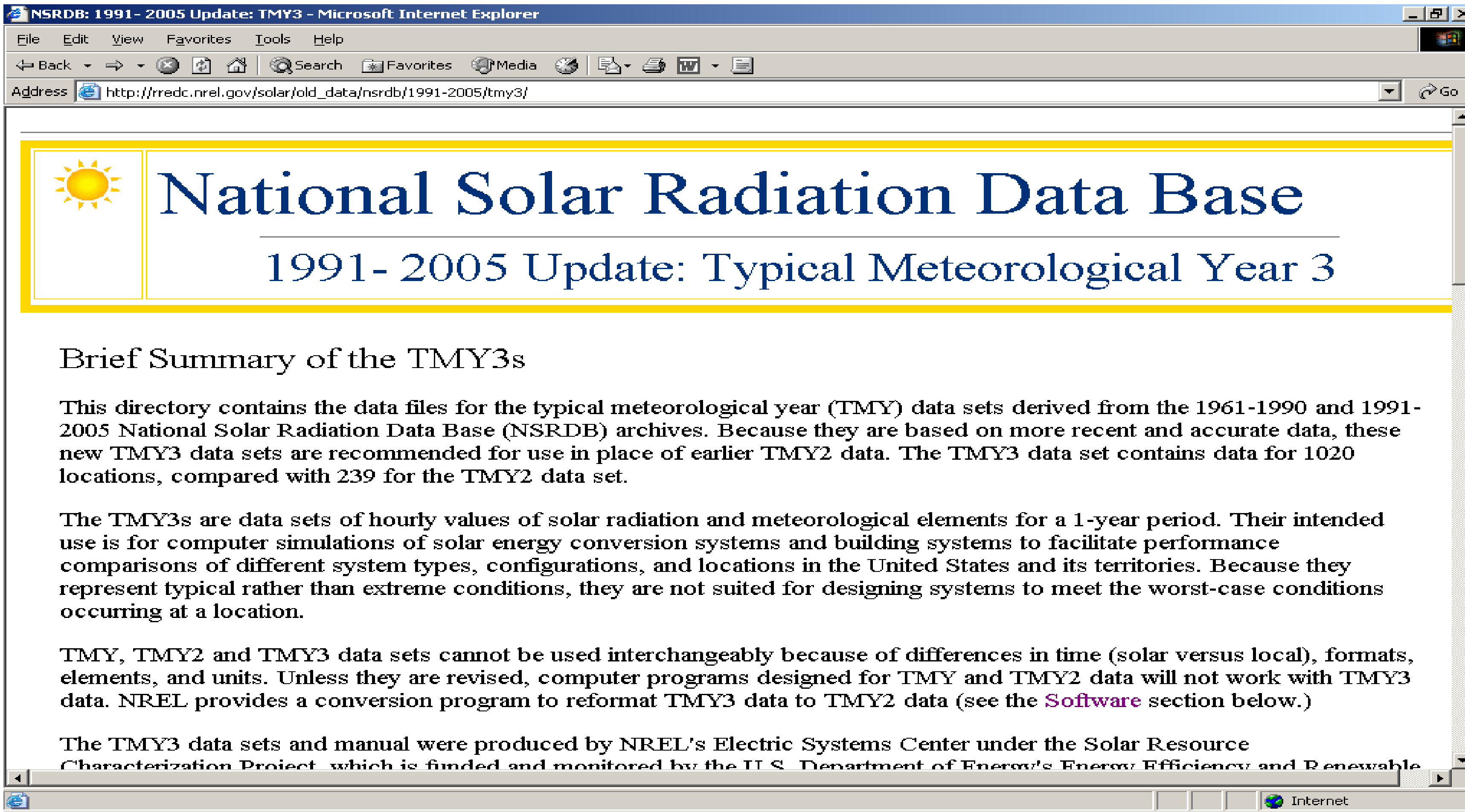


TMY3

- Set of hourly values of solar radiation and meteorological elements for a 1-year period,
- Consists of months selected from individual years and concatenated to form a complete year,
- Intended use is for computer simulations of solar energy conversion systems and building systems.
- Represent typical rather than extreme conditions, they are not suited for designing systems and their components to meet the worst-case conditions occurring at a location.
- Available on the web. (Google “TMY3 data”)
- User’s manual also available (down on the same page

TMY3 data available directly at:

http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/



National Solar Radiation Data Base

1991- 2005 Update: Typical Meteorological Year 3

Brief Summary of the TMY3s

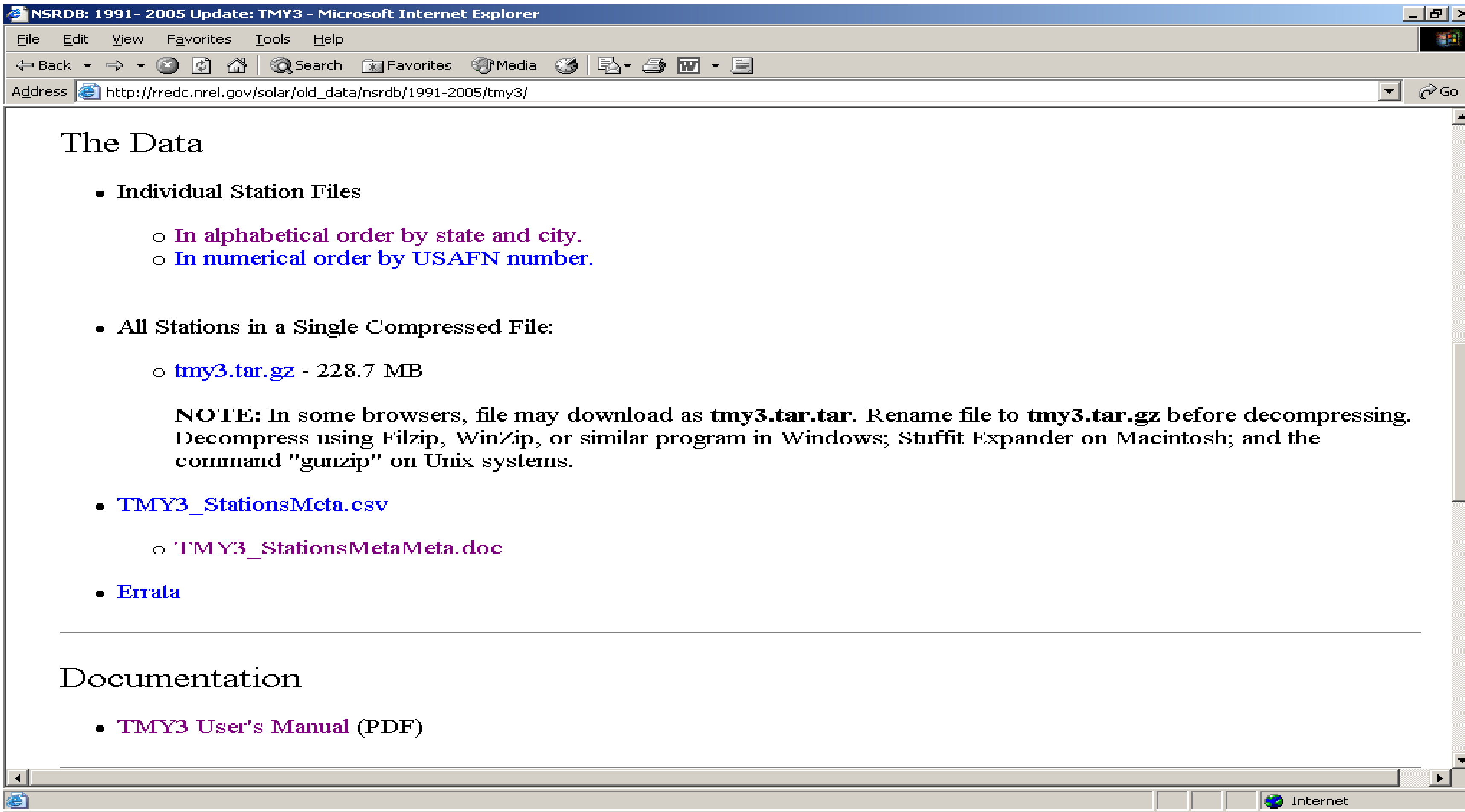
This directory contains the data files for the typical meteorological year (TMY) data sets derived from the 1961-1990 and 1991-2005 National Solar Radiation Data Base (NSRDB) archives. Because they are based on more recent and accurate data, these new TMY3 data sets are recommended for use in place of earlier TMY2 data. The TMY3 data set contains data for 1020 locations, compared with 239 for the TMY2 data set.

The TMY3s are data sets of hourly values of solar radiation and meteorological elements for a 1-year period. Their intended use is for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations in the United States and its territories. Because they represent typical rather than extreme conditions, they are not suited for designing systems to meet the worst-case conditions occurring at a location.

TMY, TMY2 and TMY3 data sets cannot be used interchangeably because of differences in time (solar versus local), formats, elements, and units. Unless they are revised, computer programs designed for TMY and TMY2 data will not work with TMY3 data. NREL provides a conversion program to reformat TMY3 data to TMY2 data (see the Software section below.)

The TMY3 data sets and manual were produced by NREL's Electric Systems Center under the Solar Resource Characterization Project, which is funded and monitored by the U.S. Department of Energy's Energy Efficiency and Renewable

User’s Manual



NSRDB: 1991- 2005 Update: TMY3 - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Address http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

The Data

- **Individual Station Files**
  - In alphabetical order by state and city.
  - In numerical order by USAFN number.

- All Stations in a Single Compressed File:
  - tmy3.tar.gz - 228.7 MB

    NOTE: In some browsers, file may download as **tmy3.tar.tar**. Rename file to **tmy3.tar.gz** before decompressing. Decompress using Filzip, WinZip, or similar program in Windows; Stuffit Expander on Macintosh; and the command "gunzip" on Unix systems.

- TMY3_StationsMeta.csv
  - TMY3_StationsMetaMeta.doc

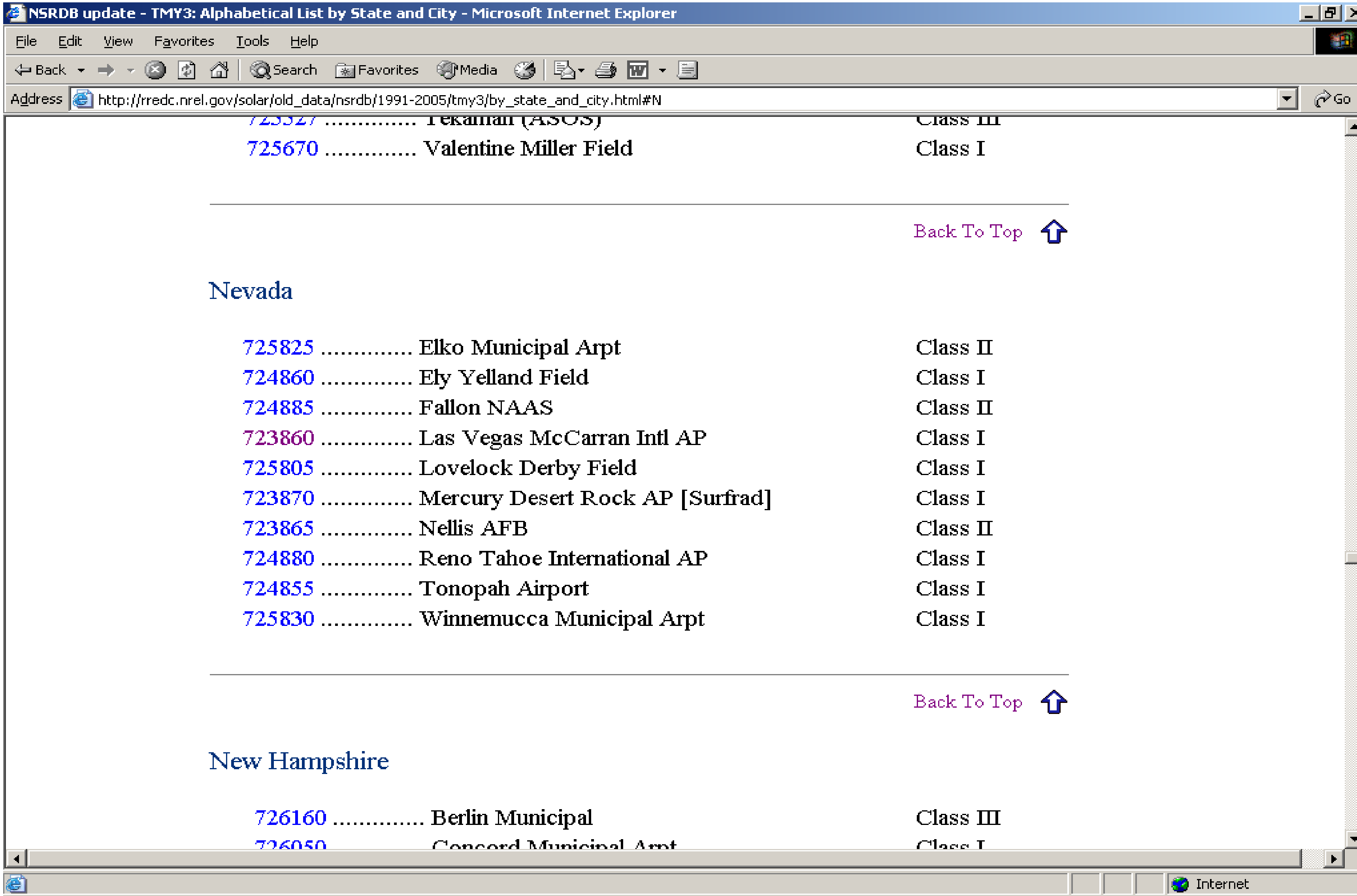
- Errata

Documentation

- TMY3 User's Manual (PDF)

Internet

The files are of .csv type



NSRDB update - TMY3: Alphabetical List by State and City - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Back Search Favorites Media

Address http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/by_state_and_city.html#N Go

725527 .... Tekamah (ASOS) Class III
725670 .... Valentine Miller Field Class I

Back To Top

Nevada

725825 .... Elko Municipal Arpt Class II
724860 .... Ely Yelland Field Class I
724885 .... Fallon NAAS Class II
723860 .... Las Vegas McCarran Intl AP Class I
725805 .... Lovelock Derby Field Class I
723870 .... Mercury Desert Rock AP [Surfrad] Class I
723865 .... Nellis AFB Class II
724880 .... Reno Tahoe International AP Class I
724855 .... Tonopah Airport Class I
725830 .... Winnemucca Municipal Arpt Class I

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New Hampshire

726160 .... Berlin Municipal Class III
726050 .... Concord Municipal Arpt Class I

Internet

User’s Manual Table 1-3 to interpret the data:

Table 1-1. TMY3 data header (line 1)

Field	Element	Unit or Description
1	Site identifier code	USAF number
2	Station name	Quote delimited
3	Station state	Two-letter U.S. Postal abbreviation
4	Site time zone	Hours from Greenwich, negative west
5	Site latitude	Decimal degree
6	Site longitude	Decimal degree
7	Site elevation	Meter

Table 1-3. TMY3 data fields (lines 3-8762)

Field	Element	Unit or Range	Resolution	Description
1	Date	MM/DD/YYYY	--	Date of data record
2	Time	HH:MM	--	Time of data record (local standard time)
3	Hourly extraterrestrial radiation on a horizontal surface	Watt-hour per square meter	1 Wh/m^2	Amount of solar radiation received on a horizontal surface at the top of the atmosphere during the 60-minute period ending at the timestamp
4	Hourly extraterrestrial radiation normal to the sun	Watt-hour per square meter	1 Wh/m^2	Amount of solar radiation received on a surface normal to the sun at the top of the atmosphere during the 60-minute period ending at the timestamp
5	Global horizontal irradiance	Watt-hour per square meter	1 Wh/m^2	Total amount of direct and diffuse solar radiation received on a horizontal surface during the 60-minute period ending at the timestamp

Glimpse at some data: (68 columns,8760 rows)

723860TY [Read-Only]

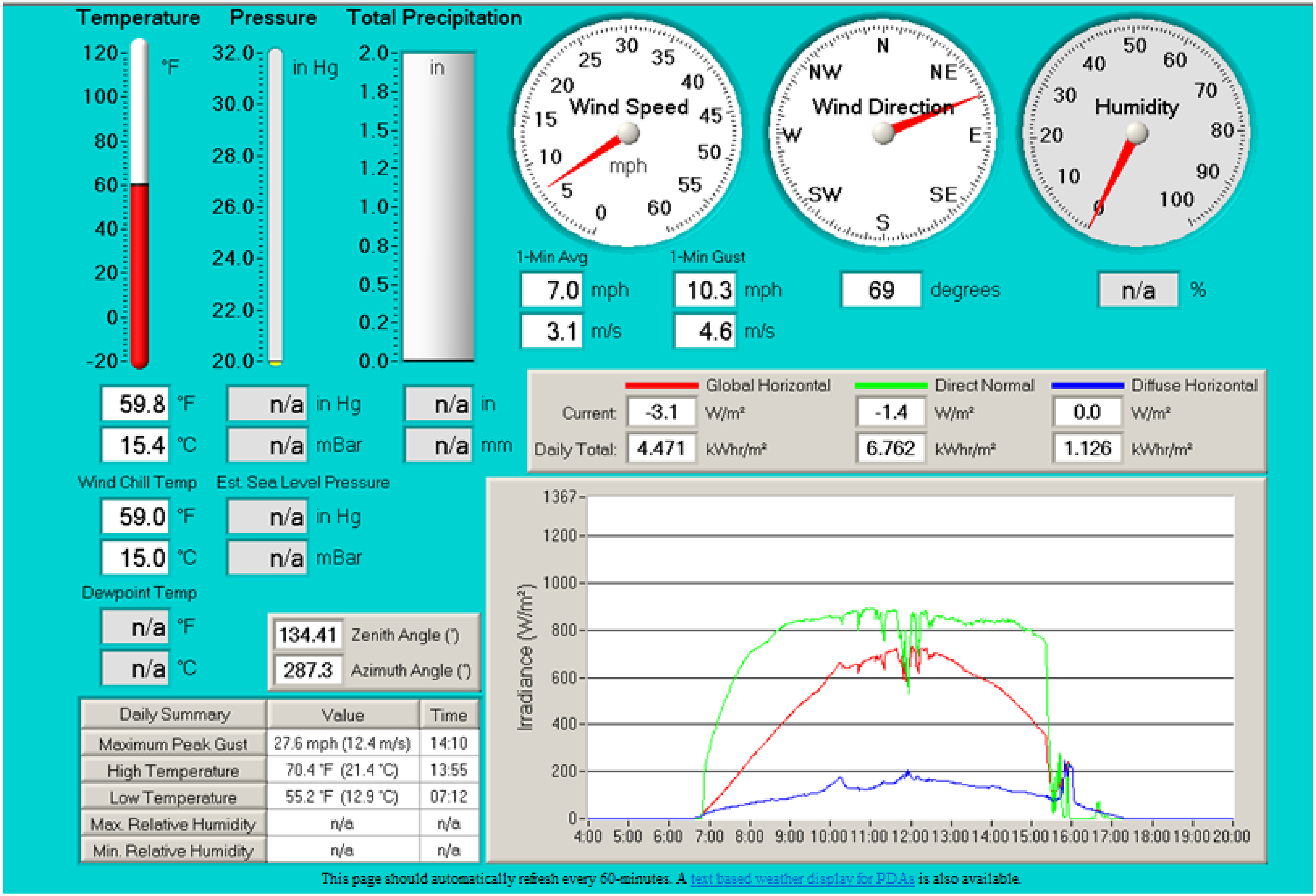
	A	B	C	D	E	F	G	H	I	J	K	L	M	
1	723860	LAS VEGA:	NV	-8	36.083	-115.15	648							
2	Date (MM	Time (HH:	ETR (W/m	ETRN (W/	GHI (W/m	GHI sourc	GHI uncer	DNI (W/m	DNI sourc	DNI uncer	DHI (W/m	DHI sourc	DHI uncer	GH
3	1/1/2001	1:00	0	0	0	2	0	0	2	0	0	2	0	
4	1/1/2001	2:00	0	0	0	2	0	0	2	0	0	2	0	
5	1/1/2001	3:00	0	0	0	2	0	0	2	0	0	2	0	
6	1/1/2001	4:00	0	0	0	2	0	0	2	0	0	2	0	
7	1/1/2001	5:00	0	0	0	2	0	0	2	0	0	2	0	
8	1/1/2001	6:00	0	0	0	2	0	0	2	0	0	2	0	
9	1/1/2001	7:00	1	153	0	2	9	0	2	21	0	2	9	
10	1/1/2001	8:00	146	1415	65	2	9	485	2	21	15	2	9	
11	1/1/2001	9:00	371	1415	237	2	9	760	2	21	37	2	9	
12	1/1/2001	10:00	551	1415	374	2	9	784	2	21	68	2	9	
13	1/1/2001	11:00	671	1415	466	2	9	809	2	21	81	2	9	
14	1/1/2001	12:00	724	1415	522	2	9	828	2	21	97	2	9	
15	1/1/2001	13:00	705	1415	488	2	9	793	2	21	91	2	9	
16	1/1/2001	14:00	617	1415	450	2	9	894	2	21	59	2	9	
17	1/1/2001	15:00	464	1415	327	2	9	777	2	21	71	2	9	
18	1/1/2001	16:00	259	1415	191	2	9	513	2	21	96	2	9	
19	1/1/2001	17:00	42	837	4	2	9	120	2	21	2	2	9	
20	1/1/2001	18:00	0	0	0	2	0	0	2	0	0	2	0	
21	1/1/2001	19:00	0	0	0	2	0	0	2	0	0	2	0	
22	1/1/2001	20:00	0	0	0	2	0	0	2	0	0	2	0	

Ready

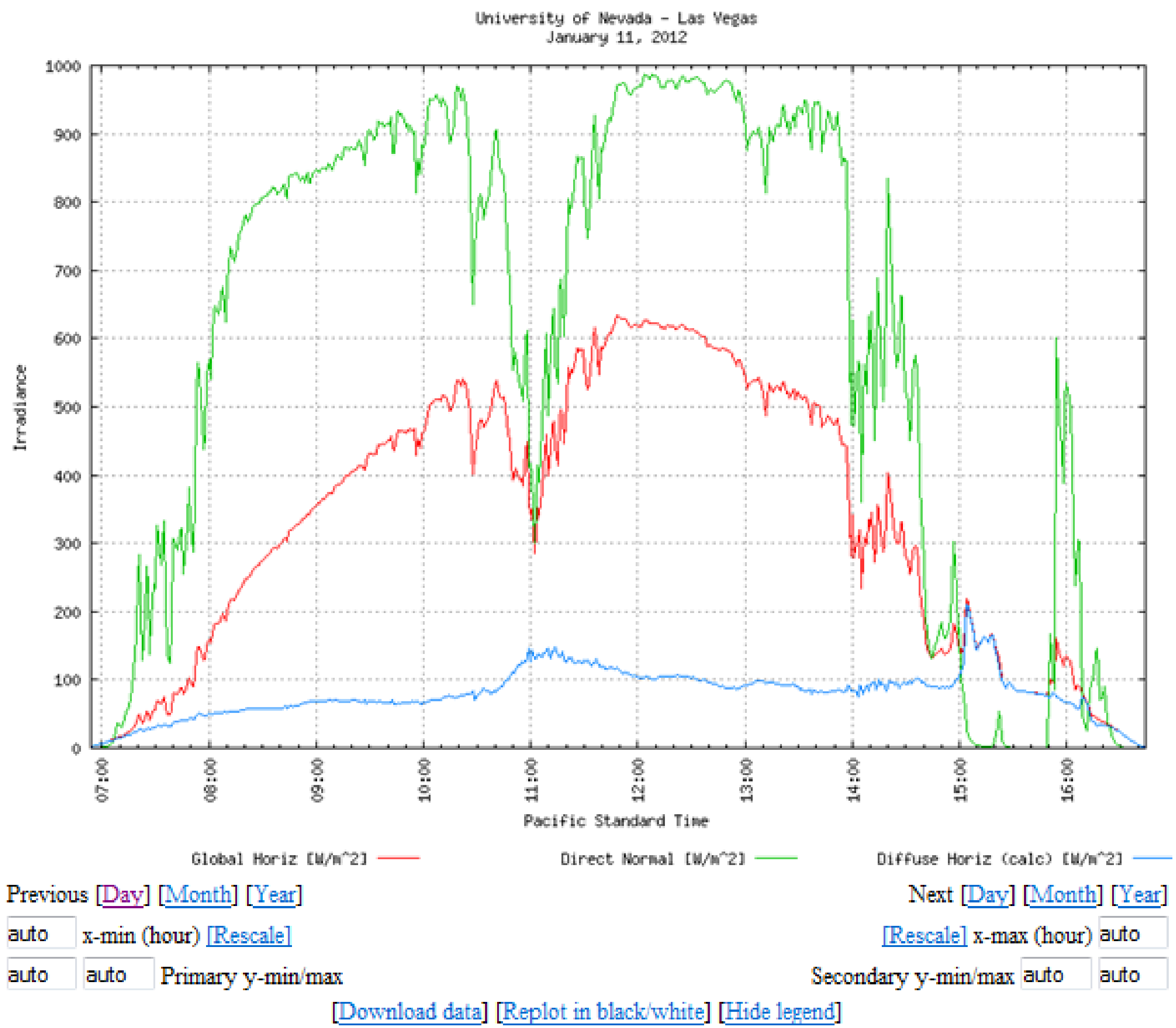
Important Hour-by-Hour Terrestrial Insolation Estimates Found TMY Data

- **Direct Normal Irradiance (DNI):** This is the direct beam I_B
- **Diffuse Horizontal Irradiance (DHI):** This is the diffuse insolation on a horizontal surface $I_{DH} = I_B C$.
- **Global Horizontal Irradiance (GHI):** This is the sum of DHI and beam insolation on a horizontal surface ($I_{BH} = I_B \sin\beta$),i.e., GHI = $I_B(C + \sin\beta)$
- The above hourly data can be converted to collector irradiance using previous formulas.

Live Local Data: http://www.nrel.gov/midc/unlv/



Live Local Data: http://www.nrel.gov/midc/unlv/



Average Monthly Insolation

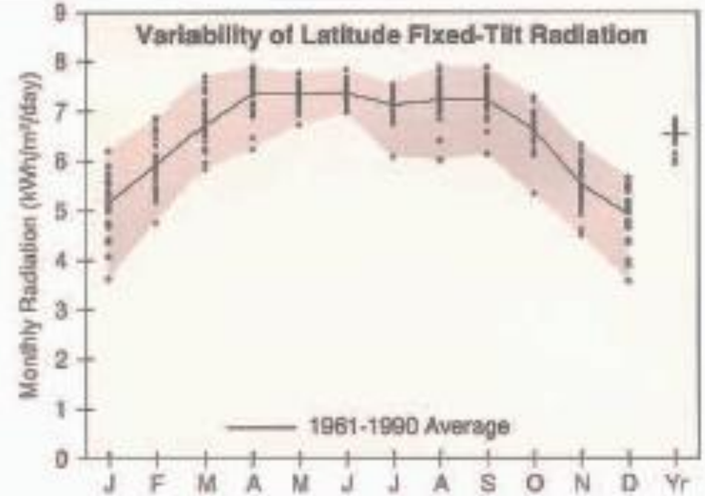
- If the average monthly insolation on a horizontal surface at a particular location is given, can you estimate the insolation on a collector that is tilted at an angle and oriented in a particular direction?
- The solution is tedious and lengthy (see example 4.14) – better use the data from the NREL Solar Radiation Manual.

Las Vegas, NV

WBAN NO. 23169

LATITUDE: 36.08° N
LONGITUDE: 115.17° W
ELEVATION: 664 meters
MEAN PRESSURE: 938 millibars

STATION TYPE: Primary



Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	3.0	4.0	5.4	6.9	7.8	8.4	7.9	7.2	6.2	4.7	3.4	2.8	5.7
	Min/Max	2.3/3.4	3.4/4.5	4.8/6.1	6.1/7.4	7.2/8.3	7.8/8.9	6.6/8.4	6.0/7.8	5.4/6.7	4.0/5.1	3.0/3.7	2.2/3.1	5.3/5.8
Latitude -15	Average	4.4	5.3	6.4	7.5	7.8	8.1	7.7	7.5	7.1	6.1	4.8	4.2	6.4
	Min/Max	3.2/5.3	4.4/6.1	5.6/7.3	6.4/8.0	7.2/8.3	7.6/8.6	6.5/8.2	6.2/8.2	6.1/7.7	5.0/6.7	4.0/5.4	3.1/4.8	5.9/6.7
Latitude	Average	5.1	5.9	6.7	7.4	7.3	7.4	7.1	7.2	7.2	6.6	5.5	4.9	6.5
	Min/Max	3.6/6.2	4.8/6.8	5.8/7.7	6.2/7.9	6.7/7.8	7.0/7.8	6.1/7.5	6.0/7.9	6.1/7.9	5.3/7.3	4.5/6.3	3.6/5.7	5.9/6.8
Latitude +15	Average	5.6	6.1	6.6	6.8	6.5	6.3	6.2	6.5	7.0	6.8	5.9	5.4	6.3
	Min/Max	3.8/6.8	4.9/7.2	5.7/7.6	5.7/7.3	5.9/6.8	6.0/6.7	5.3/6.5	5.5/7.2	5.9/7.6	5.4/7.5	4.7/6.8	3.8/6.2	5.7/6.6
90	Average	5.0	5.1	4.7	3.9	3.0	2.6	2.6	3.4	4.5	5.3	5.2	5.0	4.2
	Min/Max	3.4/6.2	4.0/6.0	4.0/5.4	3.3/4.1	2.8/3.1	2.4/2.7	2.4/2.7	2.9/3.7	3.8/4.9	4.2/5.9	4.1/6.1	3.5/5.8	3.7/4.5

Solar Radiation for 1-Axis Tracking Flat-Plate Collectors with a North-South Axis (kWh/m²/day), Uncertainty ±9%

Axis Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	4.6	5.9	7.8	9.8	10.9	11.6	10.8	10.1	9.0	7.1	5.1	4.2	8.1
	Min/Max	3.3/5.6	4.6/7.0	6.2/9.3	8.2/10.9	9.8/11.9	10.5/12.5	8.2/11.8	8.1/11.3	7.1/10.1	5.7/7.9	4.1/6.0	3.0/4.9	7.2/8.5
Latitude -15	Average	5.7	6.9	8.5	10.3	11.0	11.5	10.8	10.4	9.7	8.1	6.2	5.3	8.7
	Min/Max	3.9/6.9	5.3/8.2	6.9/10.2	8.5/11.4	9.9/12.0	10.4/12.4	8.2/11.8	8.4/11.7	7.7/10.9	6.4/9.1	4.9/7.3	3.7/6.2	7.7/9.1
Latitude	Average	6.2	7.3	8.8	10.2	10.6	11.1	10.4	10.3	9.8	8.6	6.7	5.9	8.8
	Min/Max	4.3/7.7	5.6/8.7	7.1/10.5	8.4/11.3	9.6/11.6	10.0/11.9	7.8/11.4	8.2/11.5	7.8/11.1	6.7/9.5	5.3/7.9	4.1/6.9	7.8/9.3
Latitude +15	Average	6.5	7.5	8.7	9.8	10.0	10.3	9.8	9.8	9.6	8.7	7.0	6.2	8.7
	Min/Max	4.4/8.1	5.7/9.0	7.0/10.4	8.1/10.9	9.0/11.0	9.3/11.1	7.3/10.7	7.8/11.0	7.6/10.9	6.7/9.7	5.4/8.3	4.3/7.3	7.6/9.1

Solar Radiation for 2-Axis Tracking Flat-Plate Collectors (kWh/m²/day), Uncertainty ±9%

Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
2-Axis	Average	6.6	7.5	8.8	10.3	11.1	11.8	11.0	10.5	9.8	8.7	7.1	6.3	9.1
	Min/Max	4.5/8.2	5.7/9.0	7.1/10.5	8.5/11.4	10.0/12.1	10.6/12.7	8.3/12.1	8.4/11.8	7.8/11.1	6.7/9.7	5.5/8.3	4.3/7.4	8.1/9.6