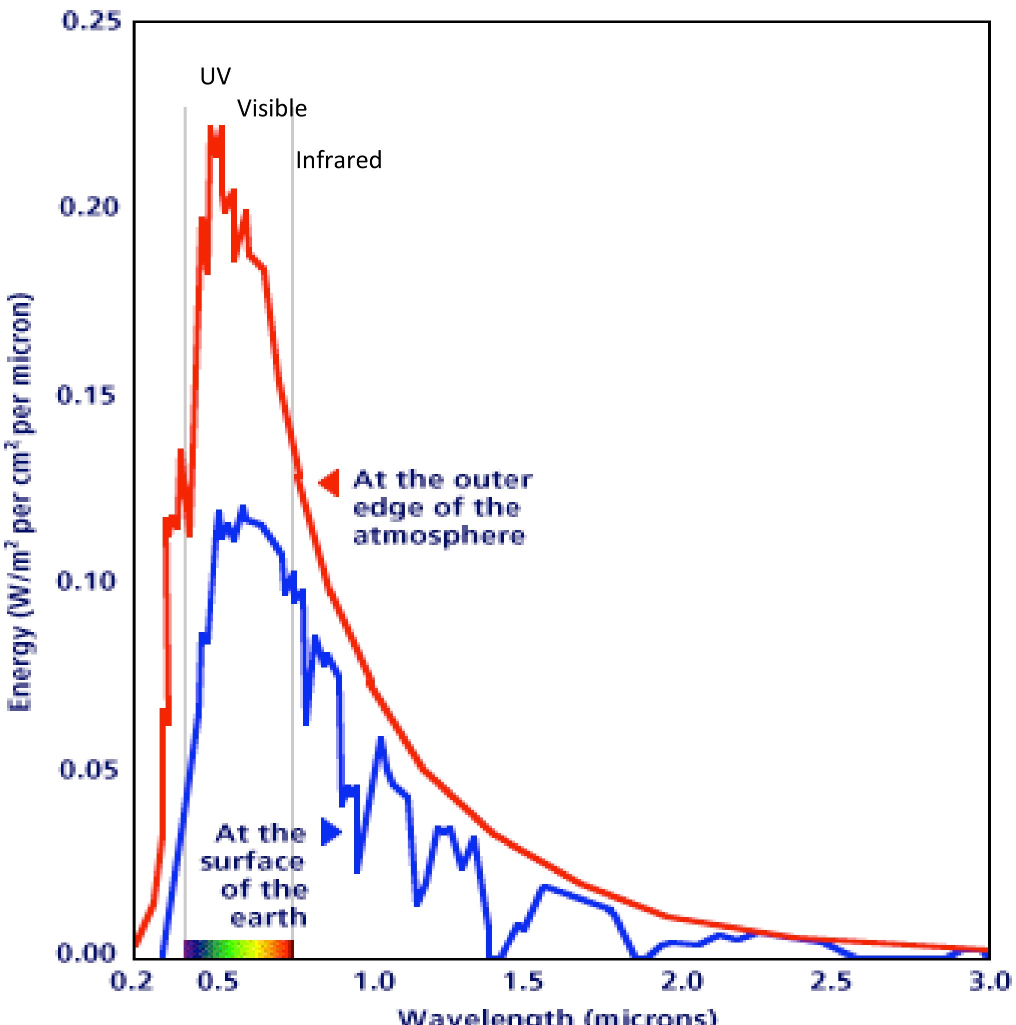
Solar Resources
Solar Photovoltaics
Concentrating Photovoltaics

What Influences the Amount of Solar Radiation?

- Latitude and season
- Time of Day
- Clouds
- Geography (mountains, oceans, large lakes)
- Air pollution and natural haze
- Volcanic activity
- Atmospheric water vapor and trace gases

Wavelength Distribution of Solar Radiation



http://www.geocities.com/dieret/re/Solar/sespectrum.gif

- The solar constant is given by the area under the red curve, 1,366 W/m^2 in space.
- Energy at the earth's surface is less due to absorption and scattering in the atmosphere.
- 6% ultraviolet, 48% visible, and 46% infrared light
- Annual average radiation, typically less than 1000 W/m2 on Earth.
- Visible 0.35 to 0.75 microns
- Selective window glass screens IR and UV
- Bandgap of Silicon PV = 0.6 microns

Latitude, l

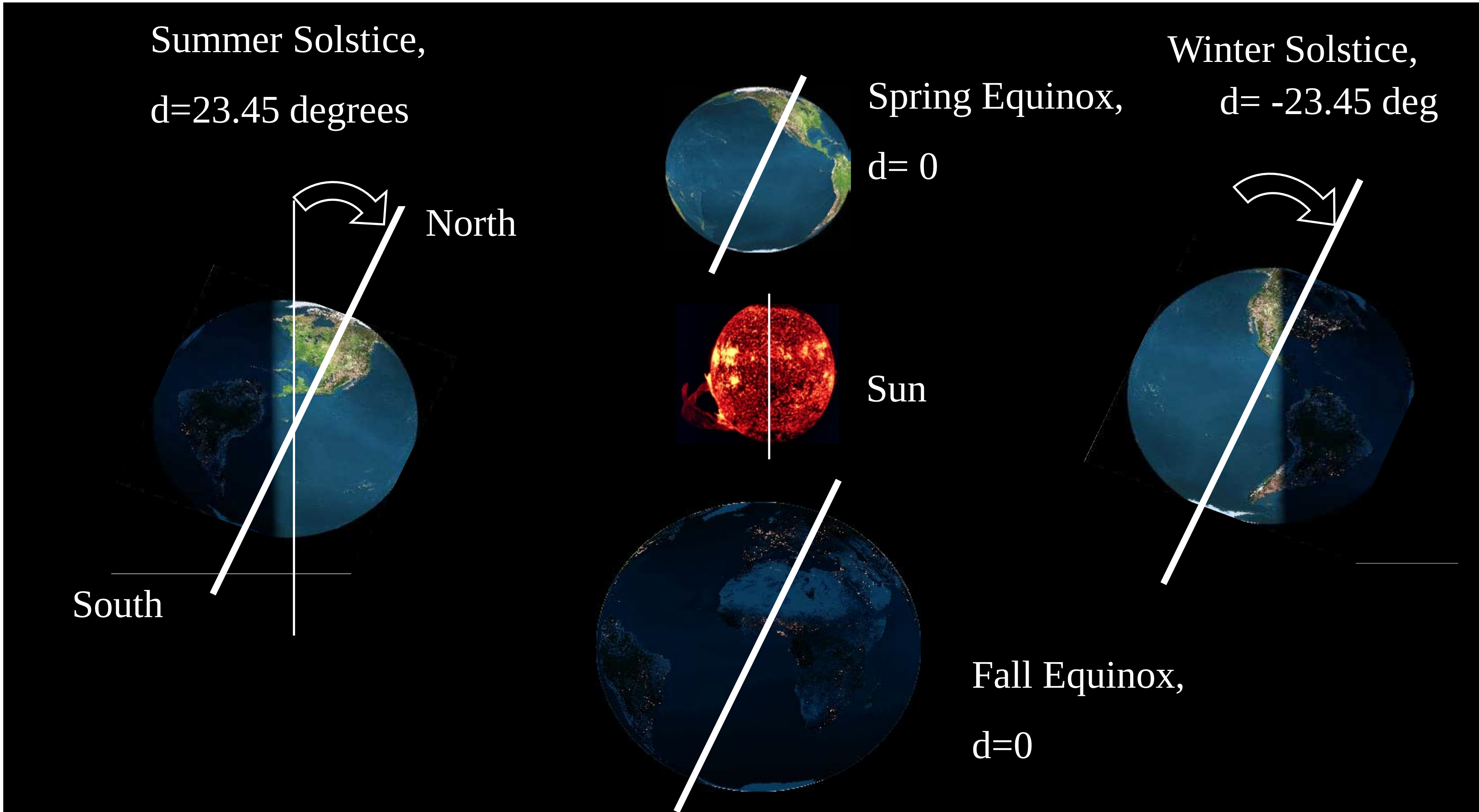
Hour angle, h

- Depends on time of day
- Earth rotates 360 deg in 24 hours, or 15 degrees per hour
- Hour angle, h=(15 degrees/hour)*(12- hour)

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

Declination, d

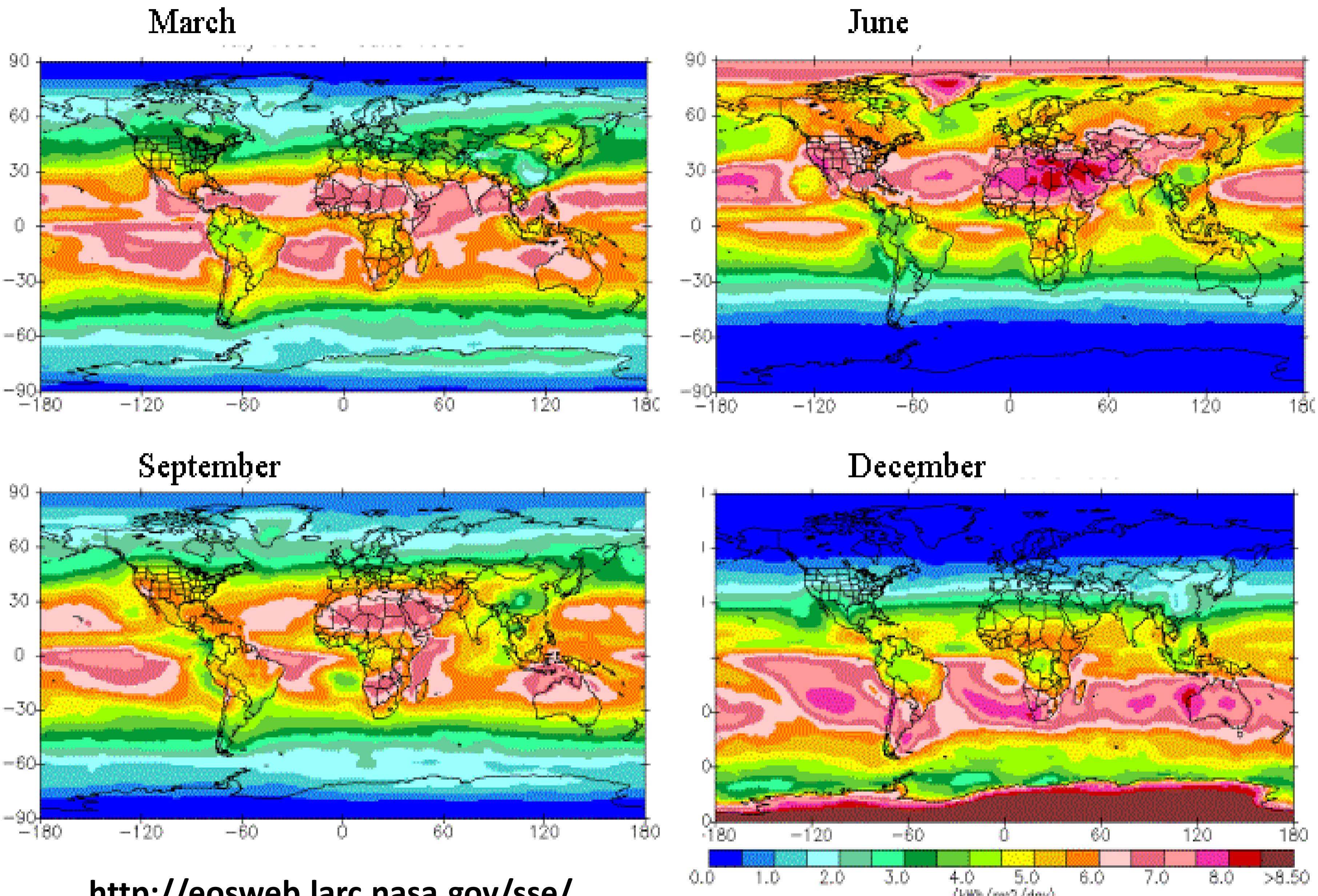
- Depends on the season



Varies like a sine wave throughout the year

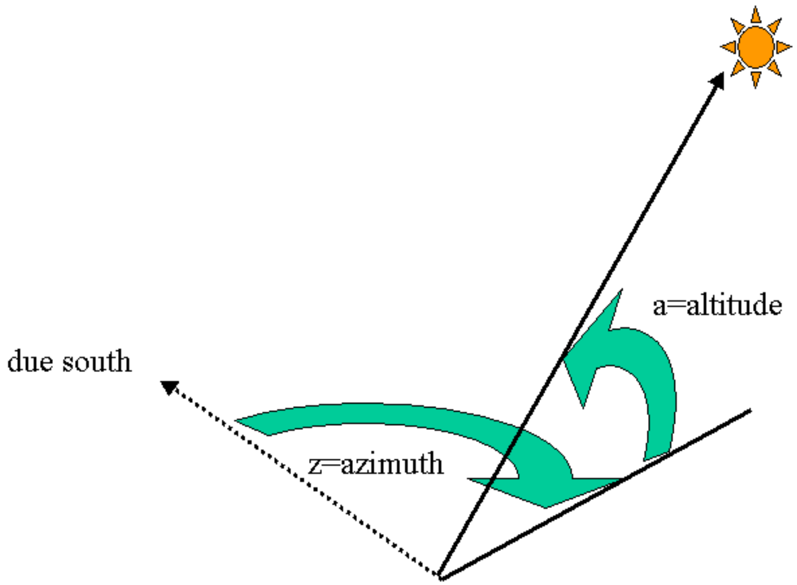
d=23.45*(SIN(360/365*(284+day of year)))

Seasonal Solar Resource



http://eosweb.larc.nasa.gov/sse/

Position of the Sun



- Altitude angle, a, angle fom 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)

Fun with Sun Angles…

Northern Cheyenne Tribal Capital Building,
Lame Deer Montana

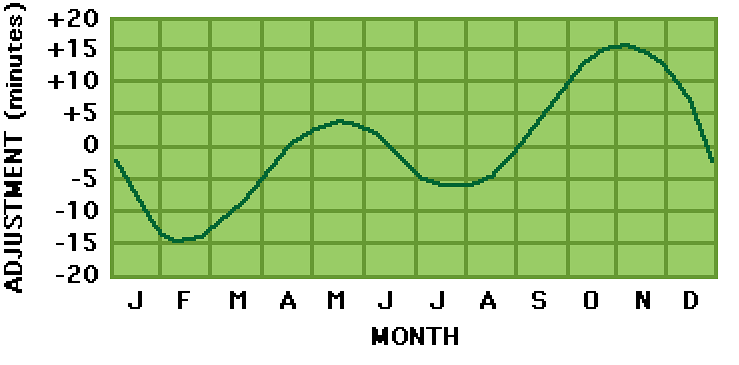
NREL Science and Technology Facility,
Golden CO

Corrections to these simple equations

- Daylight Savings Time
- Distance from Standard (time zone) Longitude;

$4(\text{min/degree})*(L_{site} - L_{standard})$

- Equation of Time.



Solar Resource Definitions

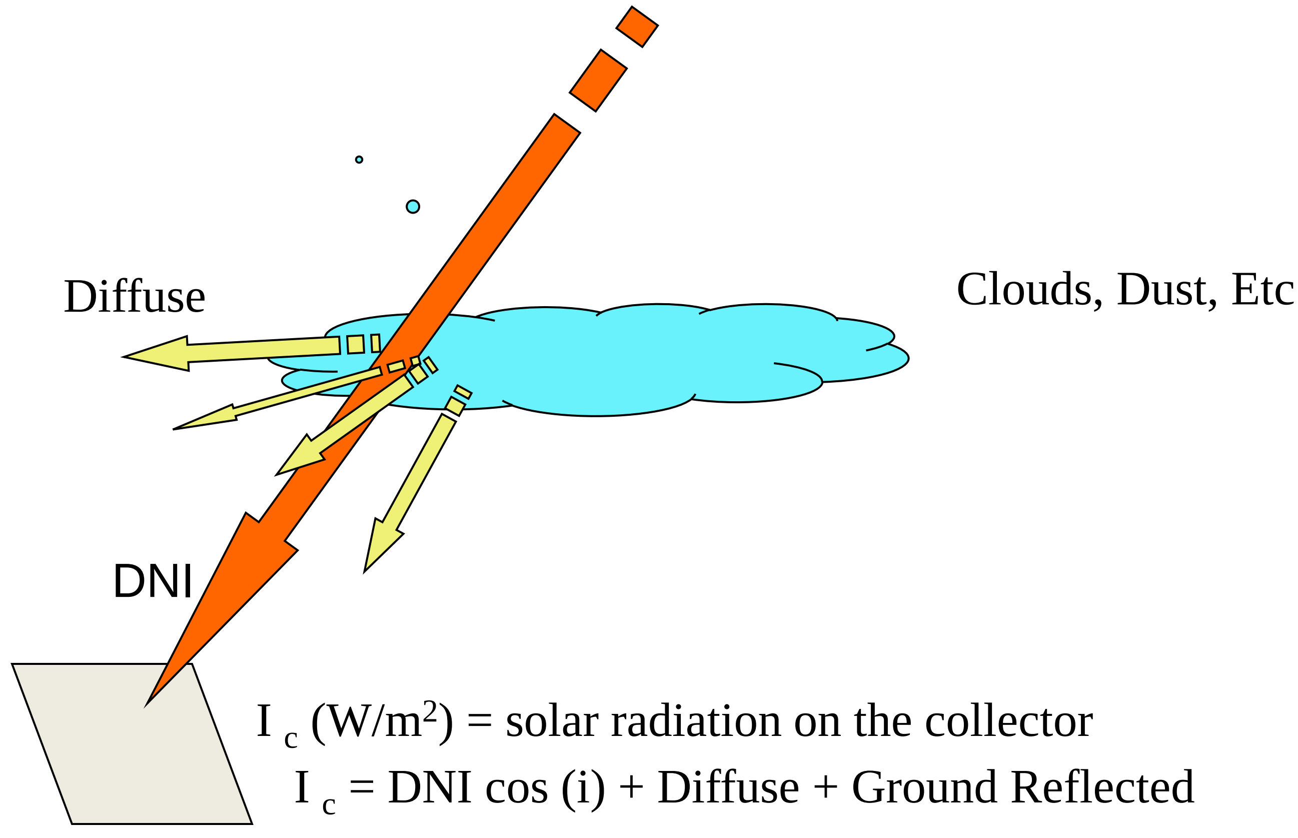
I
Irradiance or Insolation (W/m^2). Incoming solar power.

DNI
Direct Normal Irradiance is the amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line from the direction of the sun at its current position in the sky. Typically, you can maximize the amount of irradiance annually received by a surface by keeping it normal to incoming radiation. This quantity is of particular interest to concentrating solar thermal installations and installations that track the position of the sun.

DIF
Diffuse Horizontal Irradiance is the amount of radiation received per unit area by a surface (not subject to any shade or shadow) that does not arrive on a direct path from the sun, but has been scattered by molecules and particles in the atmosphere and comes equally from all directions.

GHI
Global Horizontal Irradiance is the total amount of shortwave radiation received from above by a horizontal surface. This value is of particular interest to photovoltaic installations and includes both Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DIF).

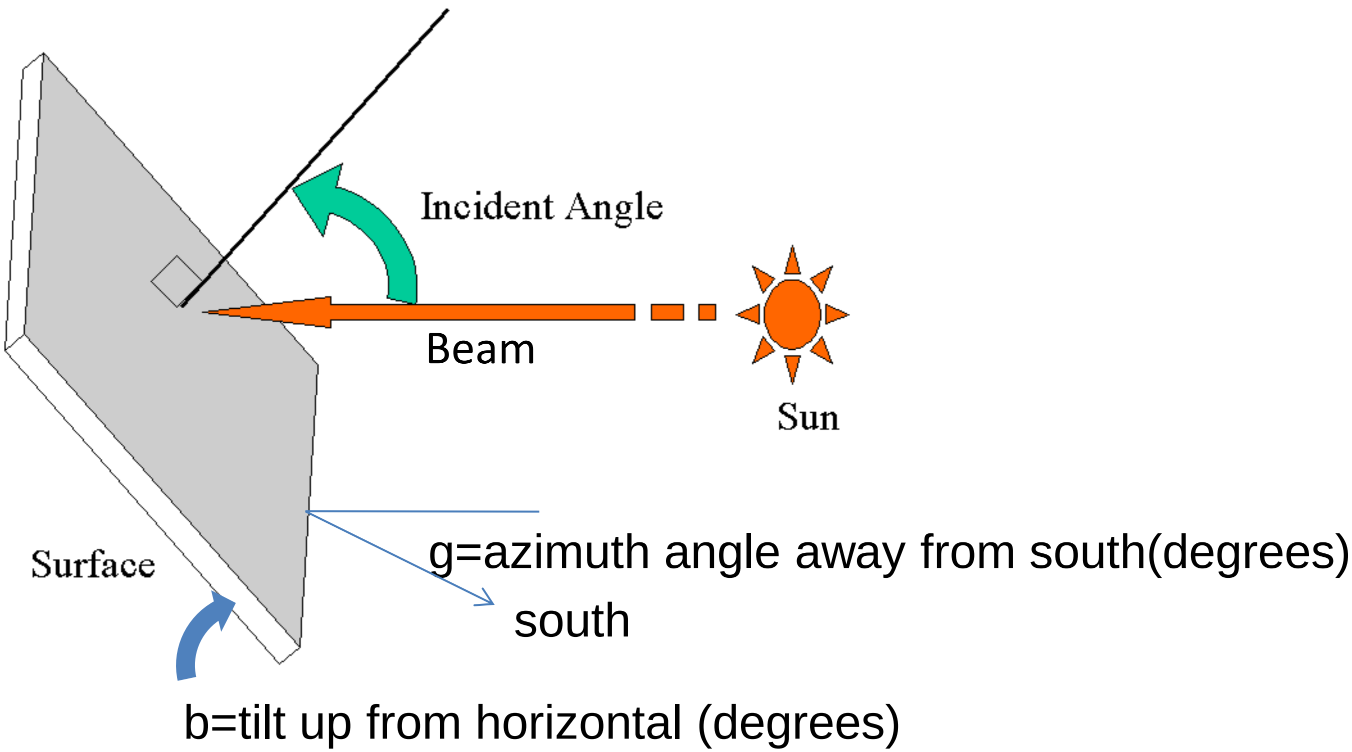
Total Radiation, I (insolation)



I_c (W/m^2) = solar radiation on the collector

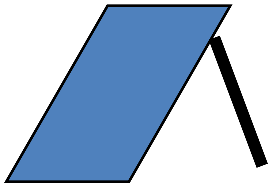
I_c = DNI cos (i) + Diffuse + Ground Reflected

Incident Angle, i

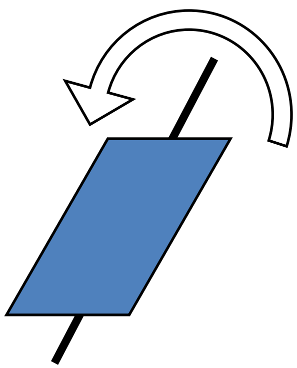


b=tilt up from horizontal (degrees)
g=surface azimuth angle (degrees), east negative, west positive

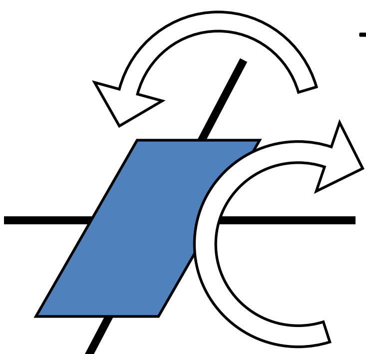
Fixed Tilt/Tracking



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

Incident Angle

Fixed Tilt toward equator at tilt b and azimuth g

cos(i)=sin(d)cos(b)-sin(d)cos(L)sin(b)cos(g)
+cos(d)cos(l)cos(b)cos(h)
+cos(d)sin(l)sin(b)cos(g)cos(h)
+cos(d)sin(b)sin(g)sin(h)

Rotated around horizontal east-west axis

$\cos(i)=(1-\cos^2(d)\sin^2(h))^{1/2}$

Rotated around horizontal north-south axis

$\cos(i)=(\cos^2(iz)+\cos^2(d)\sin^2(h))^{1/2}$

Where cos(iz)=cos(l)cos(d)cos(h)+sin(l)sin(d)

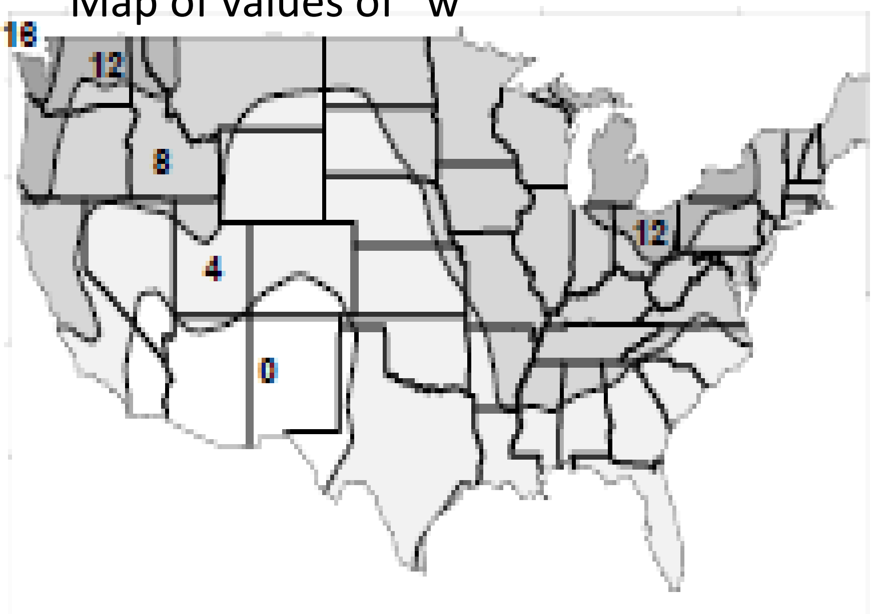
Rotated around two axes to track both azimuth and altitude of sun

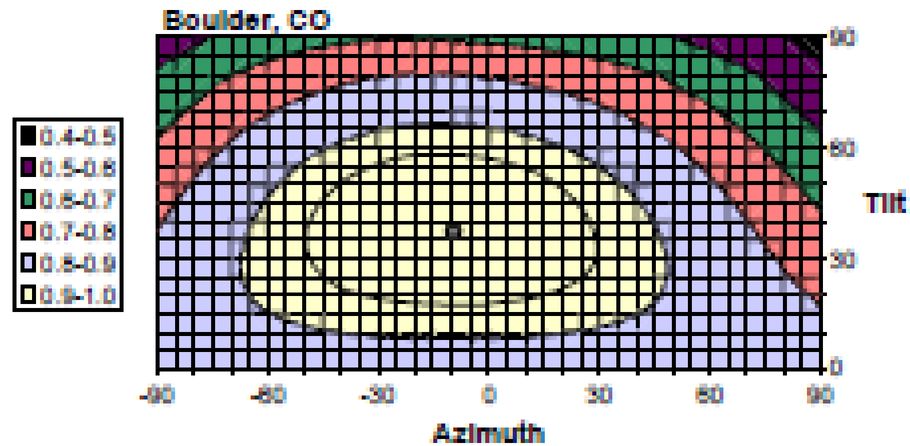
cos(i)=1

Optimal Fixed Tilt Angle

- Optimal Tilt = Latitude – “w”

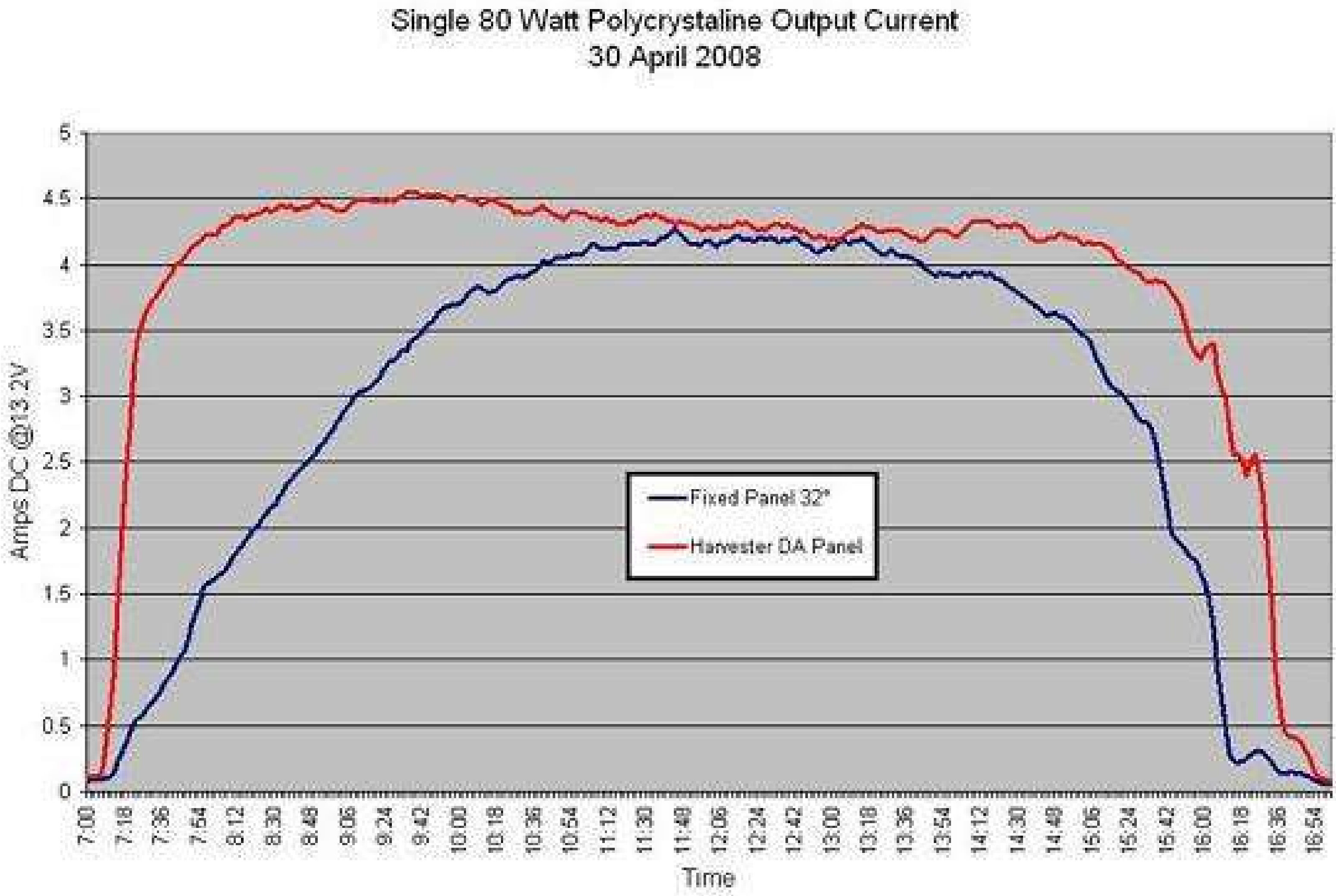
Map of values of “w”





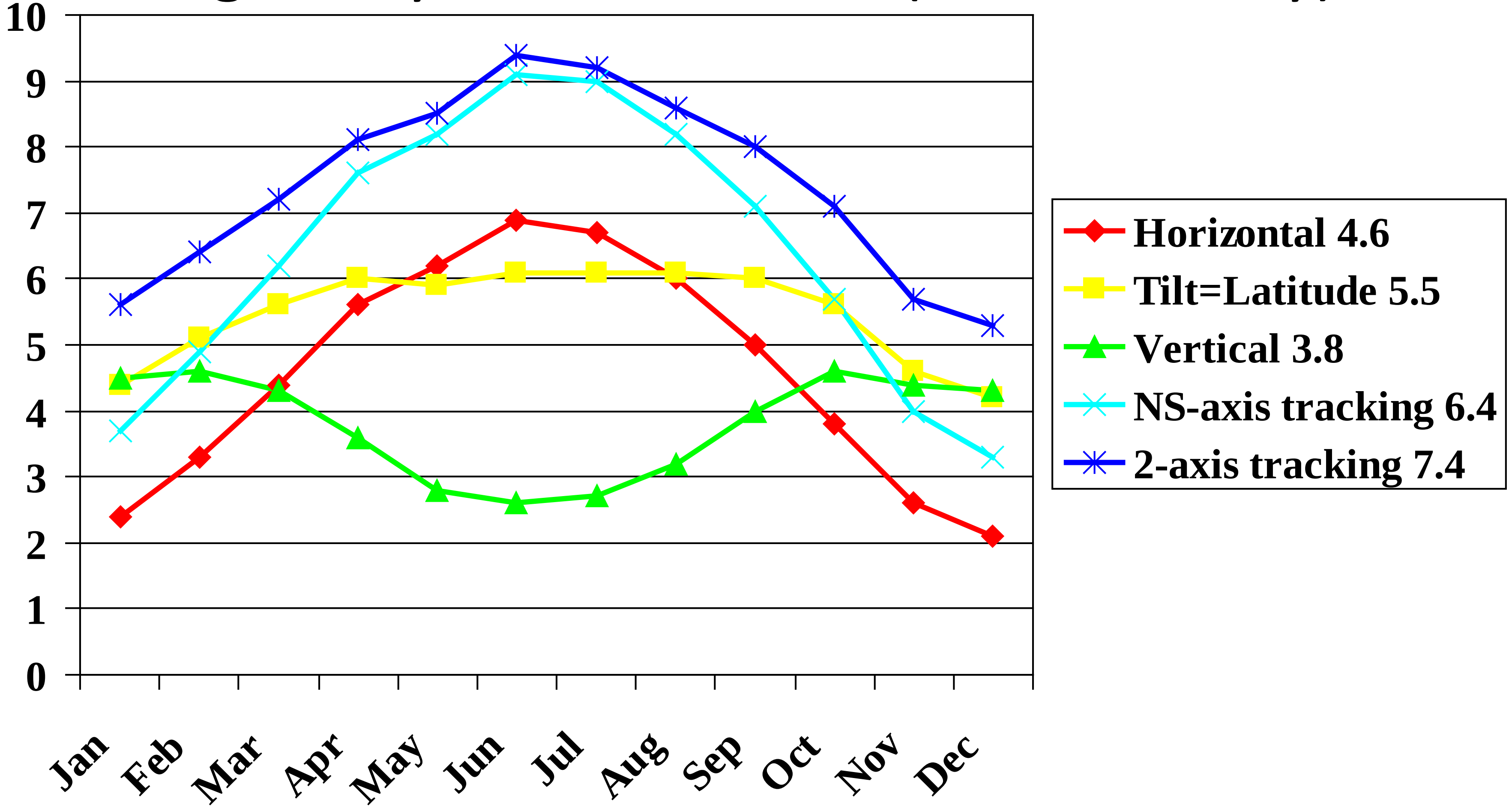
Proceedings of Solar Forum 2001: Solar Energy: The Power to Choose April 21-25, 2001, Washington, DC
EFFECTS OF TILT AND AZIMUTH ON ANNUAL INCIDENT SOLAR RADIATION FOR UNITED STATES LOCATIONS
Craig B. Christensen, Greg M. Barker

Tracking versus Fixed Tilt



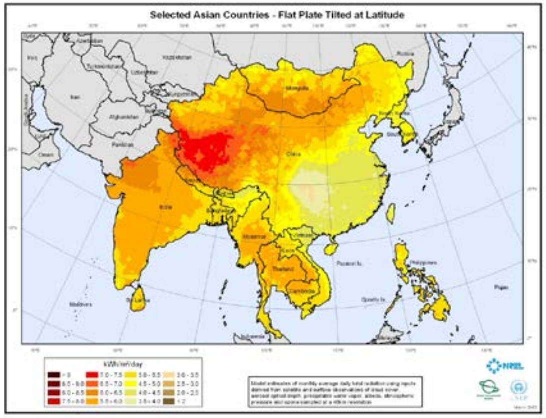
Effect of Orientation

- Average daily solar radiation (kWh/m2/day)



Data for Boulder CO

Solar Resource Data



- **NREL Maps, GIS Data, and Analysis Tools**
  http://www.nrel.gov/gis/solar.html
  - Provides renewable energy resource information online. Maps of monthly and annual direct normal irradiance (DNI) and other solar parameters at a 10 km resolution for US and 40-km resolution for Africa, South and Central America, China, India, and Southeast Asia. In addition, hourly modeled data from surface stations, and typical meteorological years (TMYs), are available for some countries.
- **Solar and Wind Energy Resource Assessment**
  http://swera.unep.net/
  Provides renewable energy resource information online. Maps of monthly and annual direct normal irradiance (DNI) and other solar parameters at a 40-km resolution for Africa, South and Central America, China, India, and Southeast Asia. In addition, hourly modeled data from surface stations, and typical meteorological years (TMYs), are available for some countries.
- **NASA Solar Data Analysis Center**
  http://umbra.nascom.nasa.gov/
  Provides data for concentrating solar power technologies.
- **NASA Surface Meteorology and Solar Energy**
  http://eosweb.larc.nasa.gov/sse/
  Provides data for concentrating solar power applications based on satellite cloud modeling, which is done on a 100-km spatial resolution. Data are available for any location in the world.
- **SOLEMI - Solar Energy Mining**
  http://www.solemi.de/home.html
  Provides high-quality irradiance data for the solar energy community. This service from the German Aerospace Center (DLR) is mainly based on Meteosat-data with a nominal spatial resolution of 2.5 km and half-hourly temporal resolution.
  - Solar radiation maps and an hourly time series will be available for almost half of the Earth's surface.

Flat Plate PV Systems Direct and Diffuse

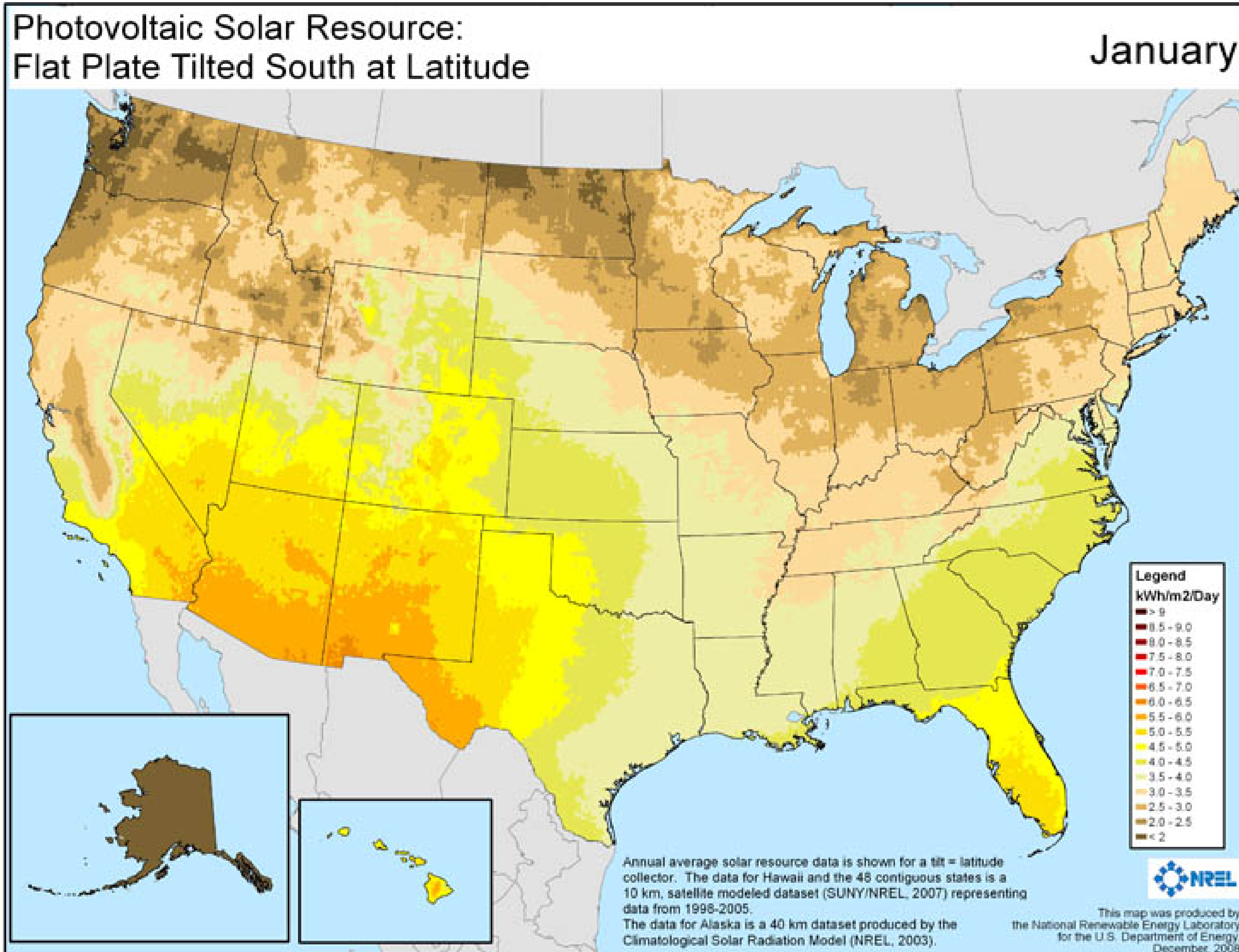
Arizona Public Service, Prescott, AZ

Dangling Rope Marina, Glen Canyon National Recreation Area, UT

Alamosa PV System, Alamosa, CO

5 – 10 acres per MW for PV systems

Land can be left as is or graded


Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
January
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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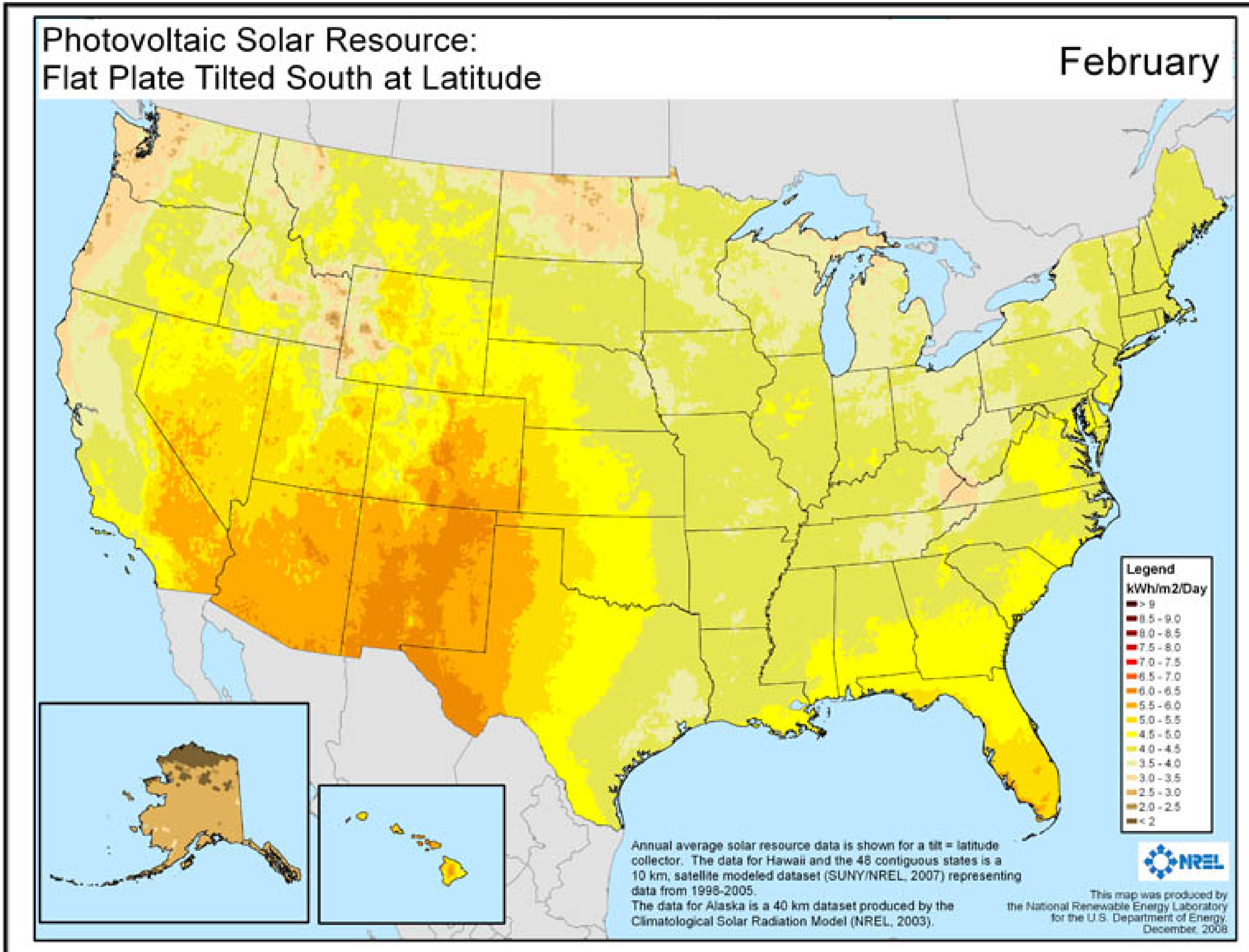
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
February
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
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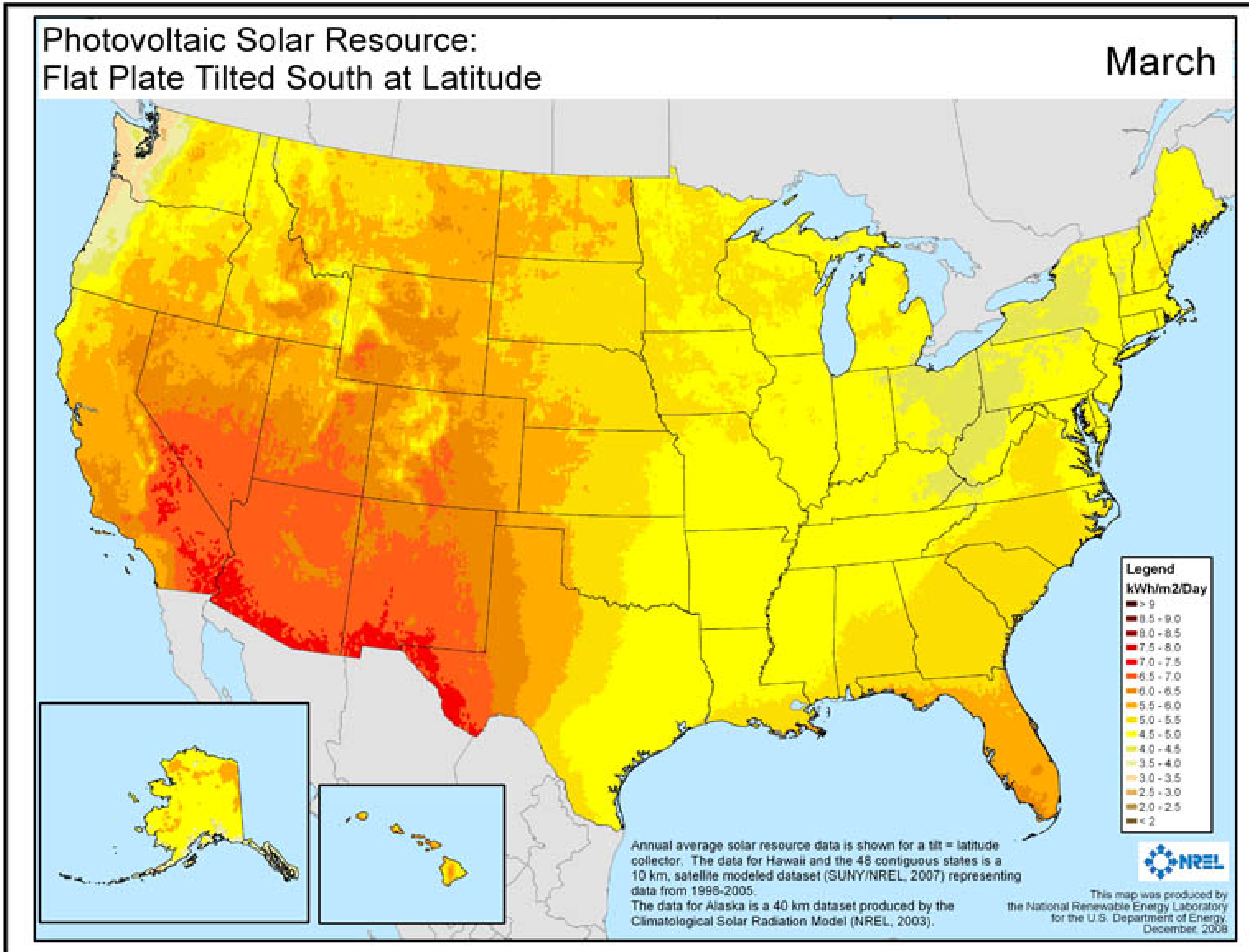
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
March
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
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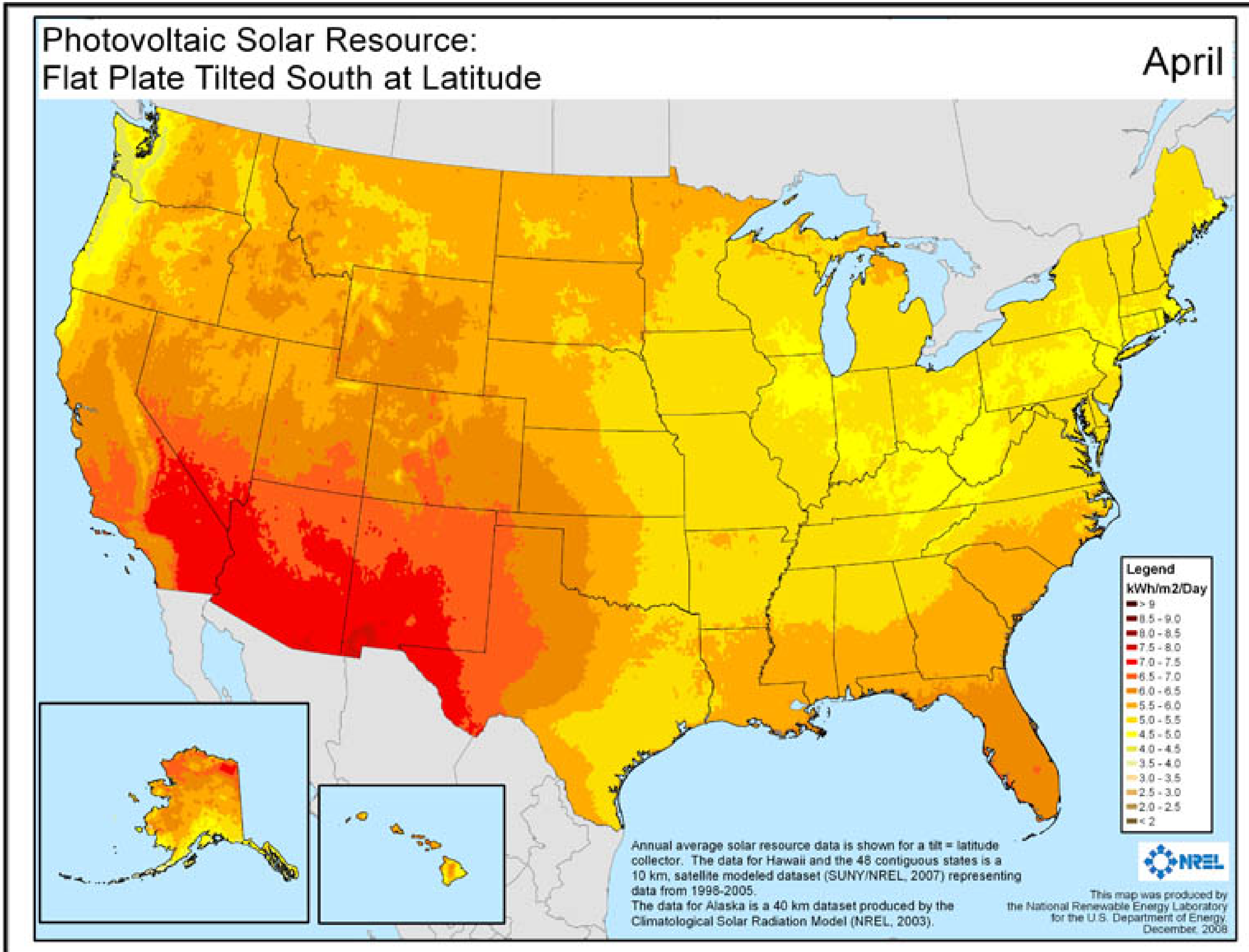
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
April
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
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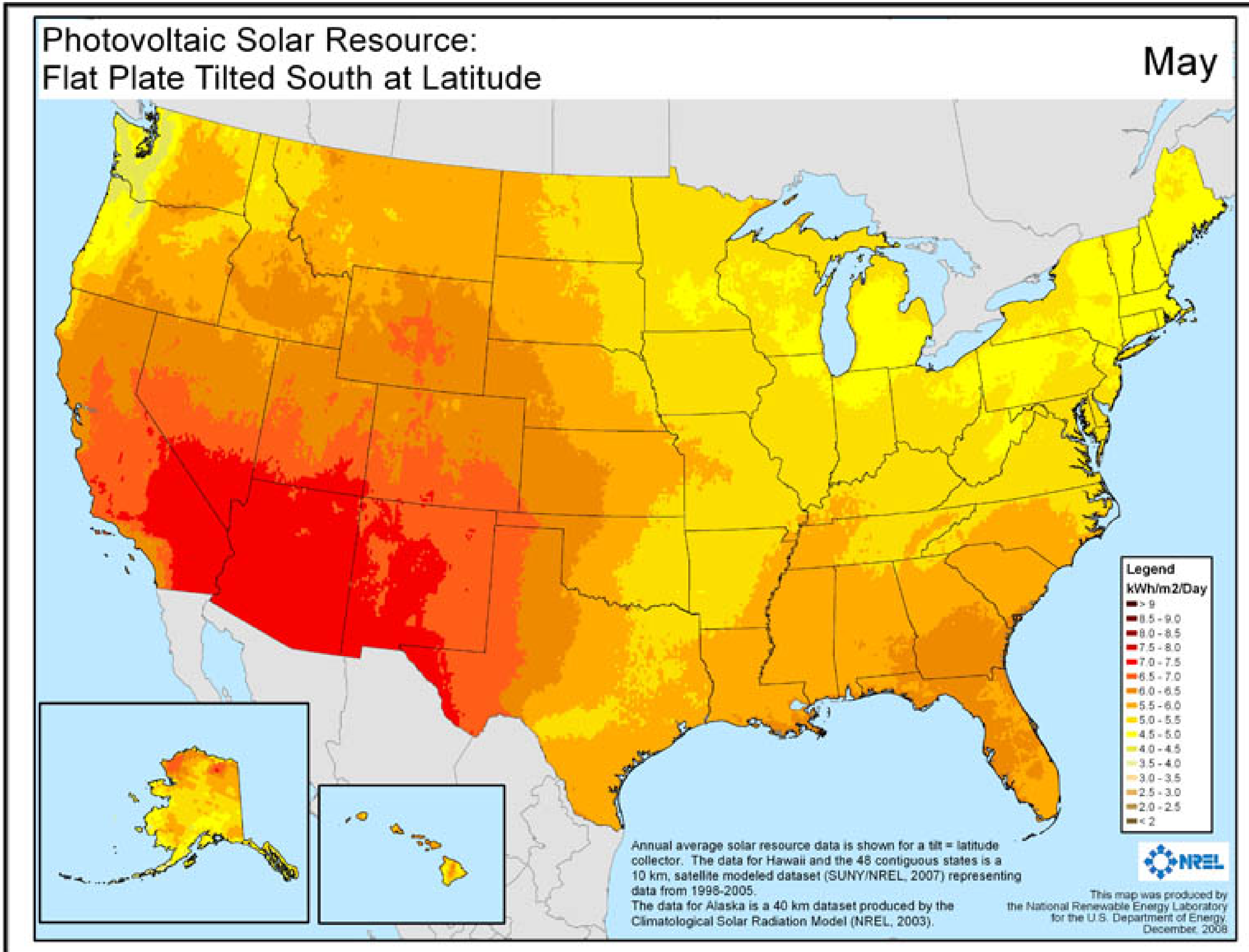
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
May
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
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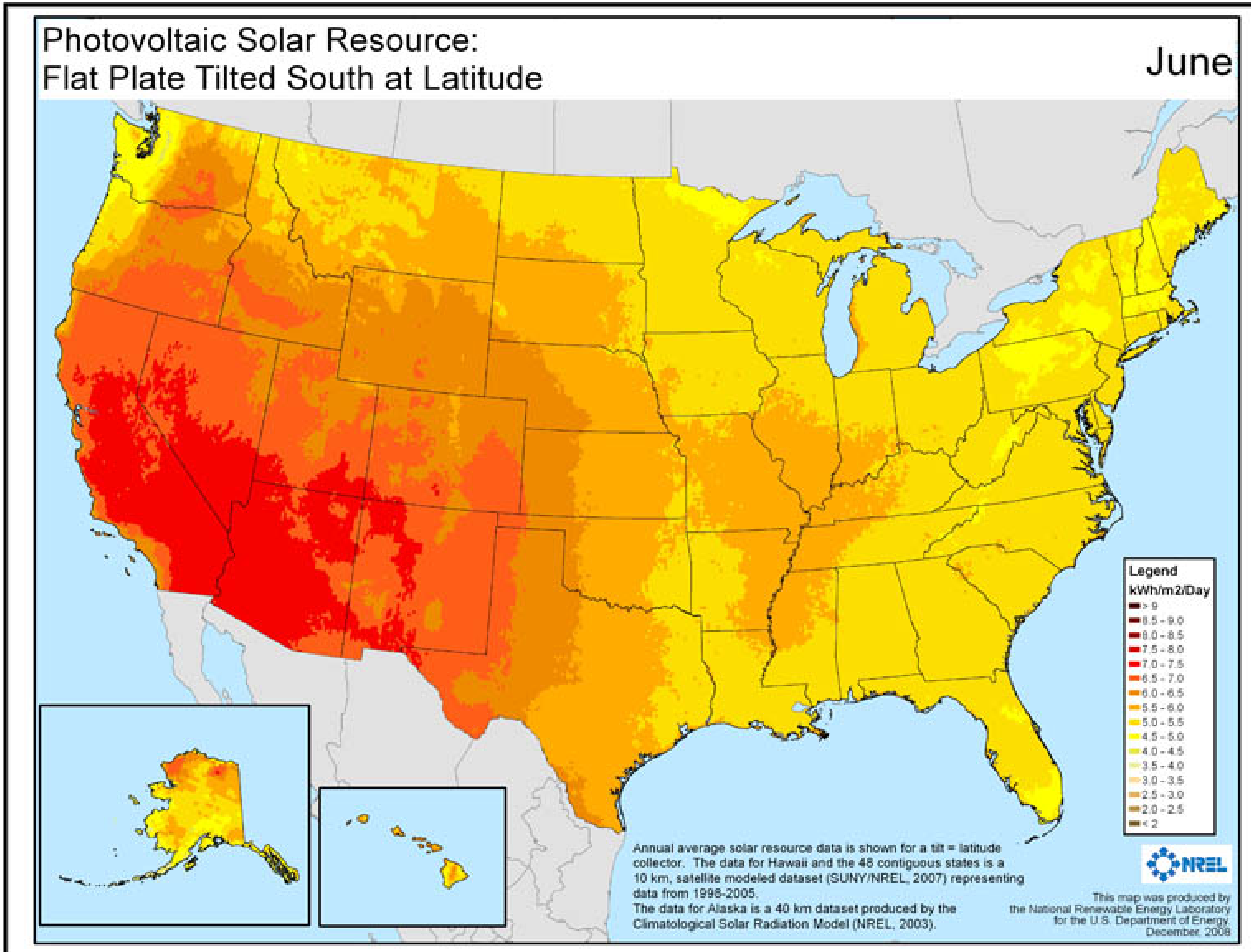
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
June
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
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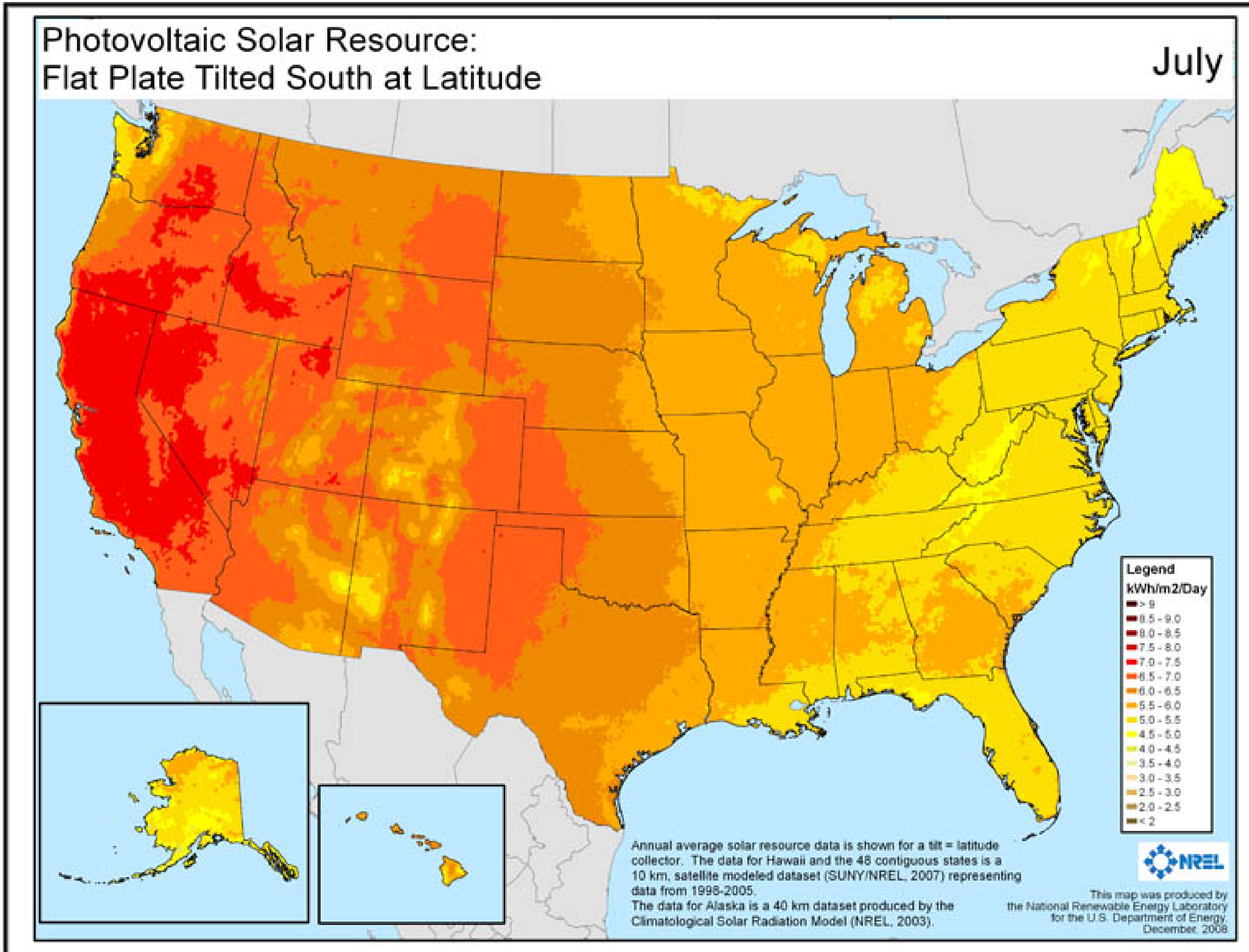
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
July
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
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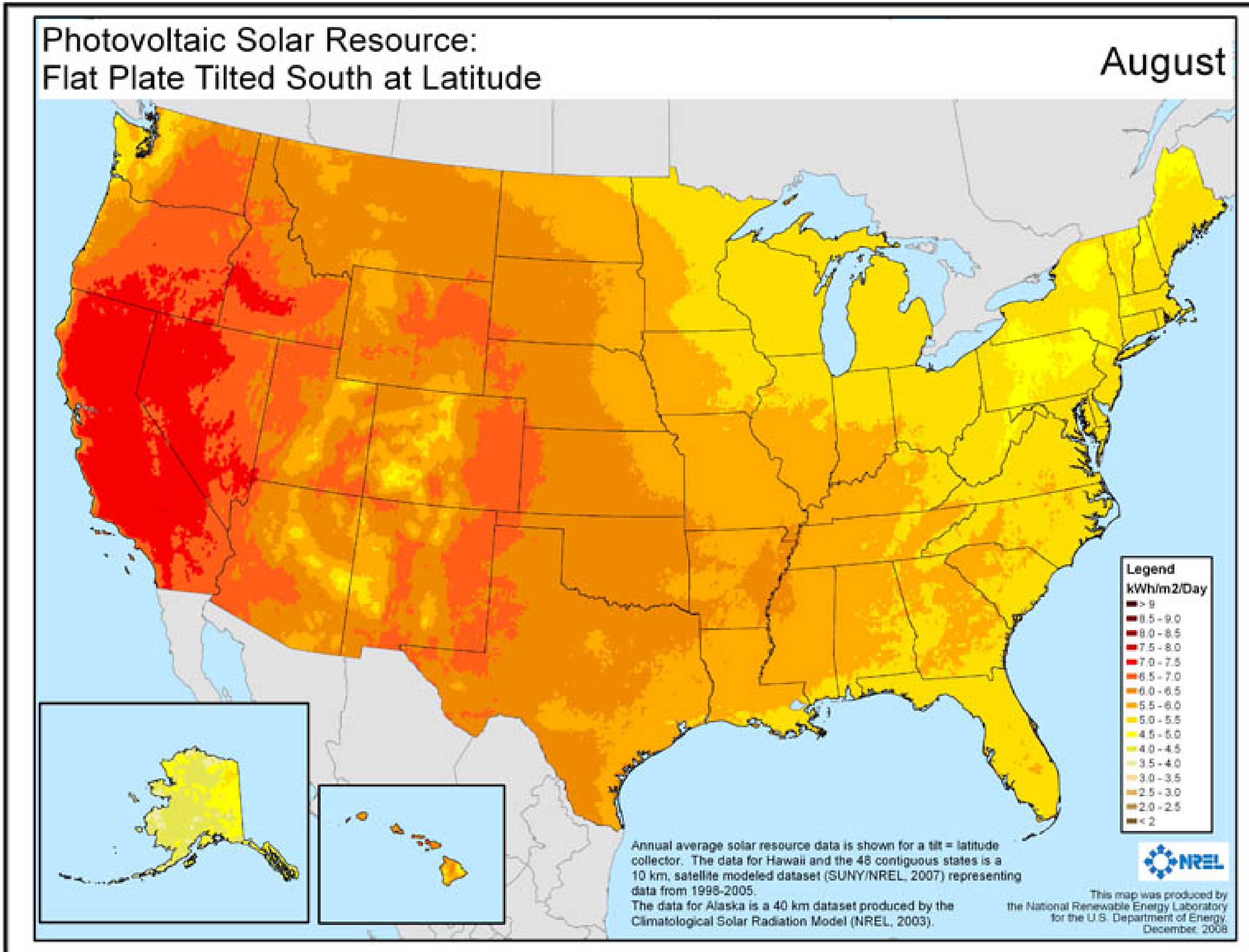

Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
August
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
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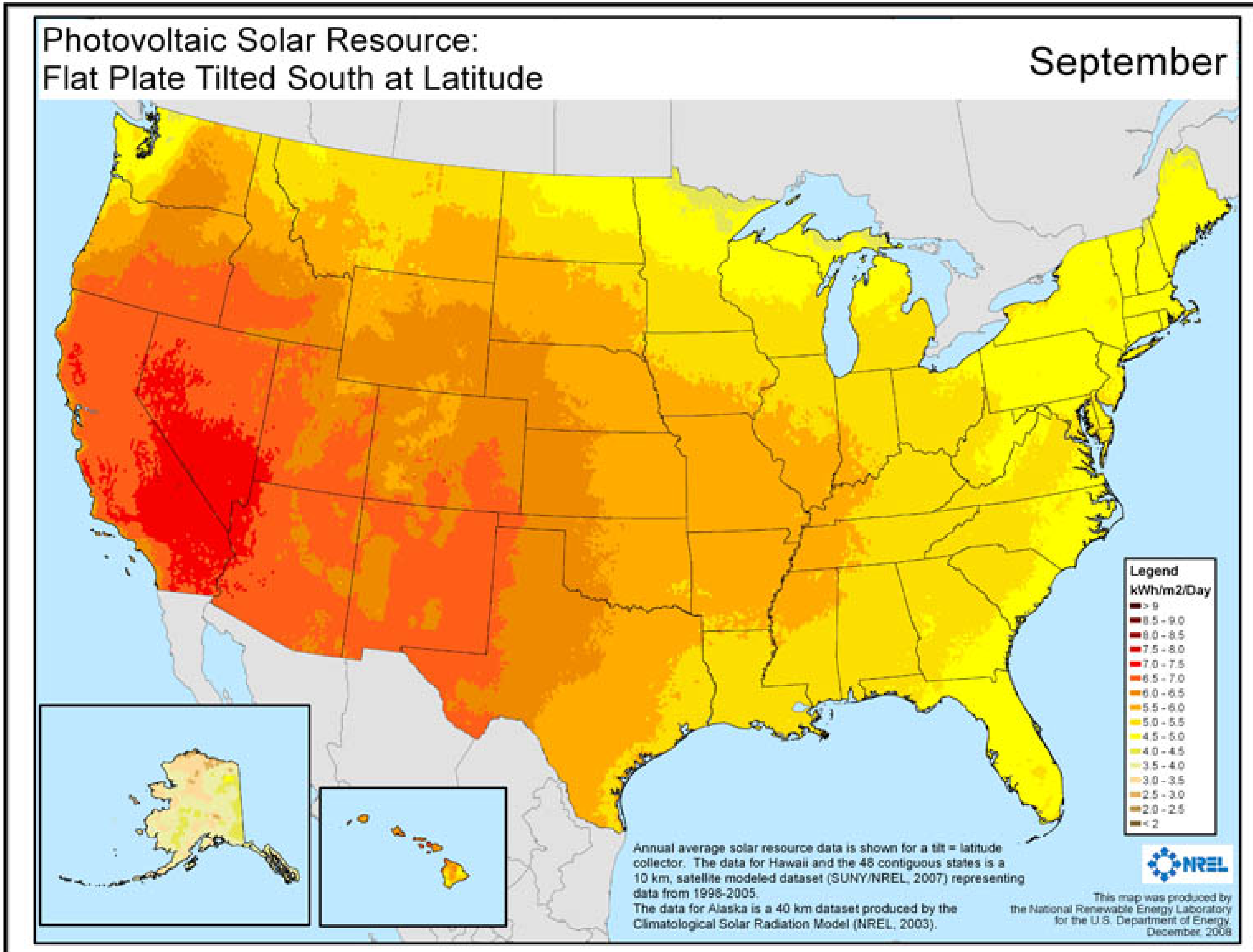
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
September
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
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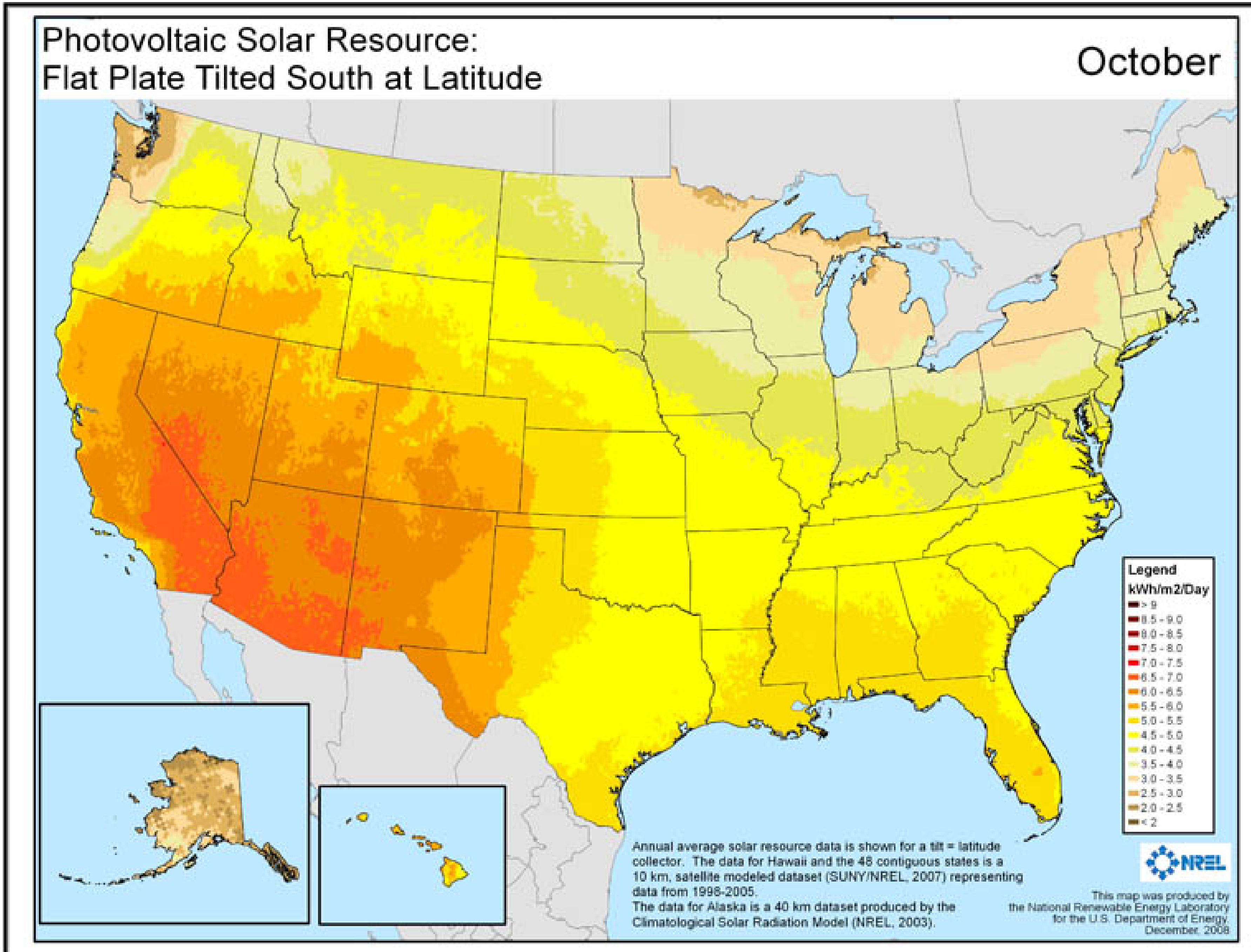

Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
October
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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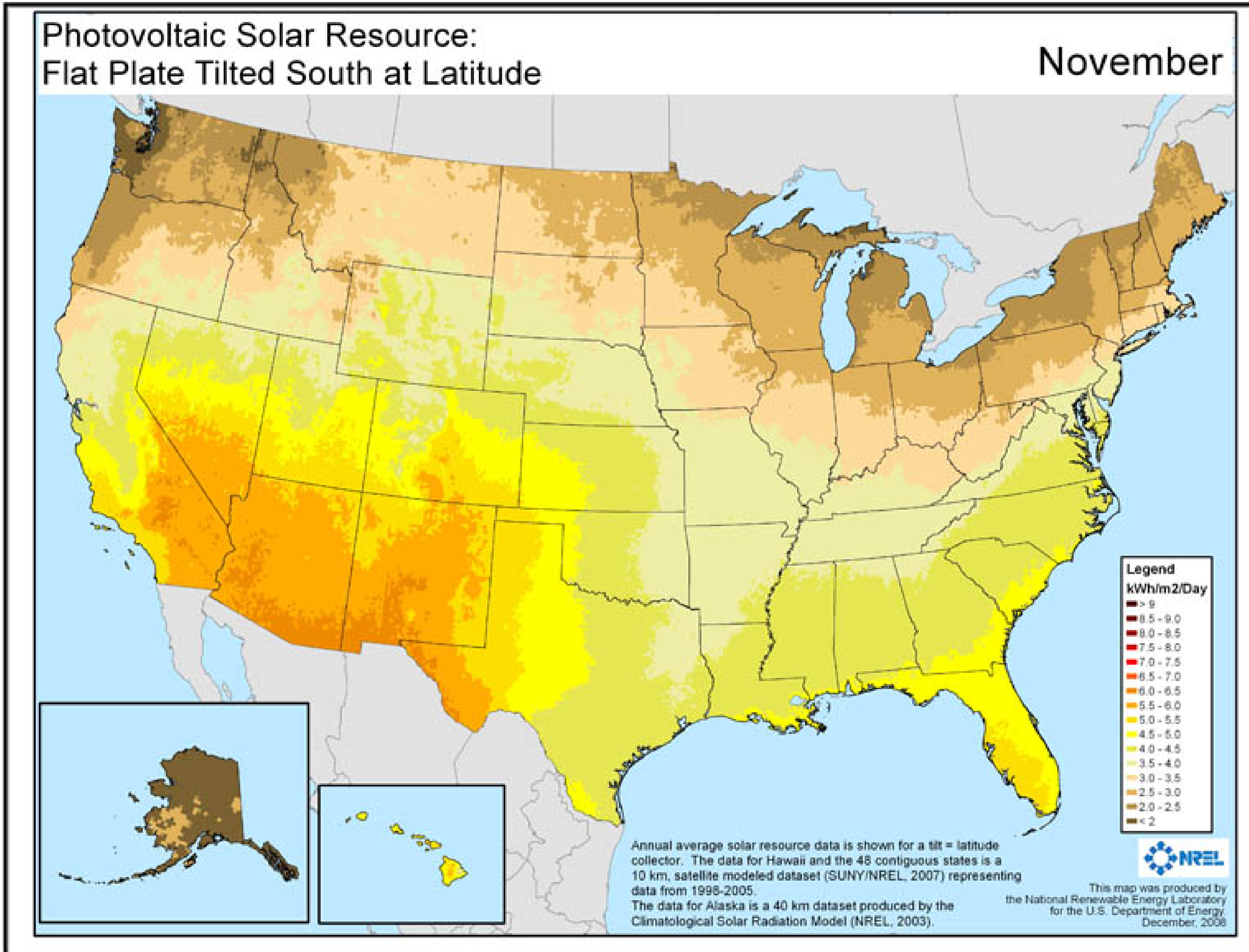
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
November
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
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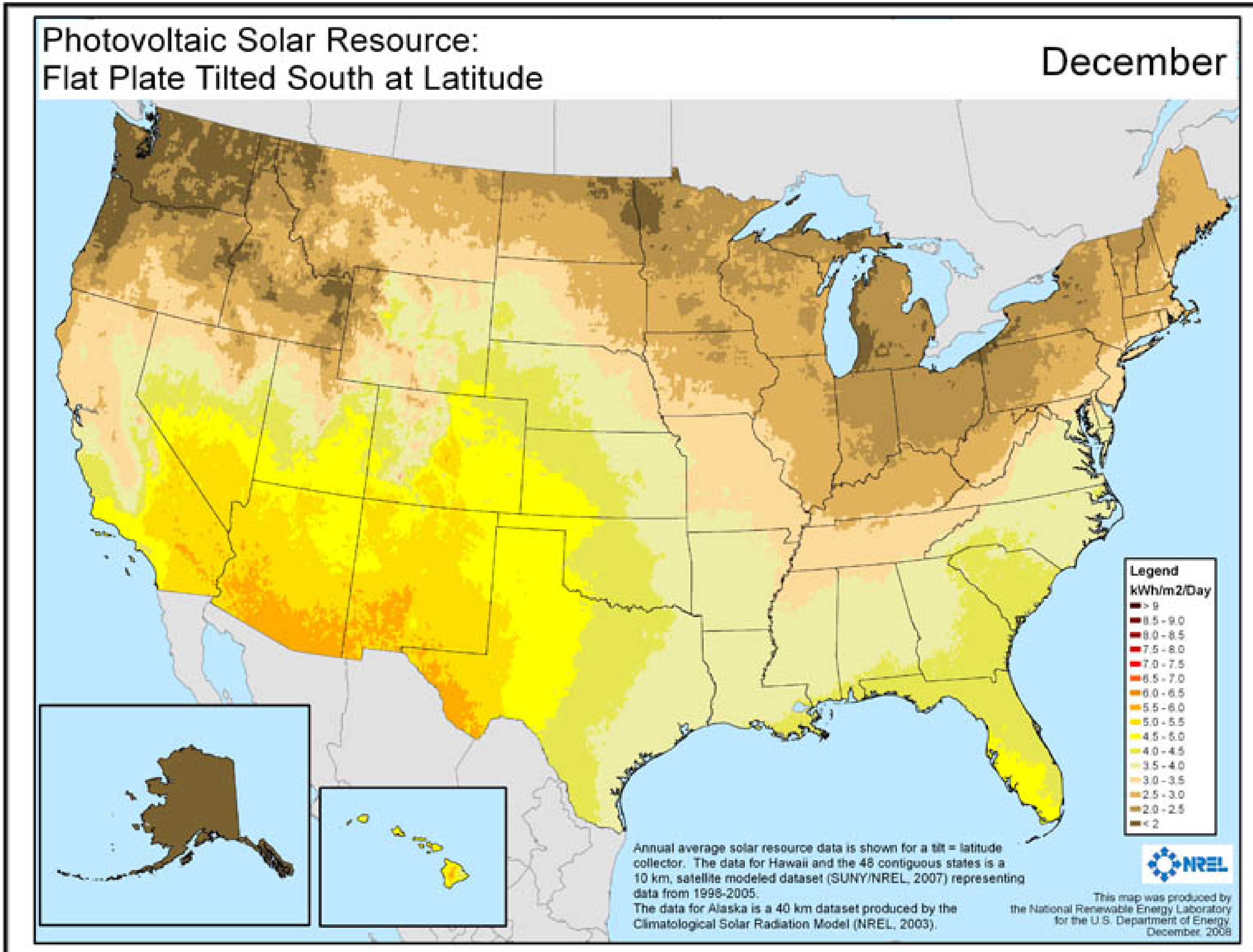

Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
December
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
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NREL
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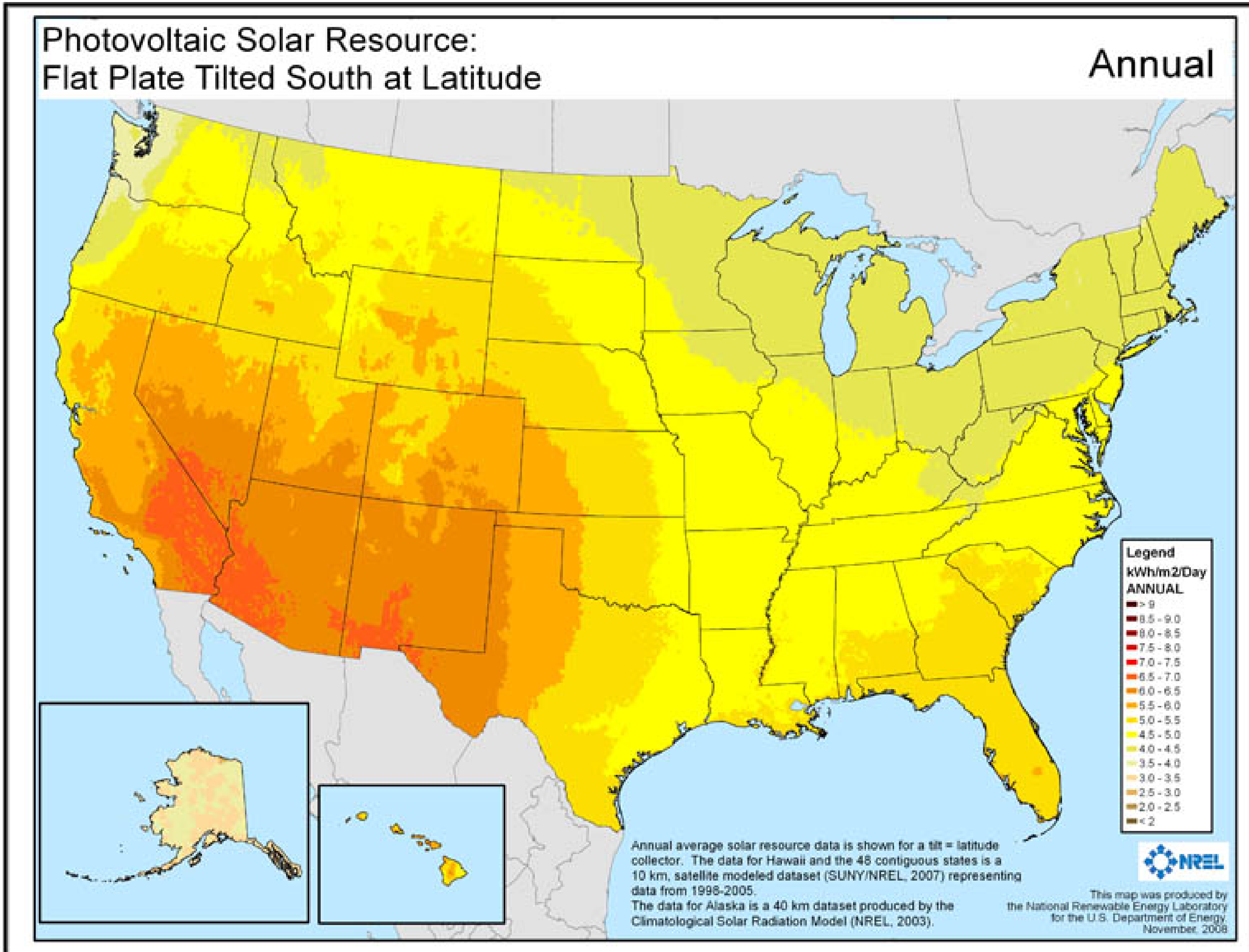
Photovoltaic Solar Resource:
Flat Plate Tilted South at Latitude
Annual
Legend
kWh/m2/Day
ANNUAL
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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NREL
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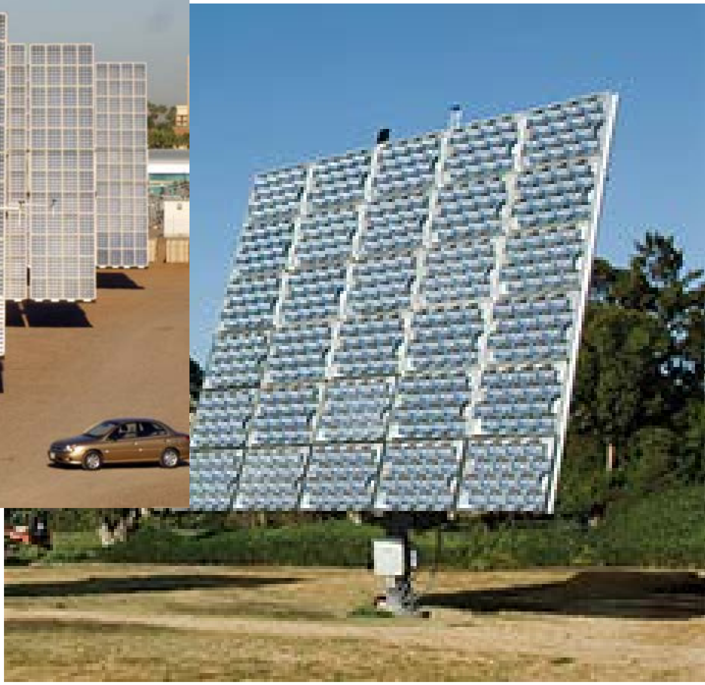
November, 2008

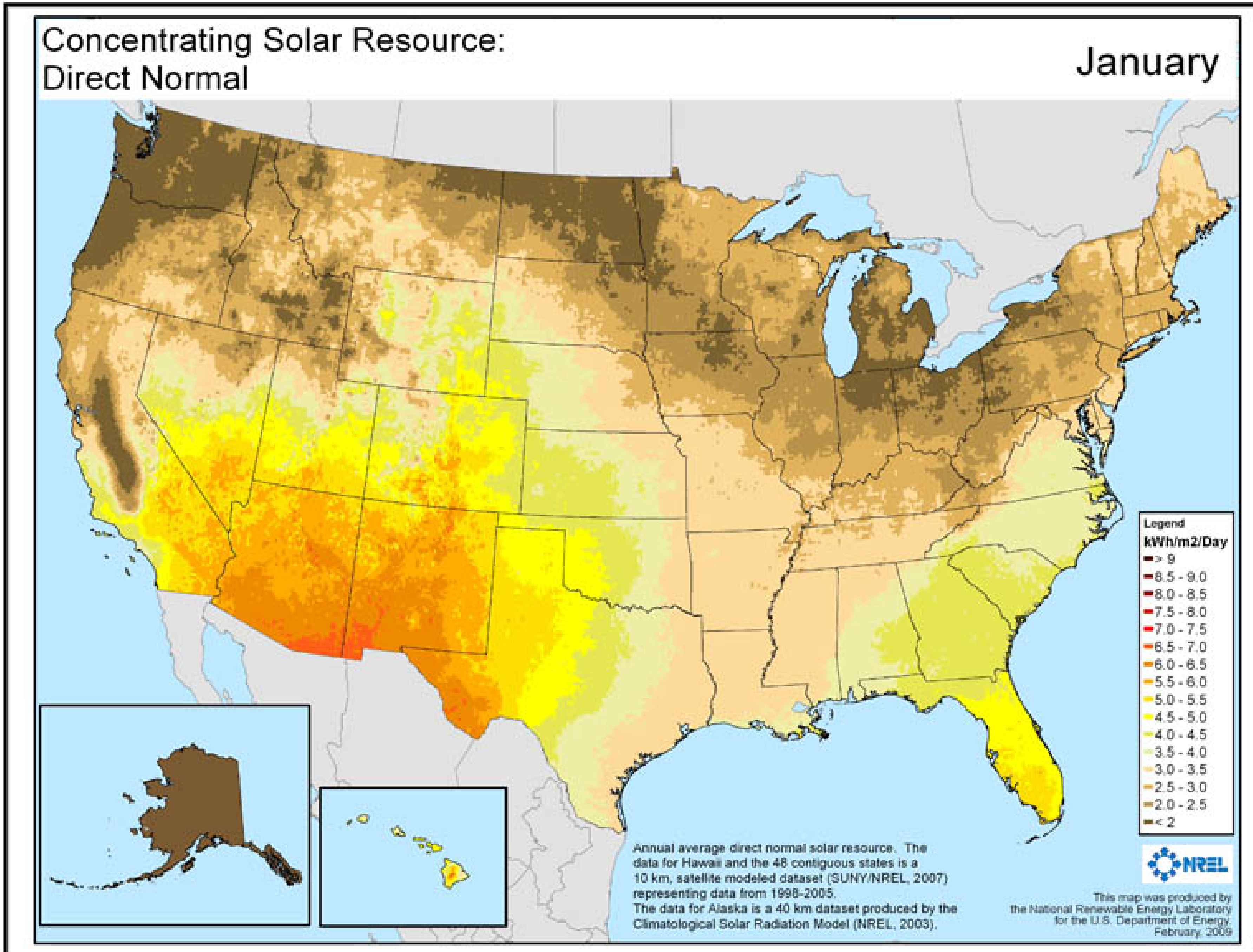
Concentrating PV Systems

- Direct Normal Insolation (kWh/m2/day)

Reflective

Refractive




Concentrating Solar Resource:
Direct Normal
January
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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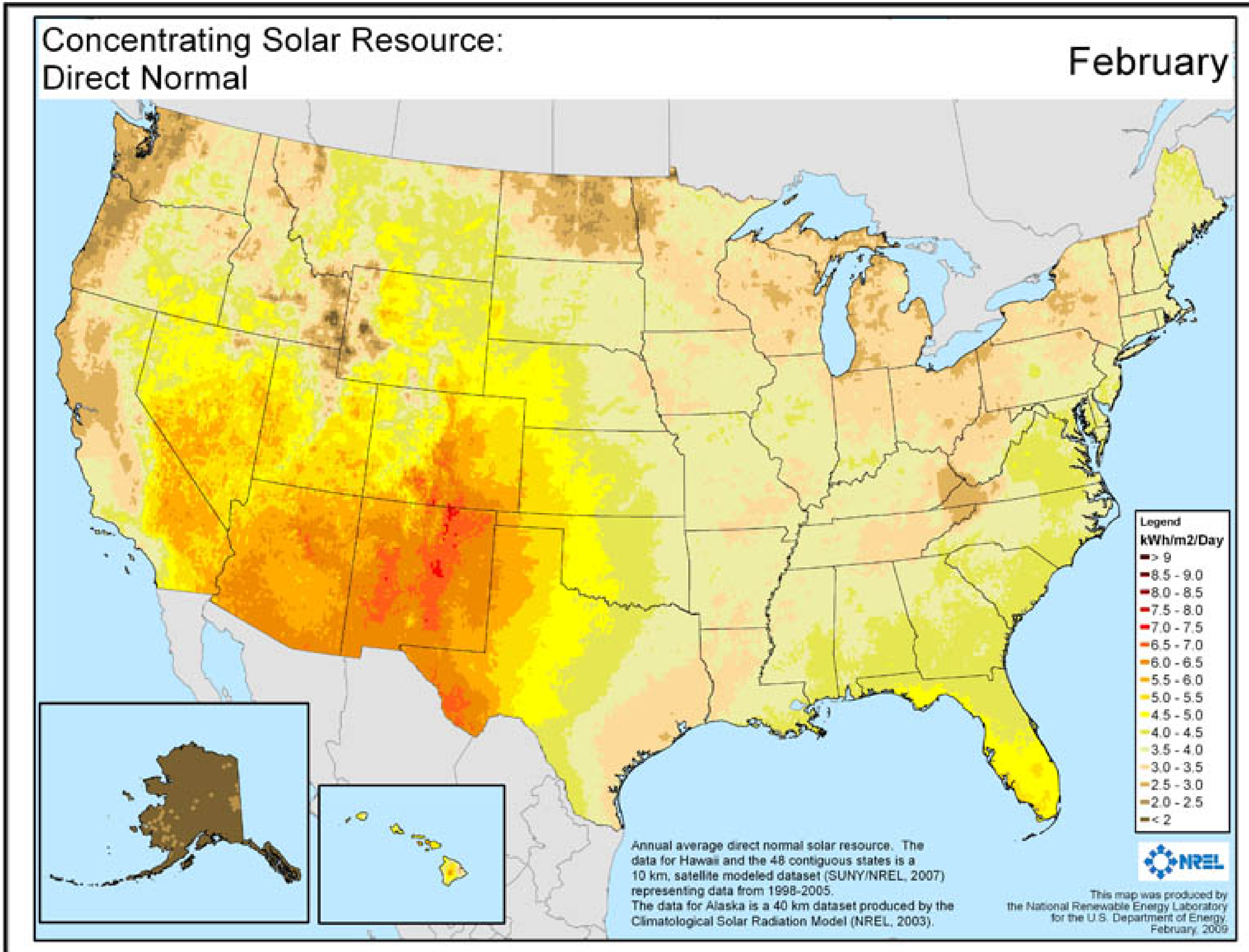
February, 2009


Concentrating Solar Resource:
Direct Normal
February
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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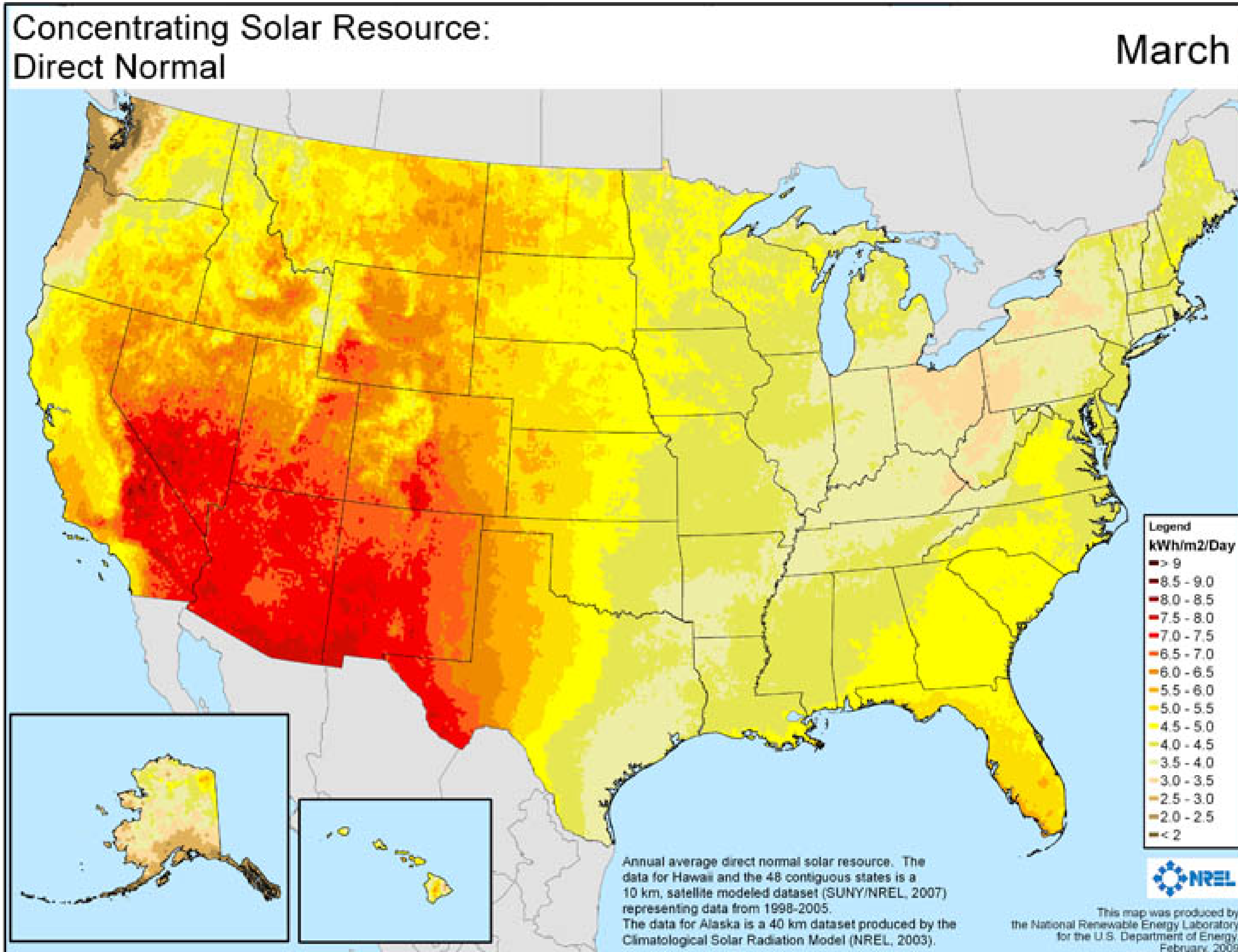
February, 2009


Concentrating Solar Resource:
Direct Normal
March
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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NREL
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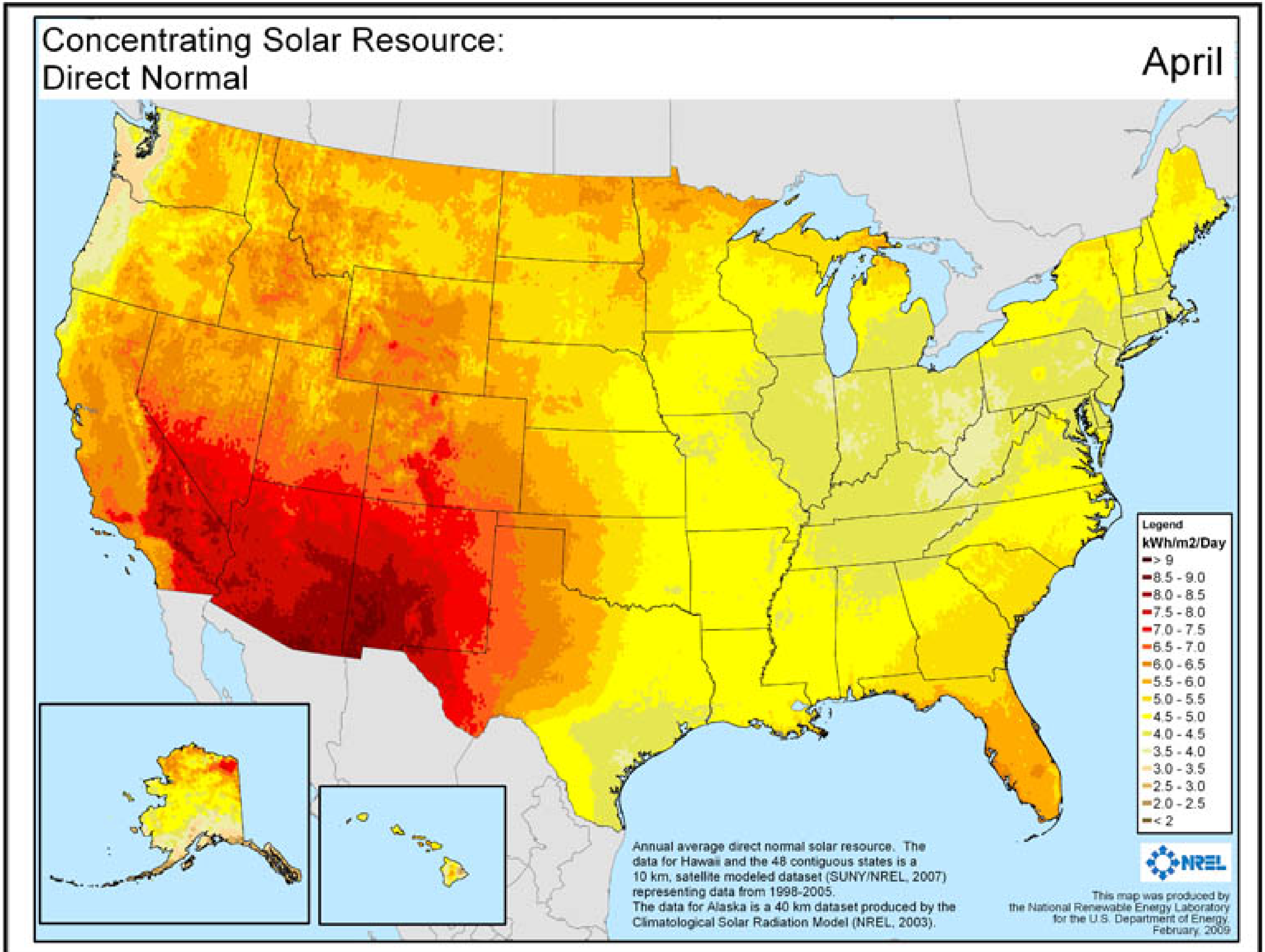
Concentrating Solar Resource:
Direct Normal
April
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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NREL
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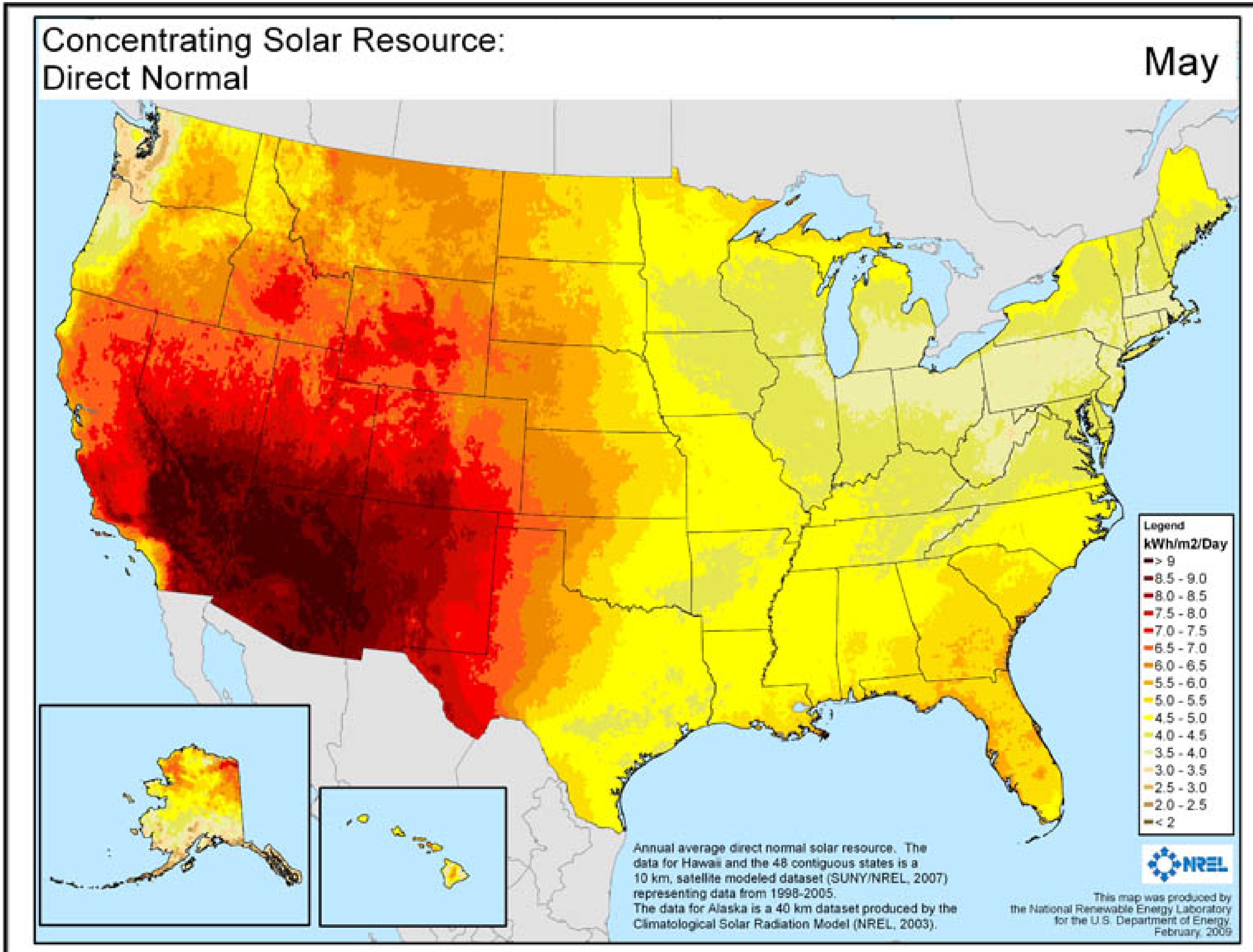
Concentrating Solar Resource:
Direct Normal
May
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
NREL
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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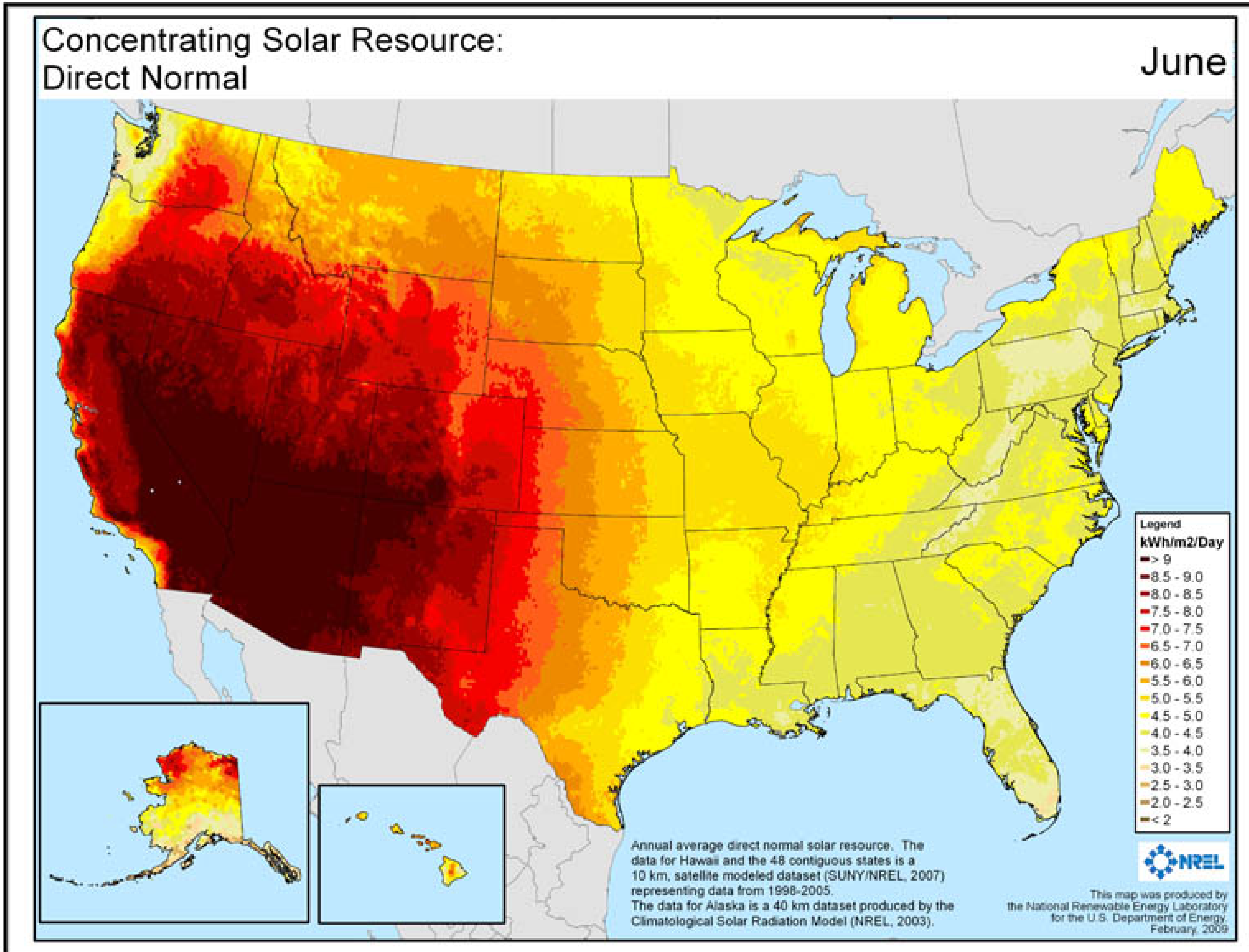
Concentrating Solar Resource:
Direct Normal
June
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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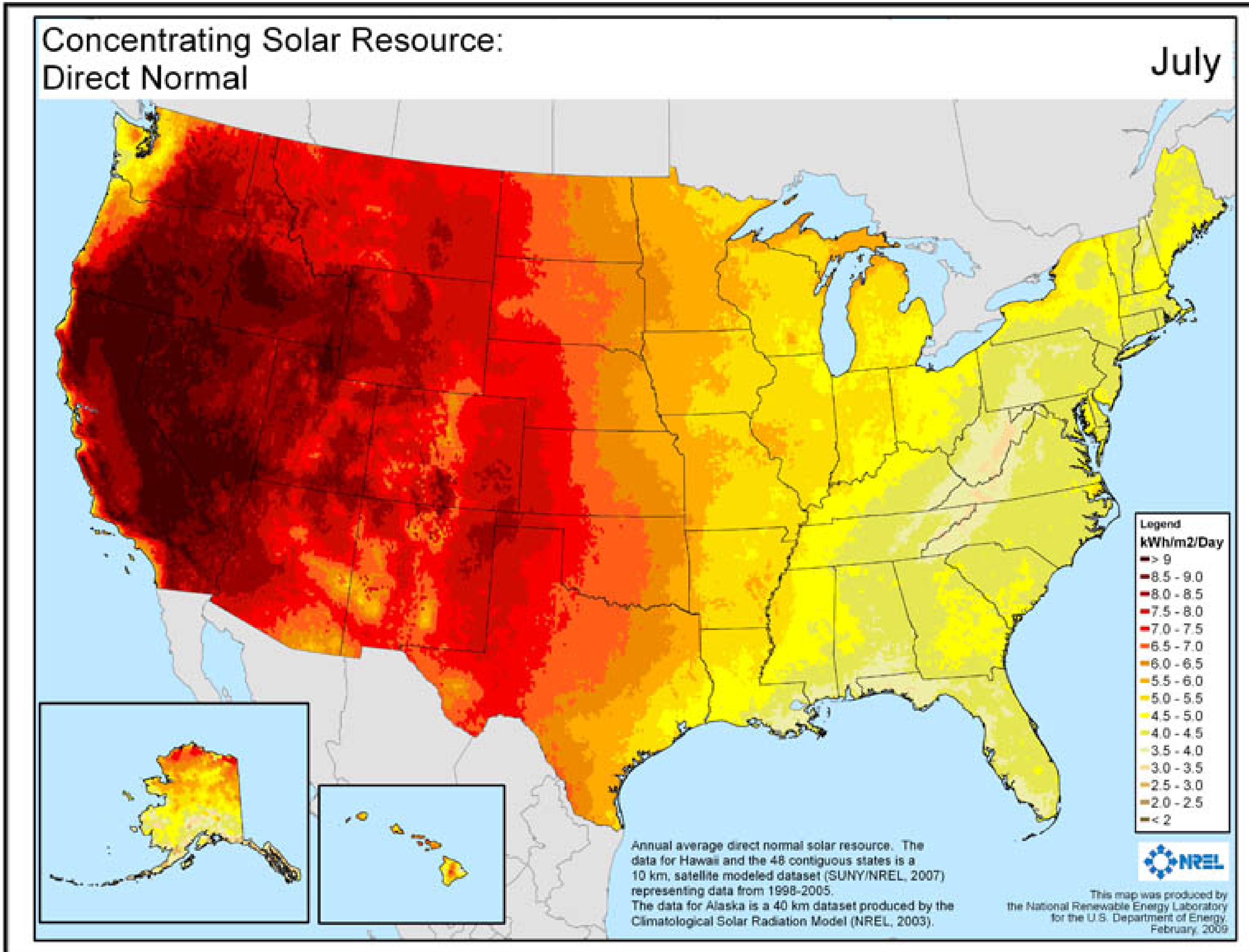
Concentrating Solar Resource:
Direct Normal
July
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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NREL
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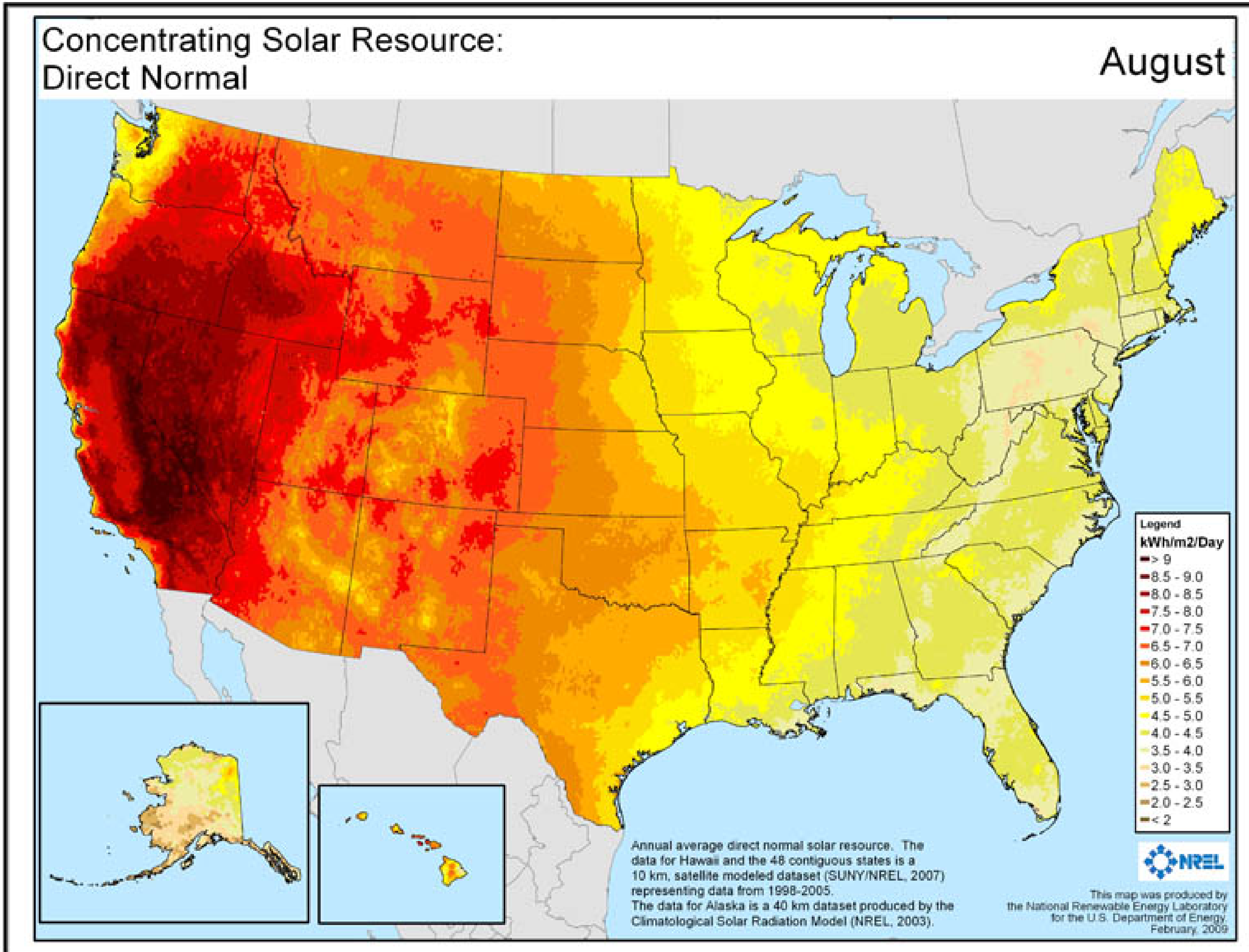
Concentrating Solar Resource:
Direct Normal
August
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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NREL
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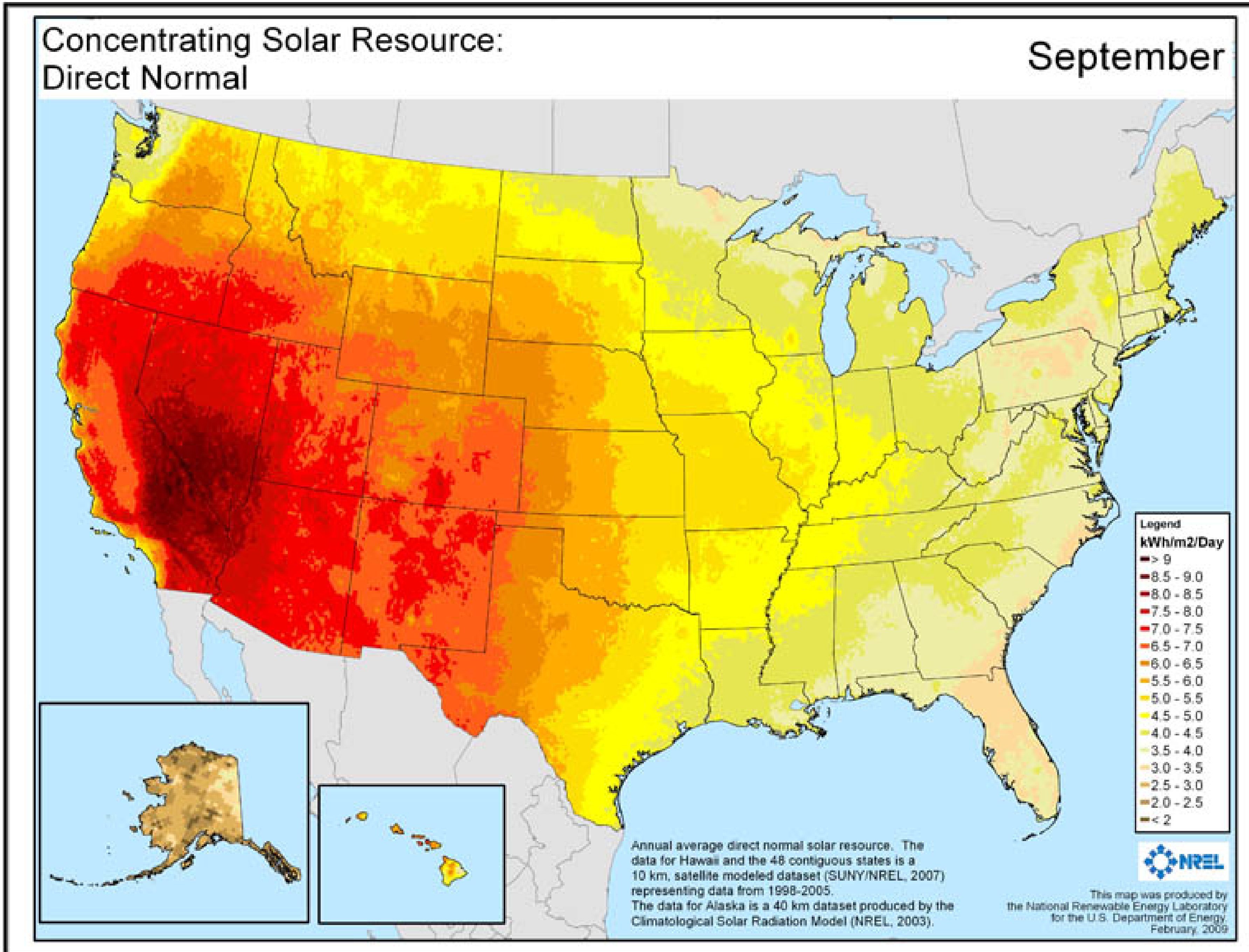

Concentrating Solar Resource:
Direct Normal
September
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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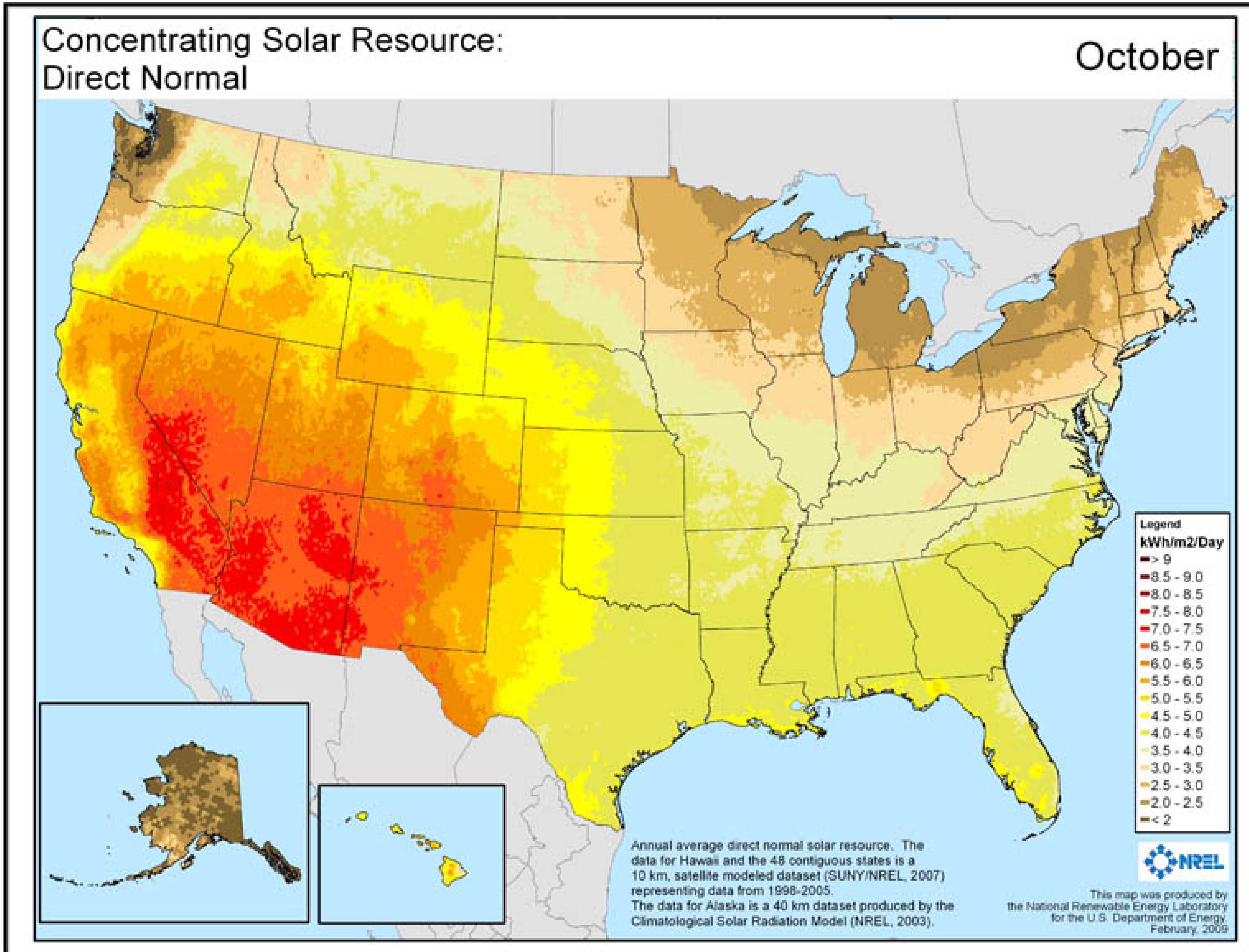

Concentrating Solar Resource:
Direct Normal
October
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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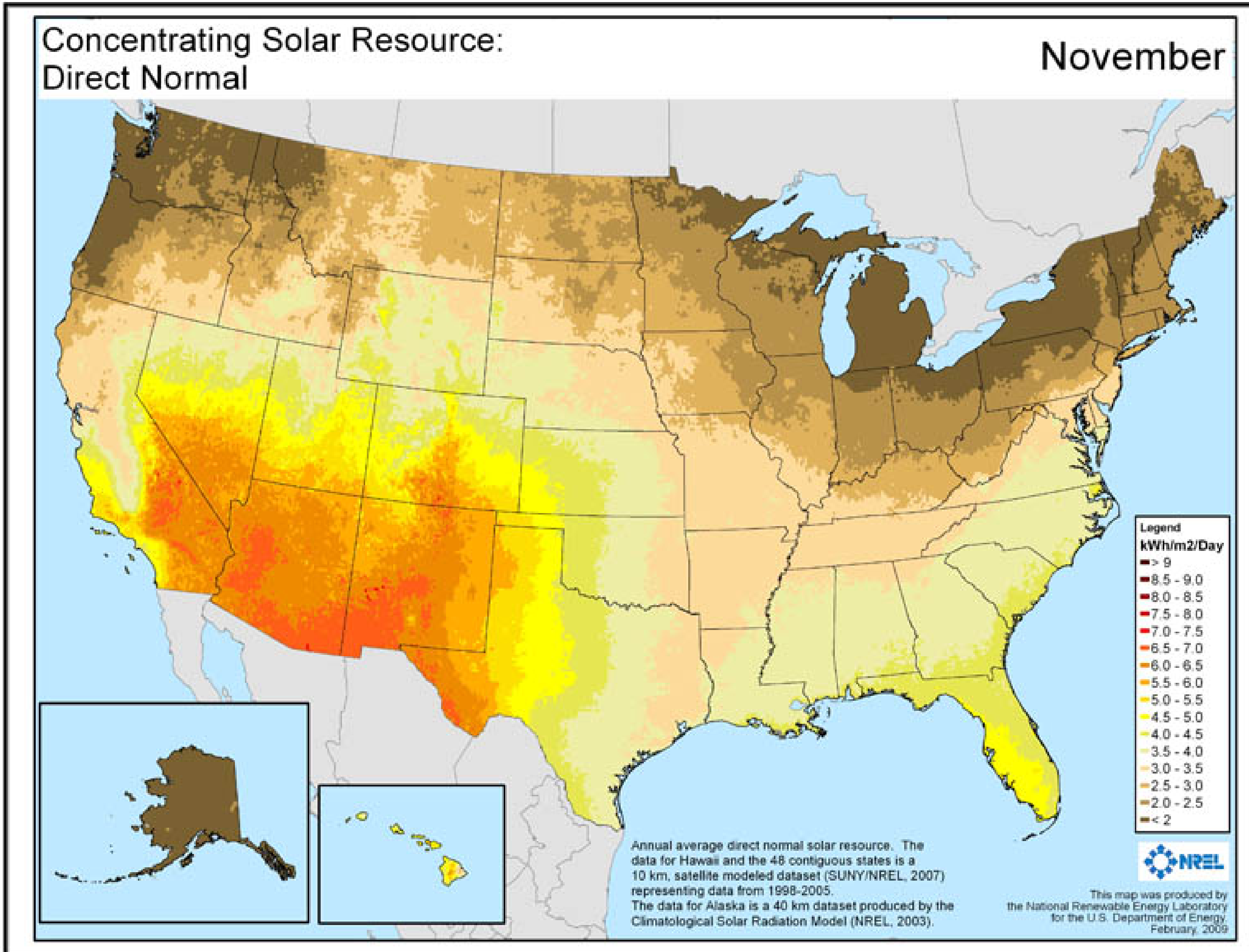
Concentrating Solar Resource:
Direct Normal
November
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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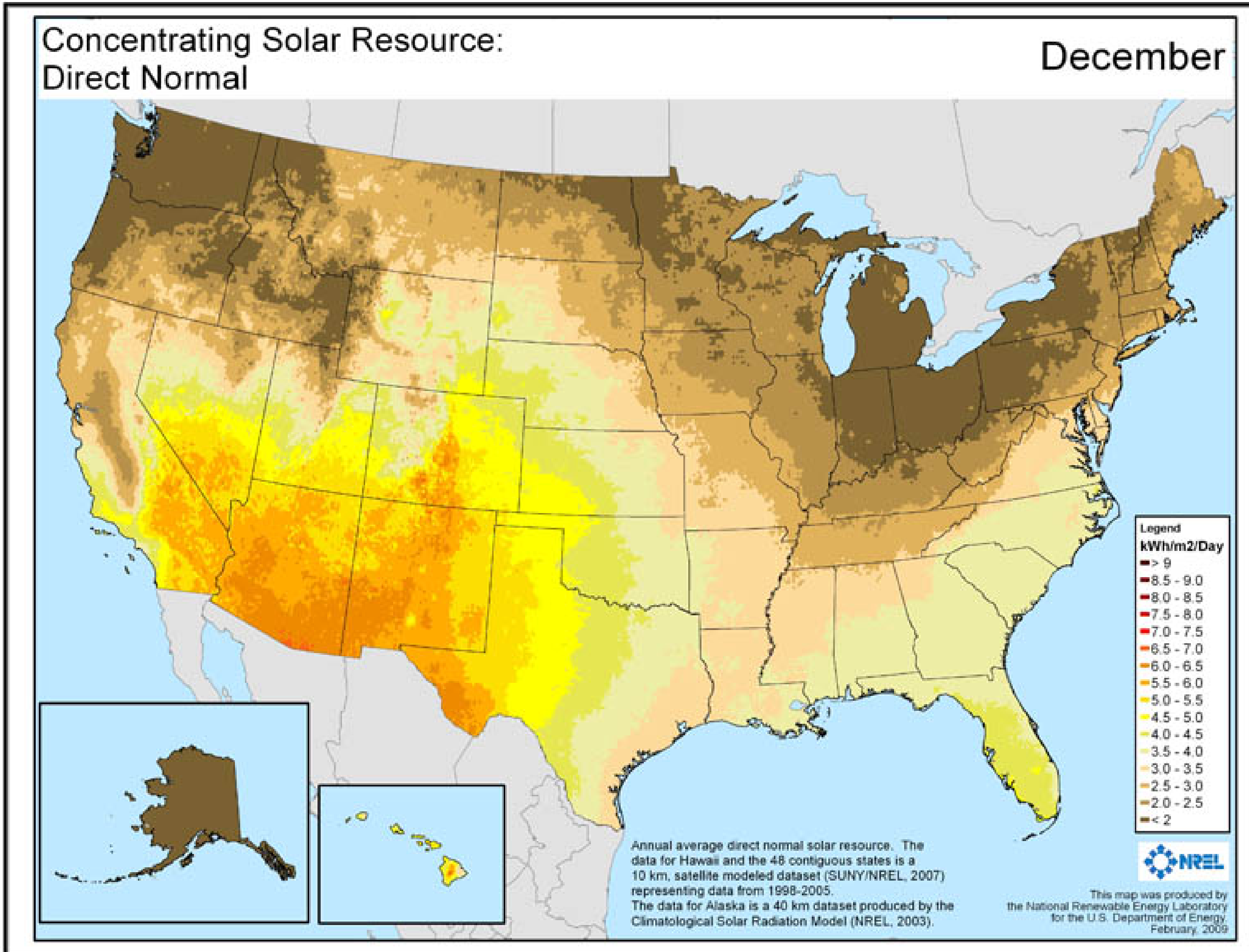
Concentrating Solar Resource:
Direct Normal
December
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
NREL
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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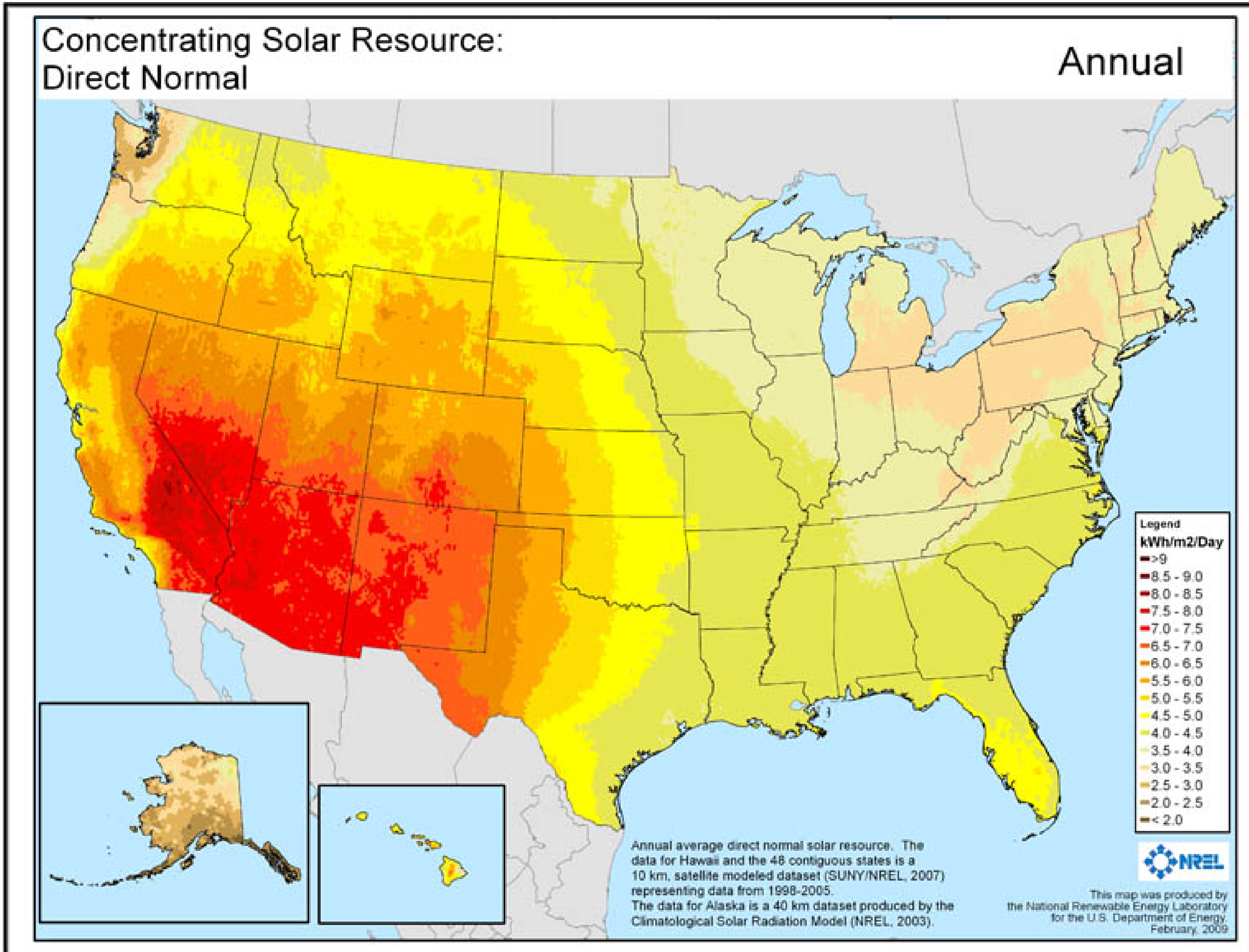

Concentrating Solar Resource:
Direct Normal
Annual
Legend
kWh/m2/Day
>9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2.0
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
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NREL
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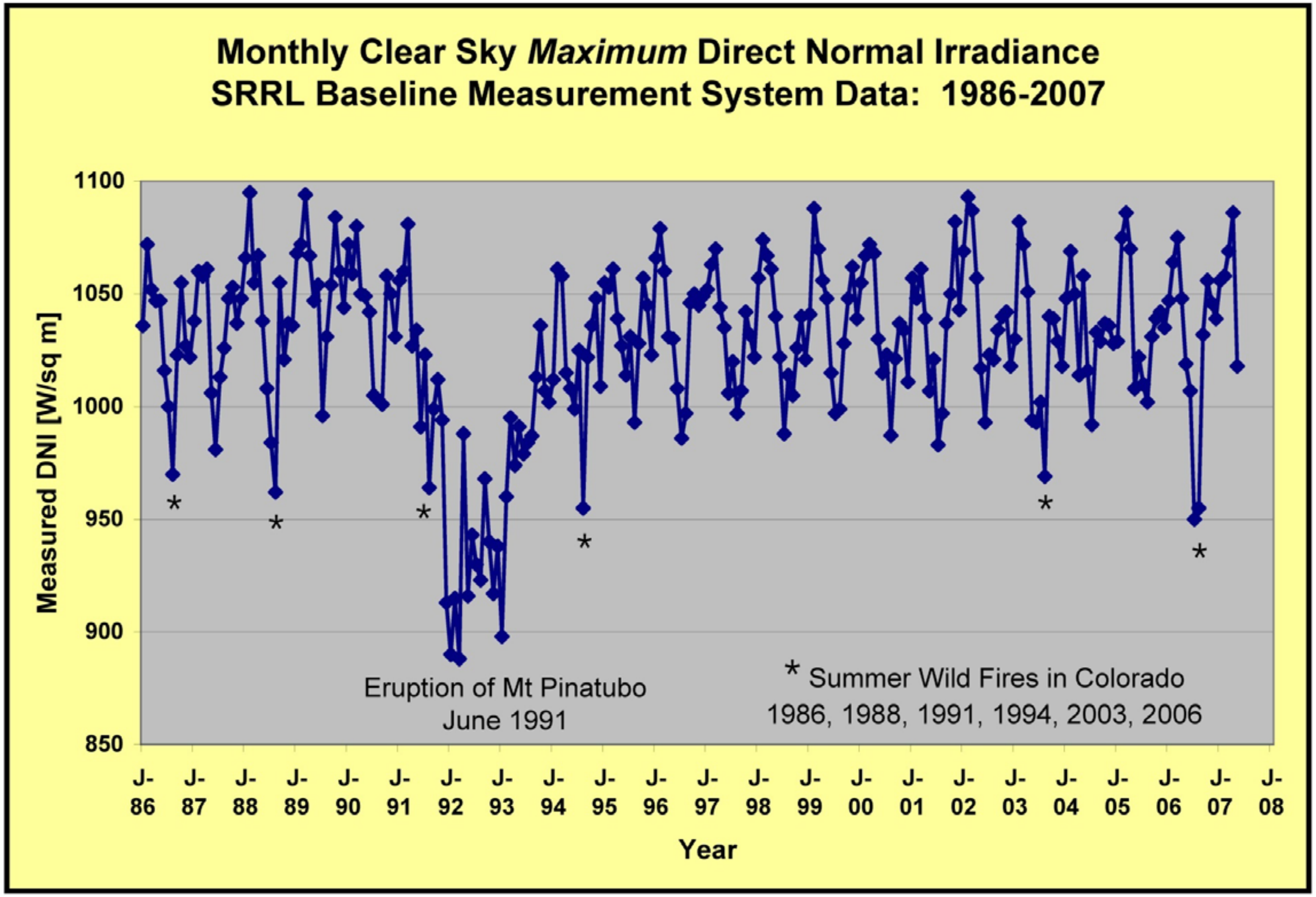
Typical Meteorological Year (TMY2) Data

- Hourly data sets of meteorological and solar radiation data for a "typical" 1-year period
- Derived from long term time series (>20 years)
- TMY data fields contain
  - Station: WMO ID#, city and country name, time zone, latitude and longitude, elevation
  - Solar radiation data: Top of Atmosphere, DNI, GHI, diffuse, illuminance, sky cover
  - Meteorological data: Temperature, dew point, relative humidity, pressure, wind direction and speed, visibility, ceiling height, present weather, precipitable water, aerosol optical depth, snow depth, days since last snow

P-values

- P-measures represent a value that is exceeded by XX % of the population of a data set.
- TMY Data is P50
- Financial world refers to P90
- The higher the accuracy of the measurement, the higher the insolation (kWh/m2) for a given P value.
- Example:
- P90 at 5% uncertainty in measurement= 1800 kW/m²/year
- P90 at 15% uncertainty in measurement= 1750 kW/m²/year

Inter-annual Variability

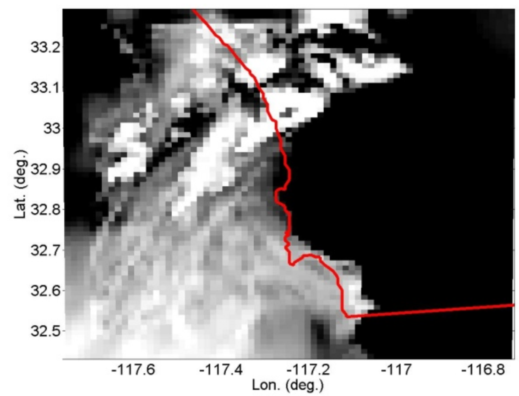


Forecasting Performance

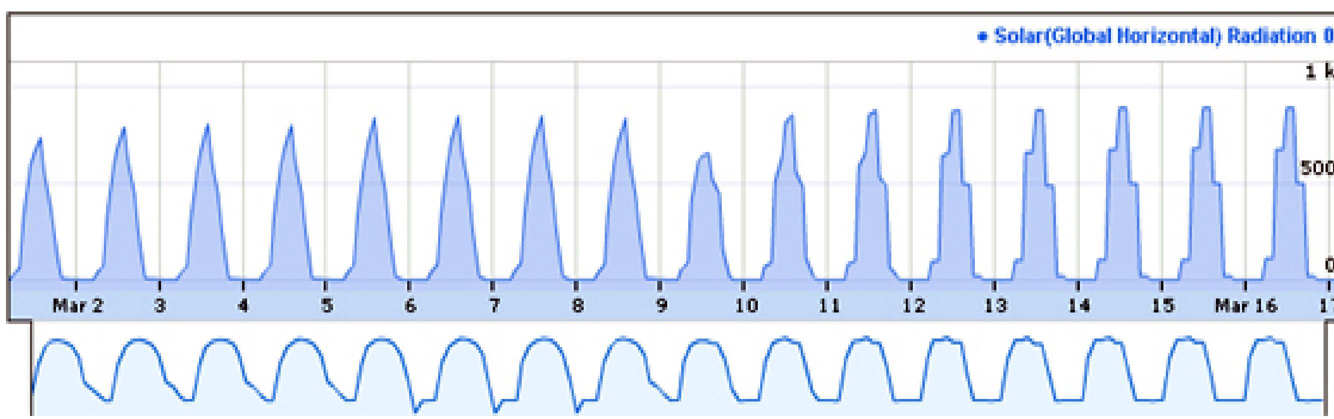
NREL PV Analytical Tool Websites:

Solar Advisor Model (SAM):
www.nrel.gov/analysis/sam/
HOMER: analysis.nrel.gov/homer/
PVWatts: www.nrel.gov/rredc/pvwatts/
IMBY: www.nrel.gov/eis/imby/

Modeling

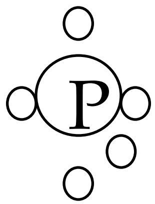


Imaging

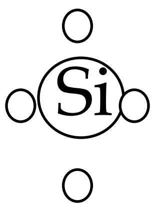


172 hour forecast example
http://weatheranalytics.com/renewableforecast.html

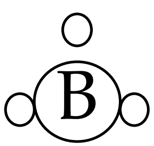
The Photovoltaic Effect



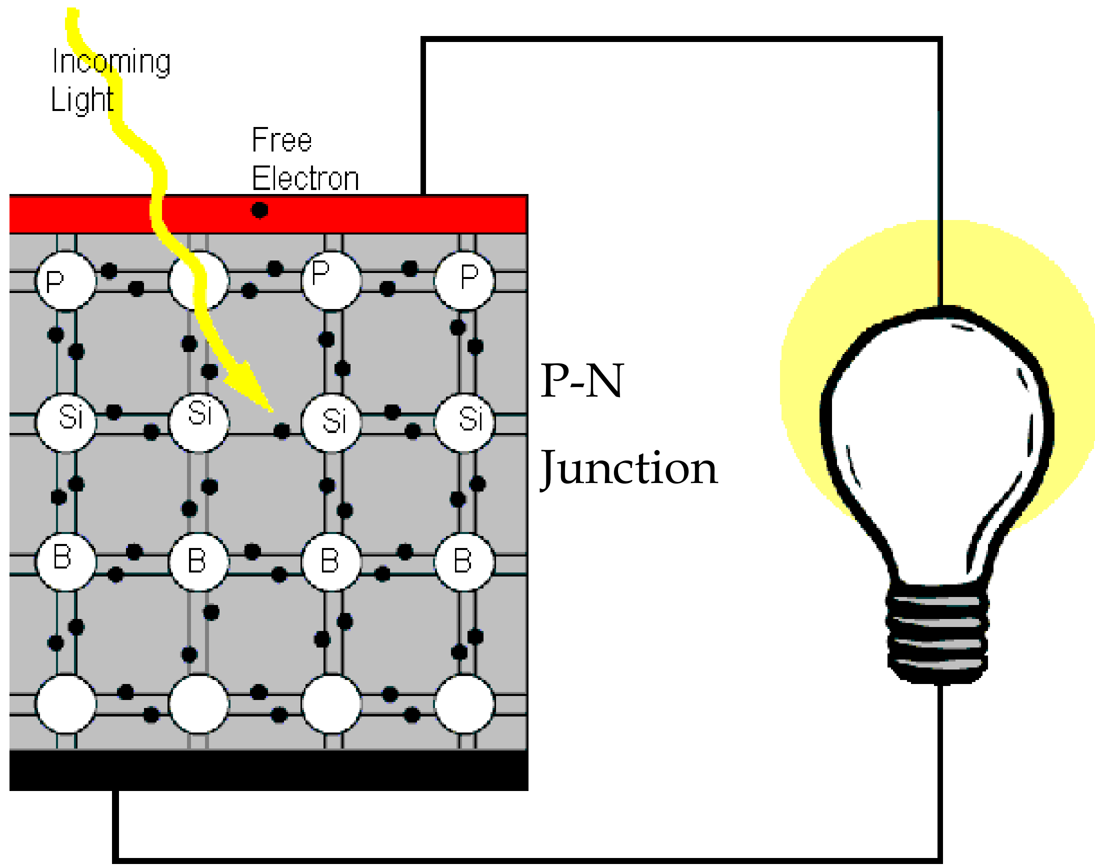
Phosphorous: 5 valence electrons



Silicon: 4 valence electrons



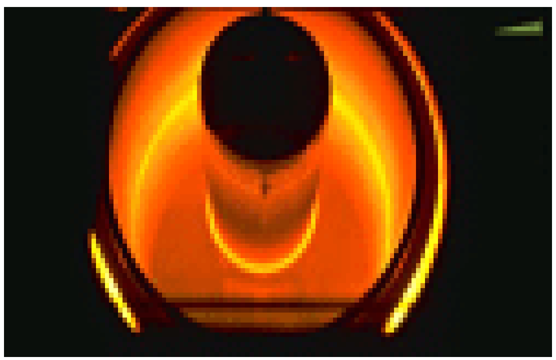
Boron: 3 valence electrons



No material is consumed and the process could continue indefinitely

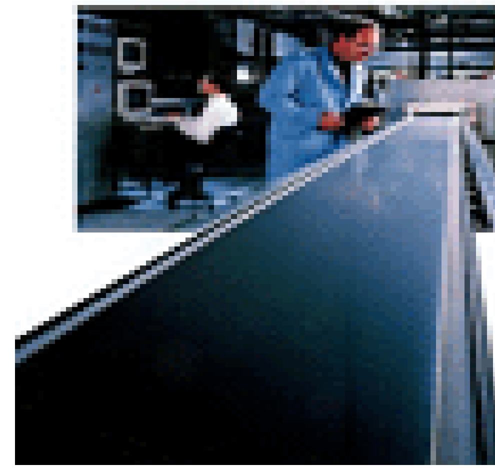
PV Manufacturing

Single Crystal



Multi-Crystal

Thin Film



Efficiency of Different Types of PV

Year	Crystalline Silicon			Thin-Film Silicon		Concentrator Silicon
	Single-Crystal	Cast	Ribbon	Amorphous Silicon	Other	
2007	17	14	12	8	12	35
2008	19	14	13	8	12	34
2009	20	14	13	8	12	38

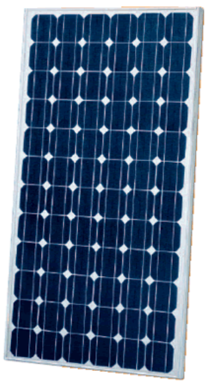
Source: U.S. Energy Information Administration, Form EIA-63B, "Annual Photovoltaic Module/Cell Manufacturers Survey."

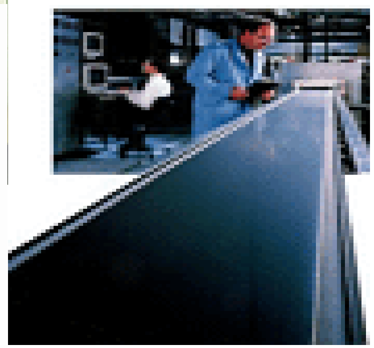
PV Manufacturers

Single Crystal * Multi-Crystal * Thin Film * Cadmium Telluride * CIGS

Efficiencies:

14 to 23% | 13 to 17% | 6 to 11% | 10% to 11% | 12% to 14%





Crystal Silicon

Kyocera
LDK Solar
LG
Mitsubishi
Q-Cells
Sanyo
SolarFun Power
SolarWorld
Solon
SunPower
SunTech
Trina Solar
Yingli Solar

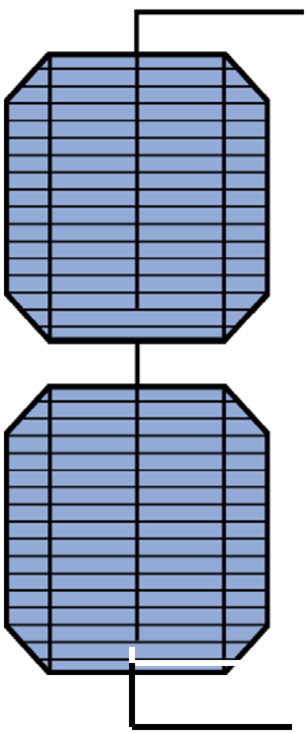
ENN Solar
Moser Baer
Sharp
SunFilm
SunWell
Uni-Solar

Abound Solar
First Solar
GE

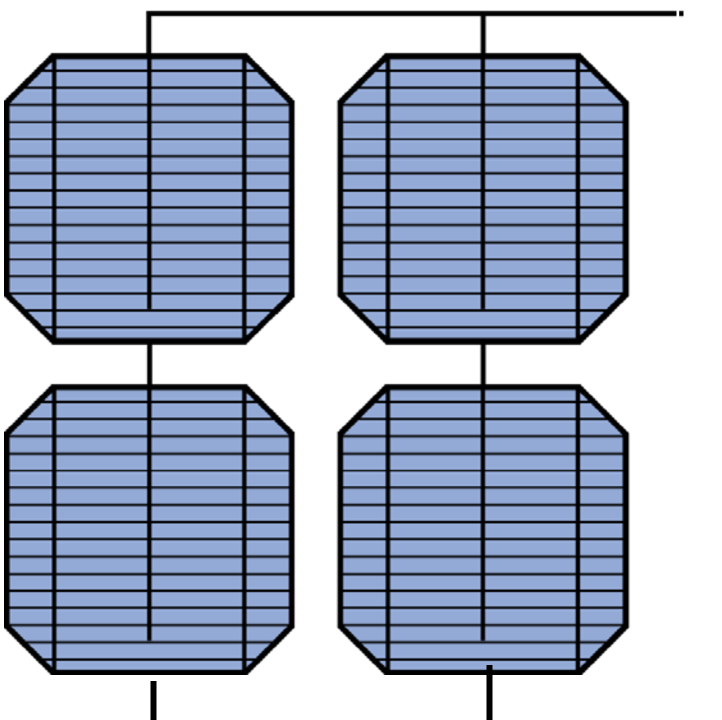
Ascent Solar
Global Solar
MiaSole
Solibro
SoloPower

PV Cells

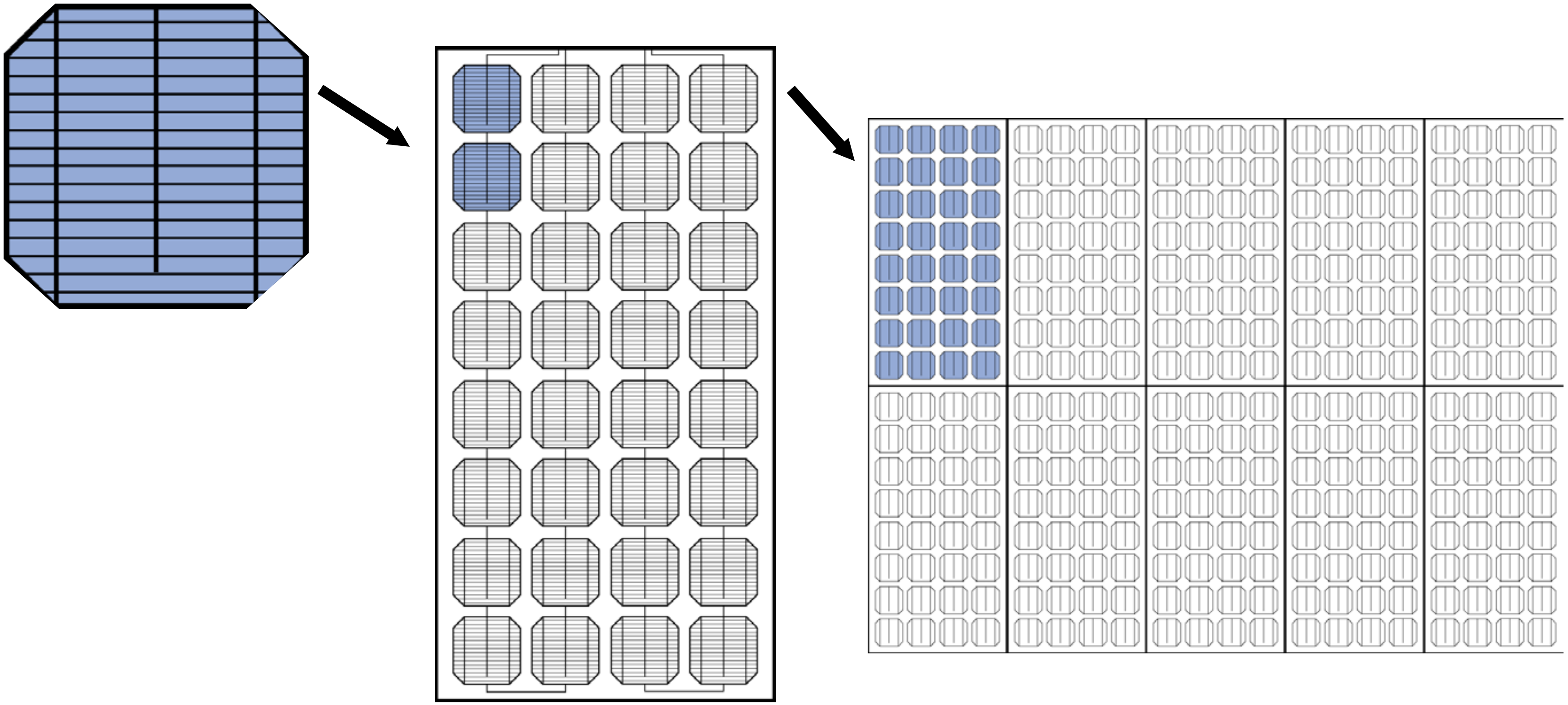
PV Cells are wired in series to increase voltage…



and in parallel to increase current



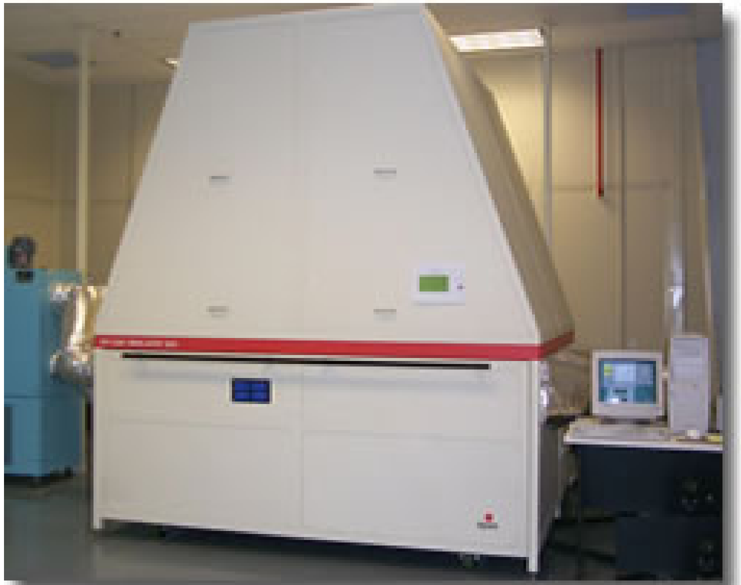
PV is ***Modular***



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

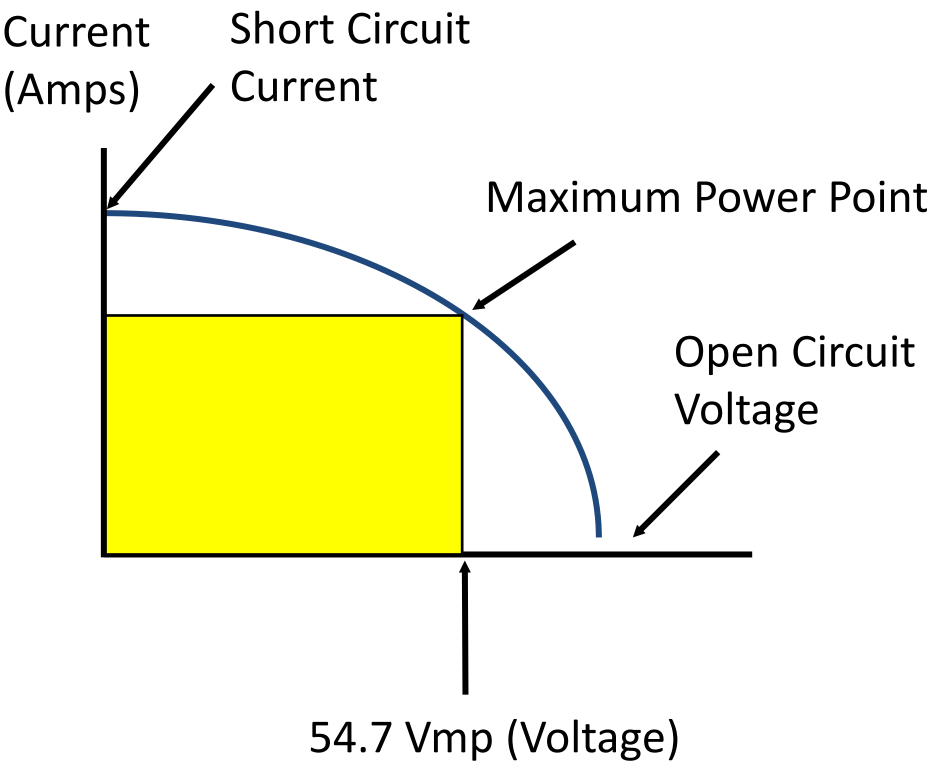
PV Module Nameplate Rating

- "Rated Power" is the output of a PV module under standard reference conditions
  - 1 kW/m^2 sunlight,
  - 25 C ambient temperature
  - 1 m/s wind speed.

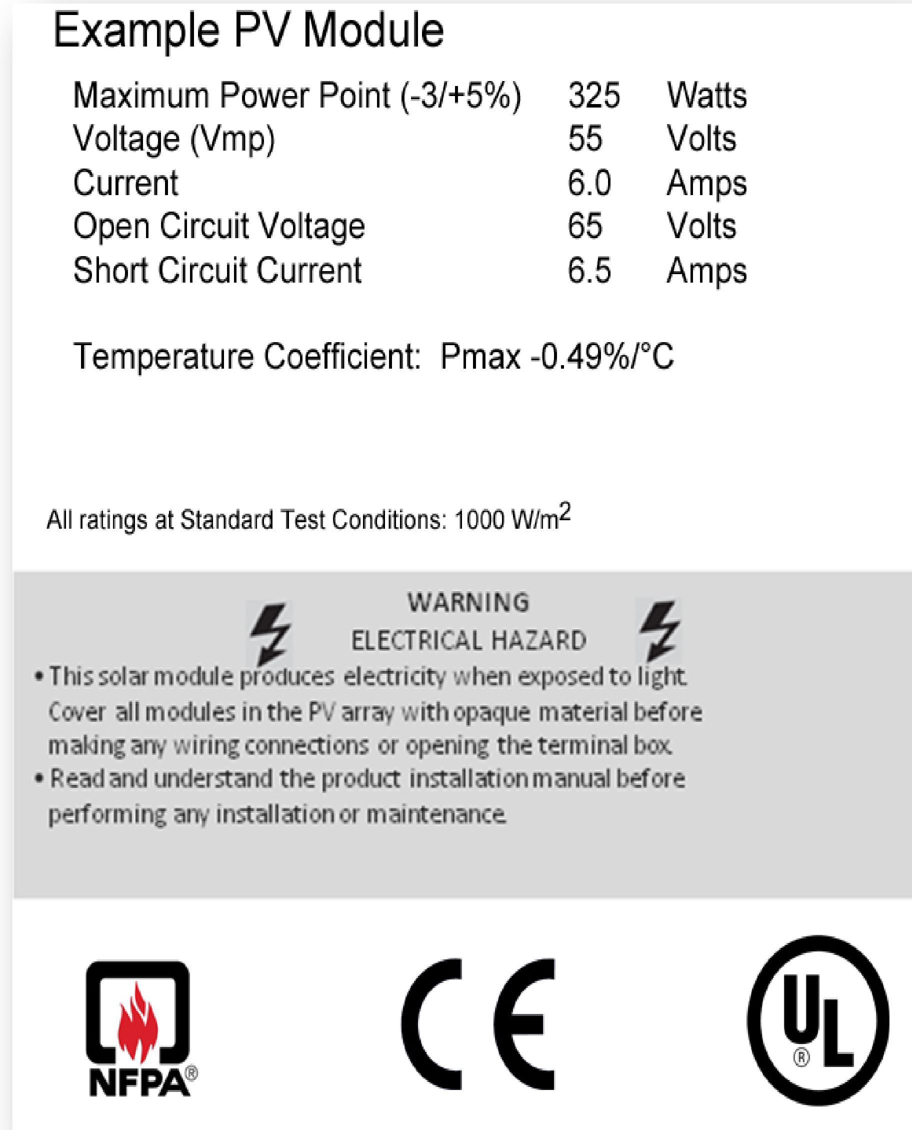


ASTM E1036-96, Standard Test Method for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells

Module Performance: I-V Curve and Nameplate



Optimal voltage changes with sunlight and temperature

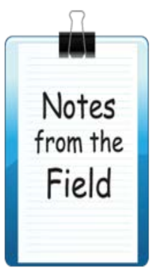


Environmental Effects on Performance

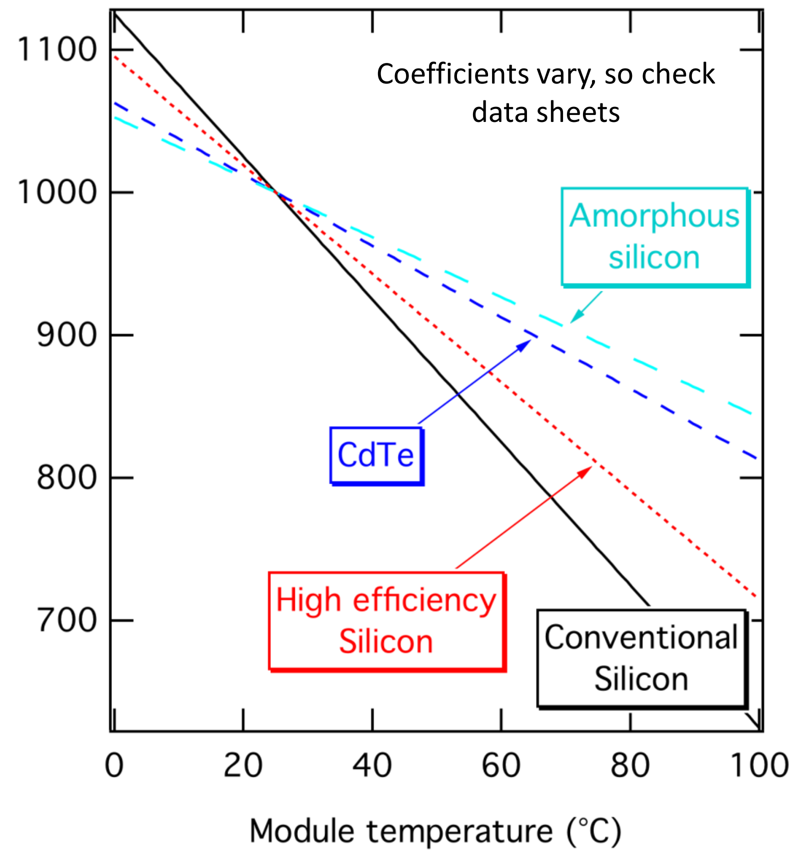
- PV performance depends on:
  - Irradiance (amount of sunshine)
  - Temperature (ambient and module)
  - Spectrum of sunshine
  - Angle of incidence

- Standard Test Conditions (STC) = 1000 W/m^2 and 25° C

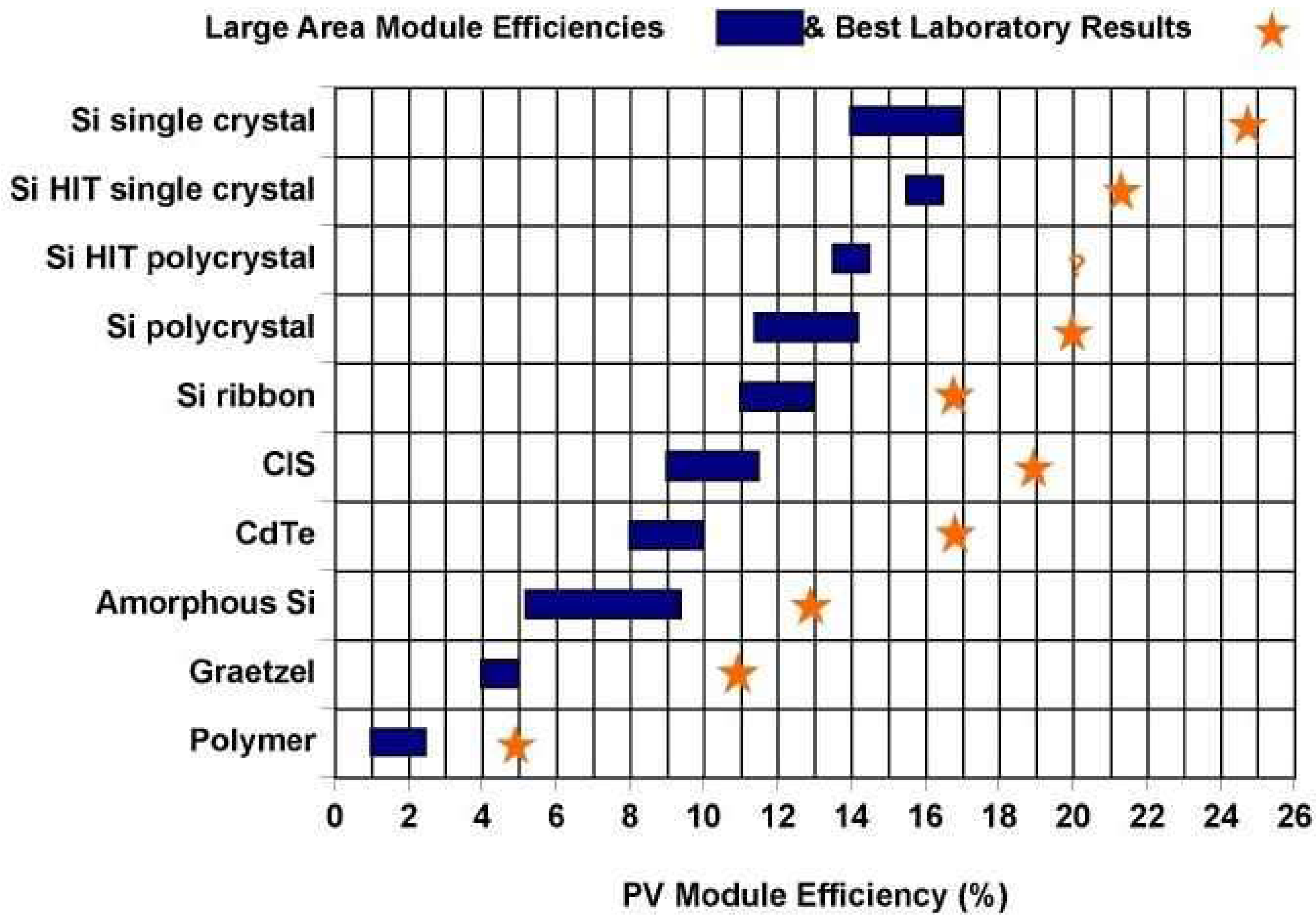
- Other factors include:
  - Shading
  - Soiling
  - System issues



PV Output vs. Temperature



Efficiencies of Different Types of PV



http://www.solarnavigator.net/solar_cells.htm

Efficiency versus Size

- Efficiency= power out/power in
- Power in = Area (m2) * 1 kW/m2
- For Example:
  - 1 kW of 15% efficient crystalline 71ft^2
  - 1 kW of 9.5 % efficient amorphous 99ft^2
  - 1 kW of 19.3% efficient hybrid 55ft^2

PV System Components (depending on type of system)

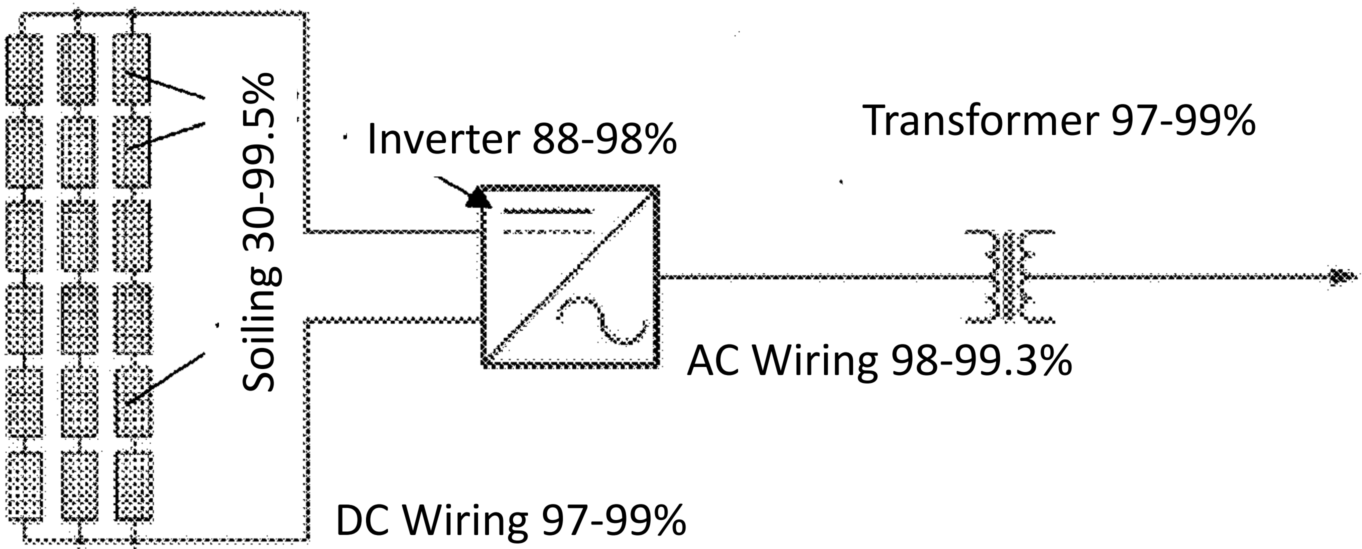
- ***PV Array*** to convert sunlight to electricity
- Array S**upport Structure** and E**nclosure** to protect other equipment
- ***Maximum Power Point Tracker*** to match load to optimal array voltage
- ***Inverter*** to convert direct current (DC) to alternating current (AC)
- Wiring, combiner boxes, fuses and disconnects
- ***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
- Automatic generator starter/stopper to start a generator when battery is too low

Balance of System Efficiency 60-82%

Module Efficiency 6-20%

Diodes and Connections 99-99.7%

I and V Mismatch 97-99.7%



Inverter

Xantrex PV150 Inverter, Tuscon Electric Power

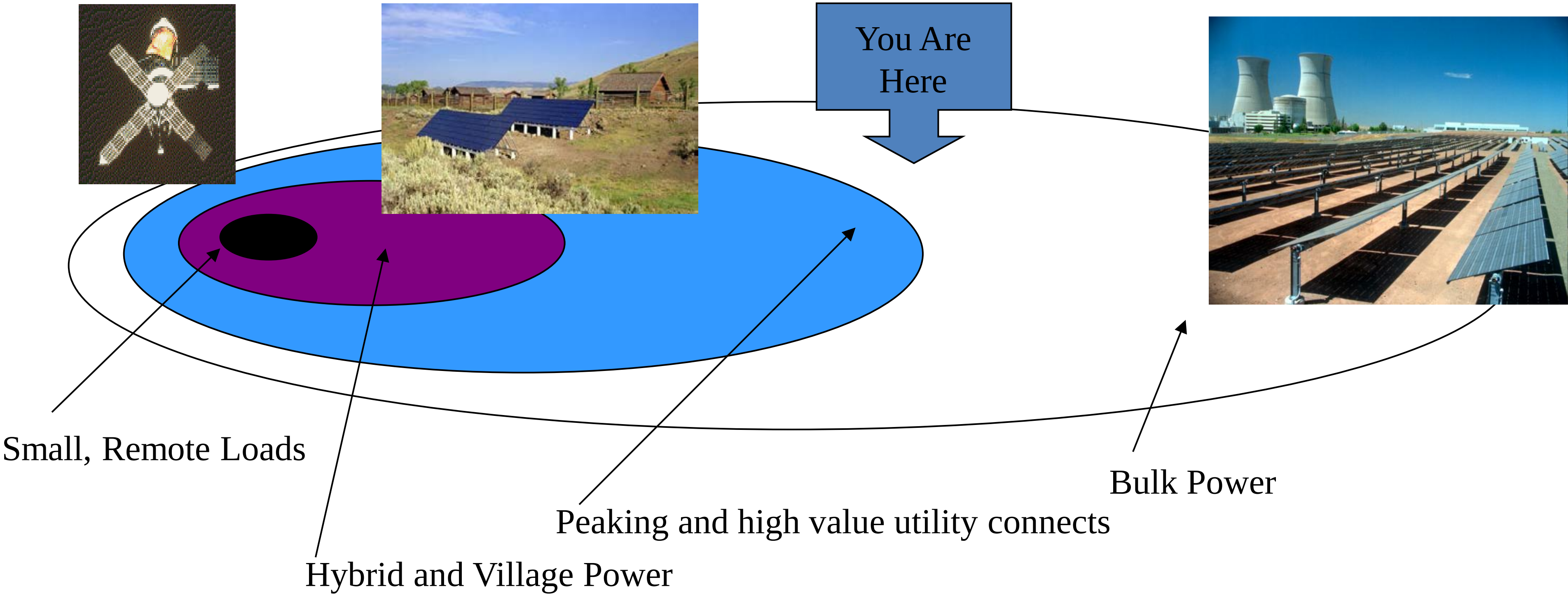
Manufacturers:

Advanced Energy
Diehls AKO Stiftung & Co.
Elettronica Santerno
Fronius International Gmbh
GE Energy
Ingeteam
KACO
Kostal Industrie Elektrik
Mitsubishi Electric
Power-One
Refu Elektronik
Satcon
Siemens
SMA Technology AG
Sputnik
Schneider (Xantrex)

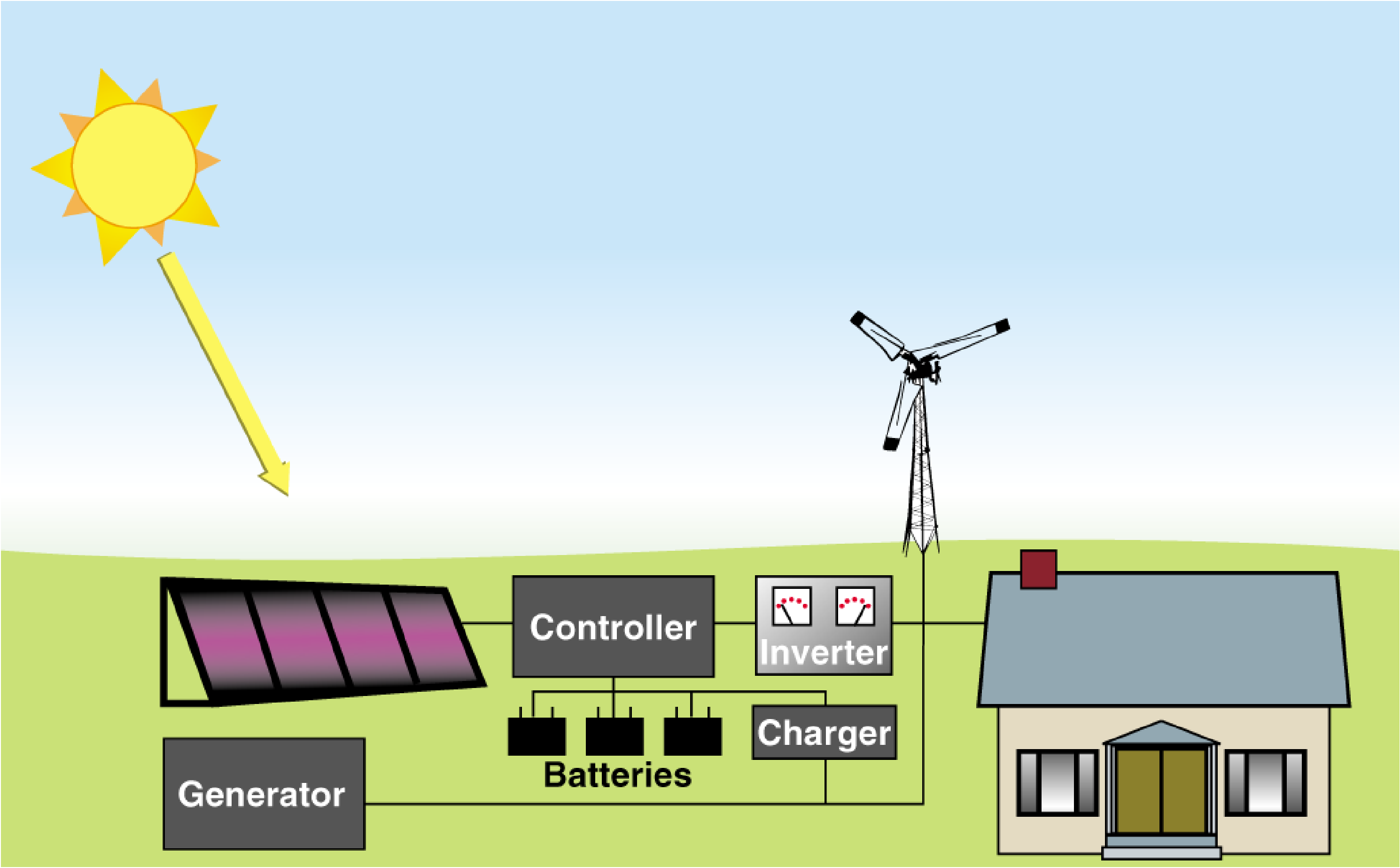
Converts Direct Current (DC) to Alternating Current (AC)

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.



Hybrid PV/Generator System



PV/Propane Hybrid Example: Joshua Tree National Park

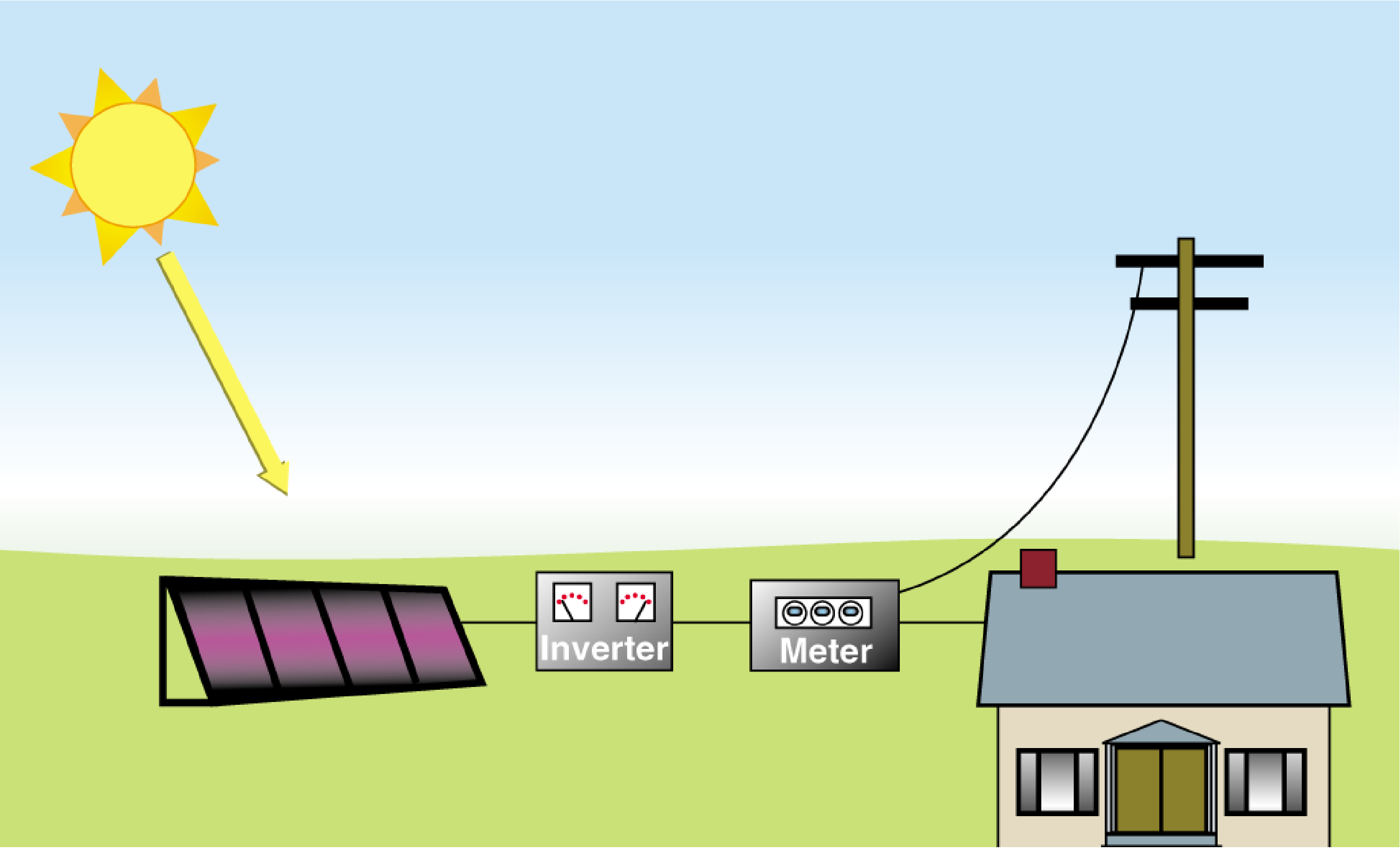
20.5 kW PV Array

613 kWh battery bank

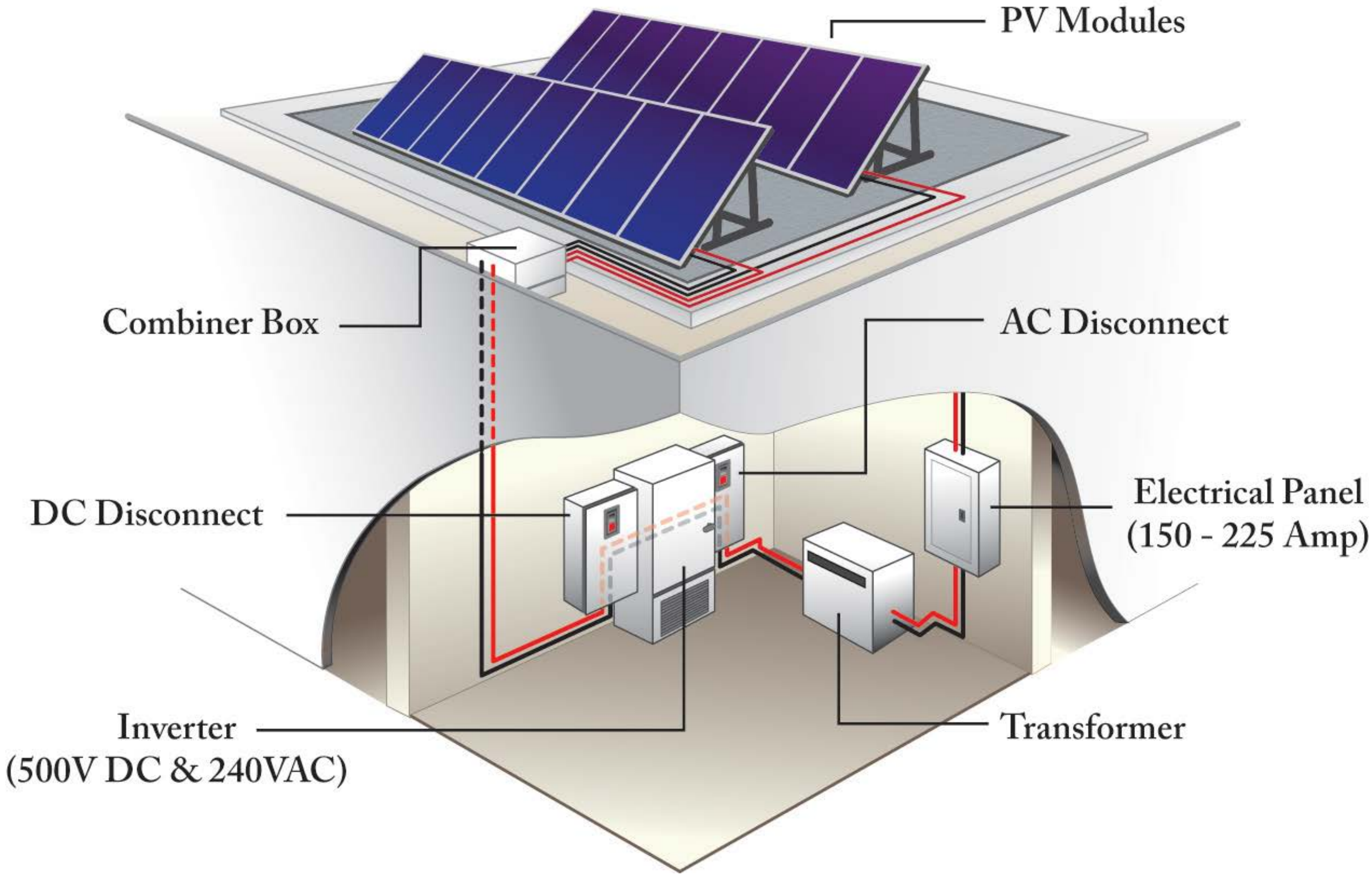
35 kW propane generator

$273,000 cost financed by Southern California Edison under 15 year tariff

Utility-Connected (Line-Tie) PV System



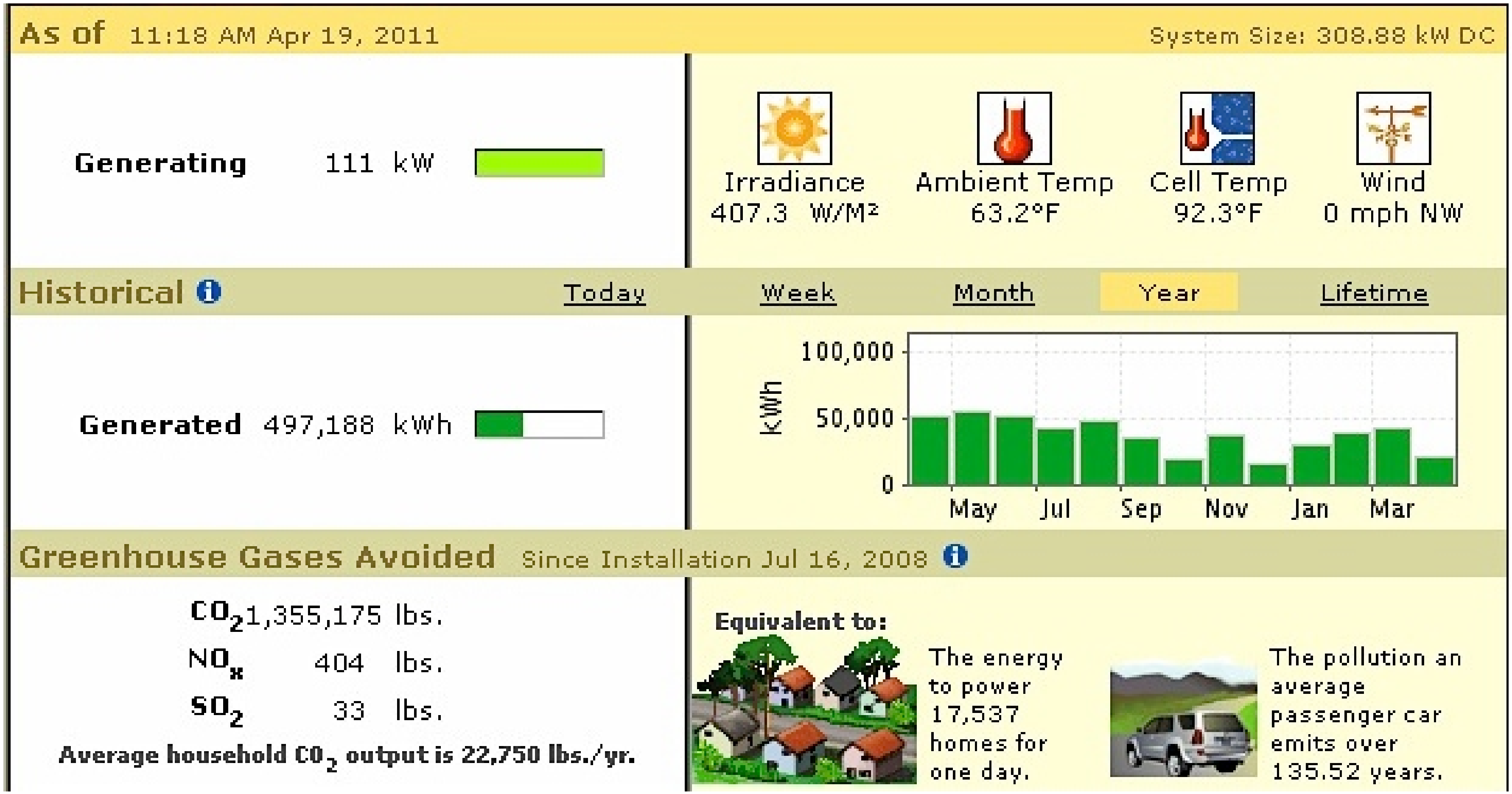
Photovoltaics System (grid connected)



Veterans Administration
Jerry L. Pettis Memorial Medical Center
Loma Linda, CA

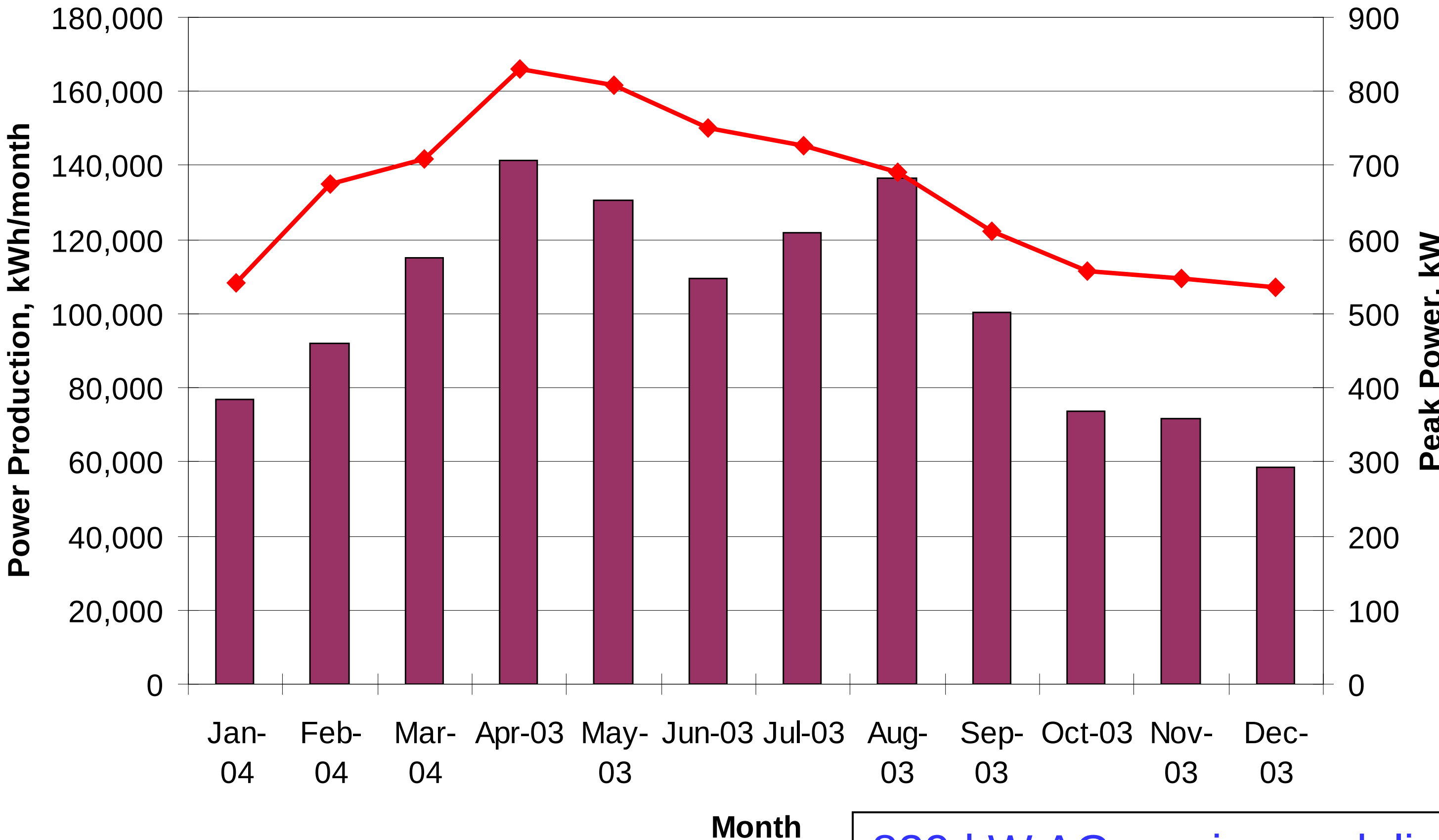
309 kWdc
1,584 Sanyo 195-watt PV modules
SunLink racks minimum roof penetration.
Advanced Energy Solaron 333kW inverter
Feasibility Study by NREL estimates:475 MWh/year delivery; $60k/year savings; $2.9million cost without any incentives
Procured off GSA Schedule for complete PV systems.

Veterans Administration
Jerry L. Pettis Memorial Medical Center
Loma Linda, CA



Example: Coronado Island CA
924 kW, cost $7.7 million

Coronado Island CA
PV System Performance



829 kW AC maximum delivery

1,228,658 kWh/year delivery

Alamosa Photovoltaic (PV) Solar Plant

8.2 MW-dc
80 acres of land near an utility substation in Alamosa, Colorado. Provide Xcel with Solar Renewable Energy Credits (SRECs) to meet Colorado`s Renewable Energy Portfolio Standard (RPS)
financed, built and maintained by SunEdison, under a Solar Power Services Agreement (SPSA) 20 years.
Three types of solar technologies:

- Single axis tracking array
- Fixed-mount array
- 1 MW of dual axis tracking array with photovoltaic concentrator technology

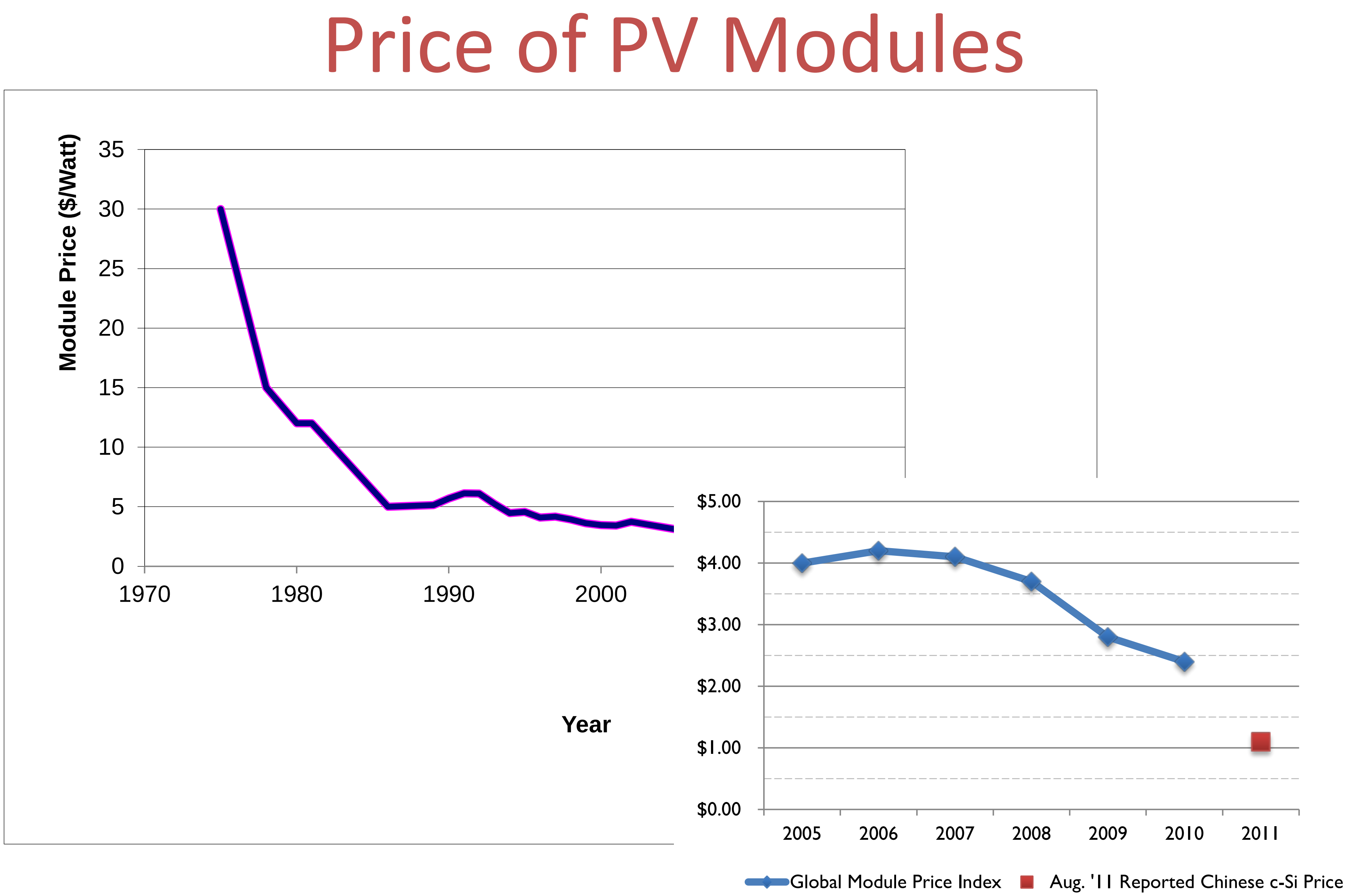
Site identified by NREL
Project constructed by 70 tradesmen.
Maintained by 2 full-time employees.
Black and Veatch performed due diligence:

review of the project participants,
assessment of the adequacy of the site,
a technology and design review,
evaluation of the status of permitting,
review of project agreements,
evaluation of project and performance estimates.

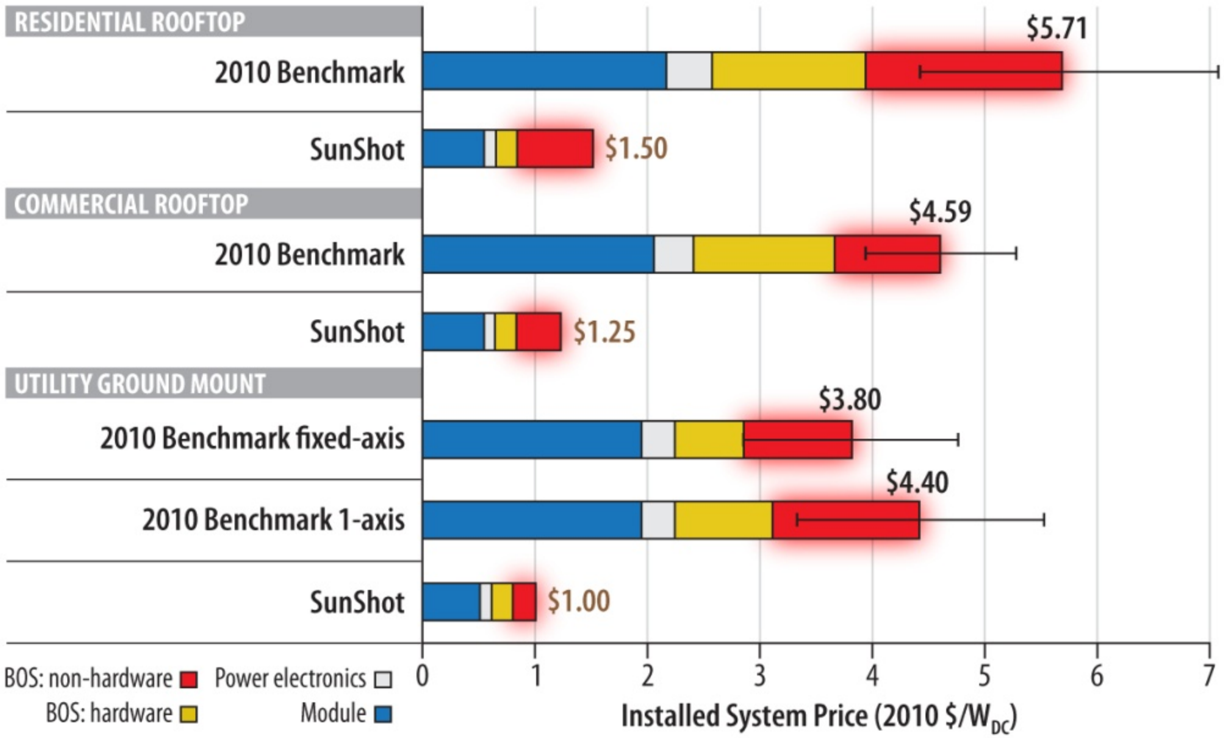
Operating since April 2007


GT500E Grid Tie Inverter

Figure 2: PV Module Price Declines



PV Cost, O&M, and Efficiency



PV System Type	Annual O&M Cost as a Percentage of Installed Cost
Ground Mounted - Fixed	0.17%
Ground Mounted - Tracking	0.35%

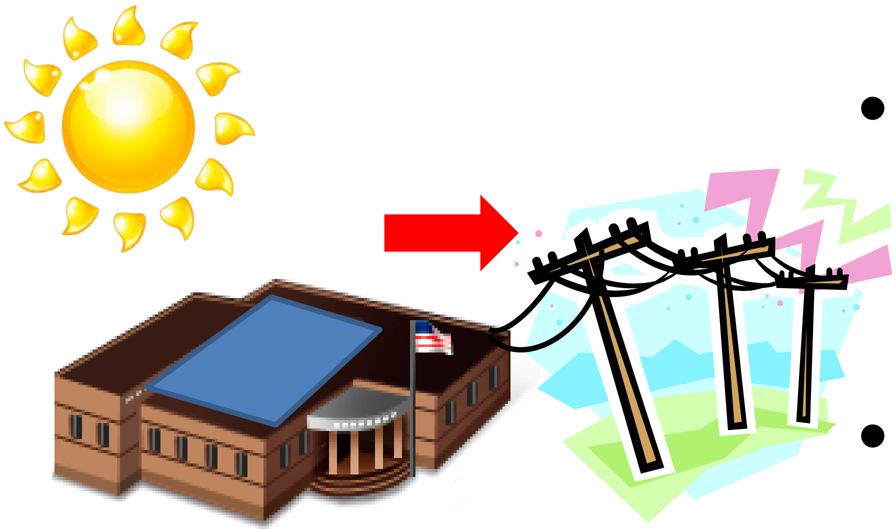
Efficiency= power out/power in

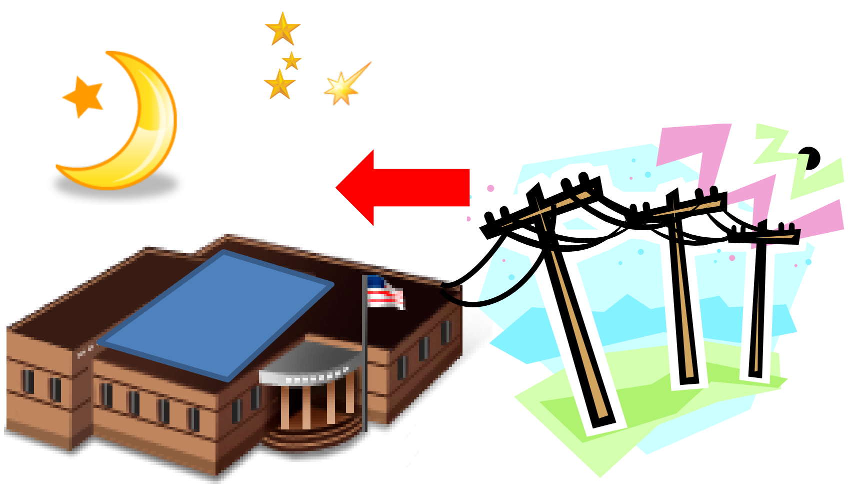
Module Efficiencies	Single Crystal	14-19%
	Multi Crystal	13-17%
	Thin Film	6-11%
Balance of System Efficiency		77%

Efficiency versus Size

– 1 kW of 15% eff. crystalline 71ft^2
– 1 kW of 9.5 % eff. amorphous 99ft^2
– 1 kW of 19.3% eff. hybrid 55ft^2

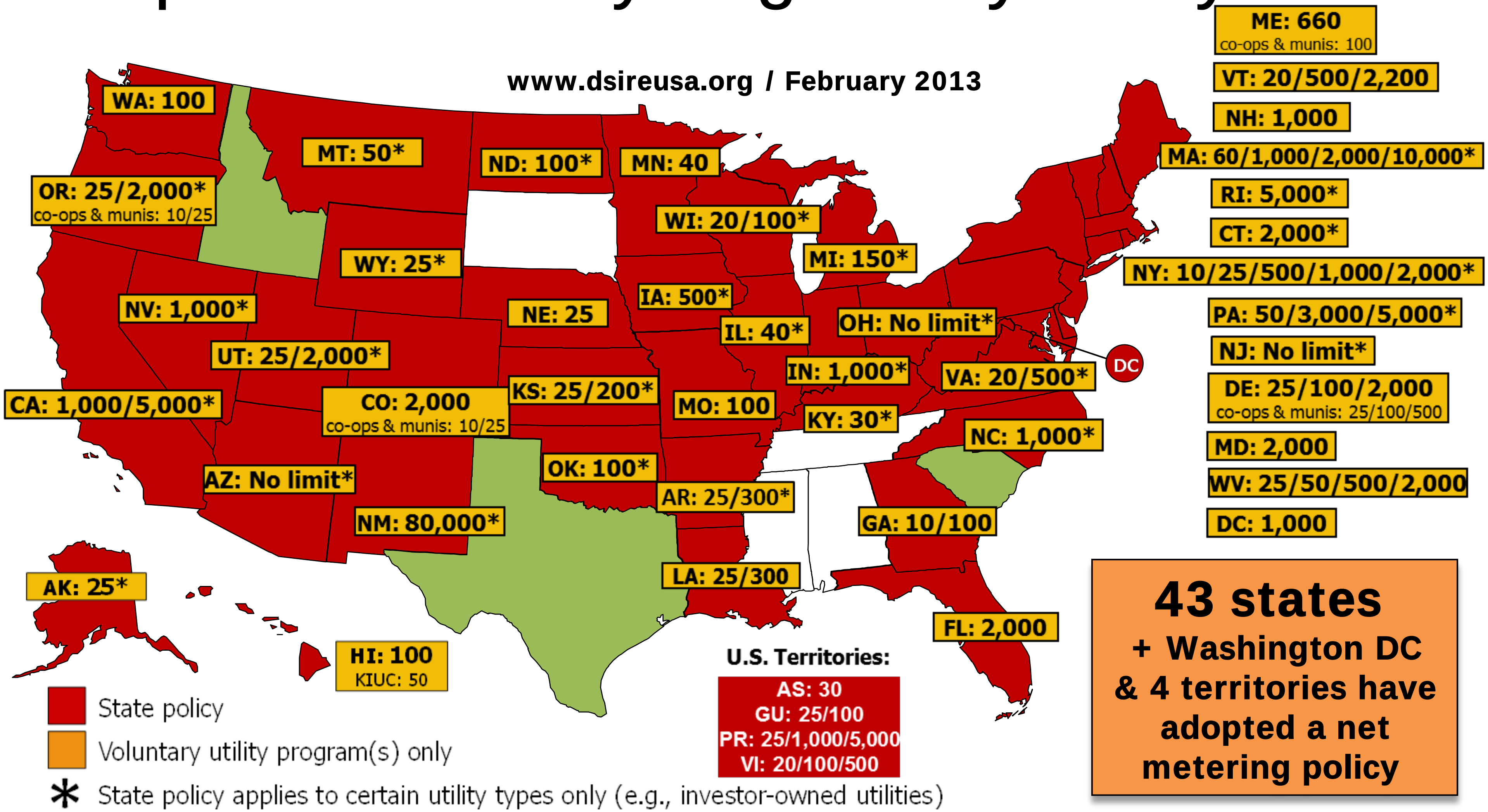
“Net Metering”





- Solar Power in excess of the Load flows TO Utility
- Load in excess of Solar Power flows FROM Utility
- Utility Bill is calculated on the “net” difference between the two on a monthly or yearly basis

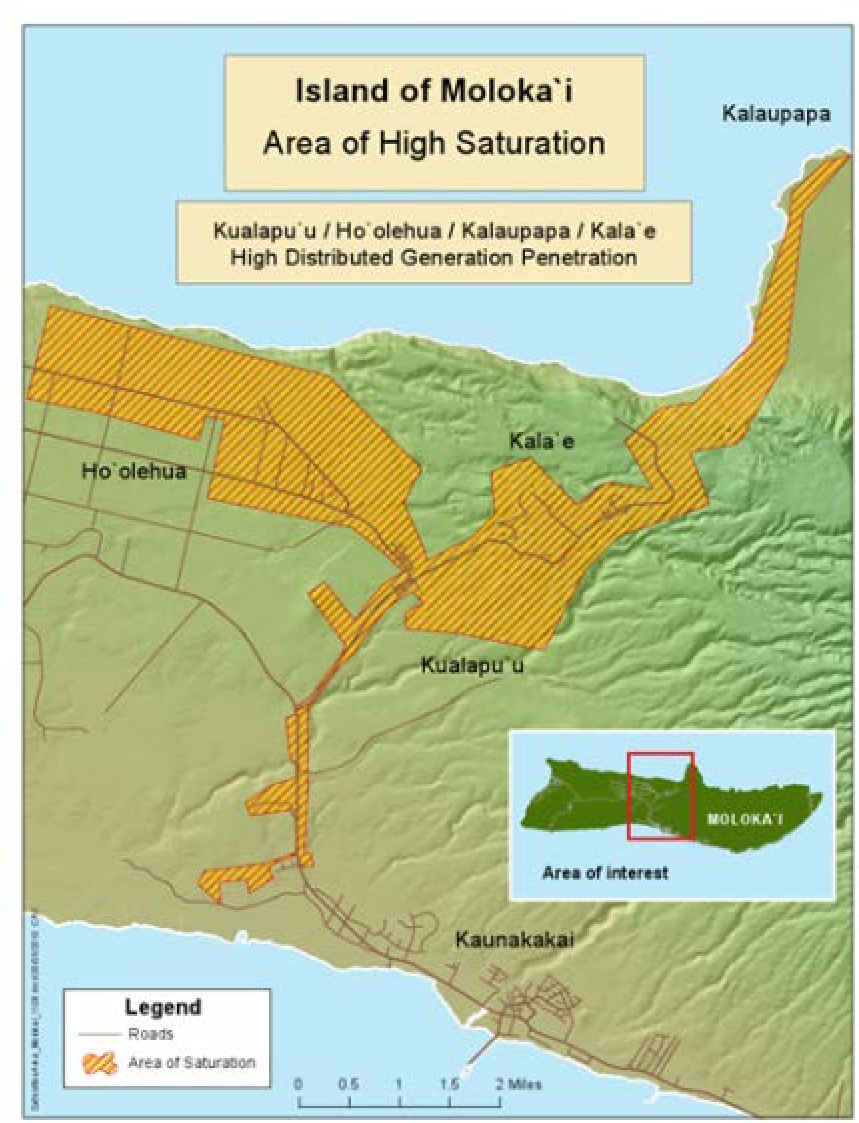
Net Metering in an *Incentive* for solar power in Utility Regulatory Policy



43 states + Washington DC & 4 territories have adopted a net metering policy

Note: Numbers indicate individual system capacity limit in kilowatts. Some limits vary by customer type, technology and/or application. Other limits might also apply. This map generally does not address statutory changes until administrative rules have been adopted to implement such changes.

Limits of "Net Metering"



- Problems with Net Metering
  - Limits to Fuel Savings (spinning reserve)
  - Doesn't save any other utility operating costs
  - RE may be curtailed; limits on installations (eg 15% in HI)
  - Socio-economic problem: foists utility costs on those least able to afford it.
- Utility Cost Recovery
  - Retail/buy-back spread (c/kWh)
  - Stand-by Charges ($/kW/month)

PV/Grid Interaction

Factors to consider when integrating renewables into the traditional electricity grid?

–Solar power is a highly variable resource on short time scales which can affect grid stability at high penetration

–Need to consider flexibility of grid to absorb this variability

–Need even more spinning reserve

Options for managing the variability of renewable energy production?

–Reconfigure utility circuits

--Tracking solar mounts

–Plan to meet, not exceed, site load

–Load shifting-short time scale and day ahead

–Transmission-spatial diversity and power balancing

–Energy storage

–Curtailment of RE

Levels of renewable generation that affect grid stability?

–Site specific study: depends on flexibility of generation assets, transmission system and load

–10% of PV generally seen as insignificant impact on minimum load

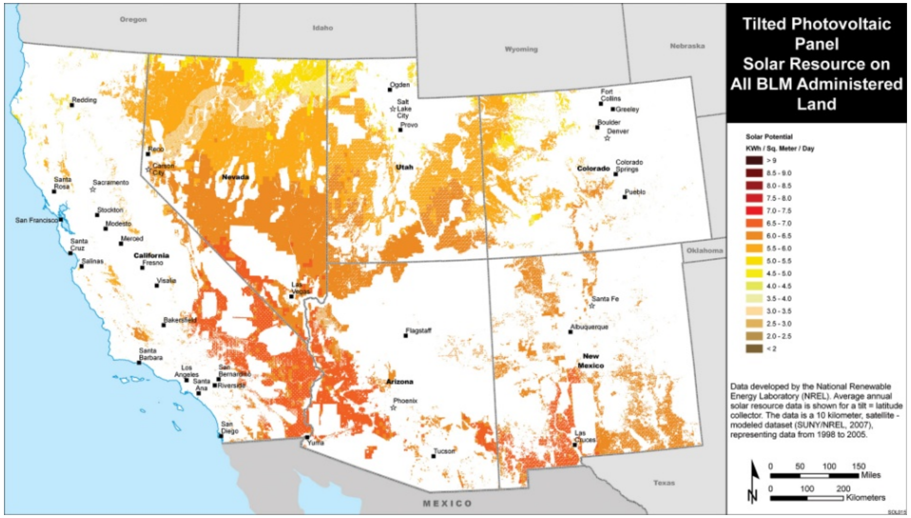
–Regional Energy Deployment System (ReEDS) type model for planning expansion of electric generation & transmission capacity (http://www.nrel.gov/analysis/reeds/)

PV Deployment Issues

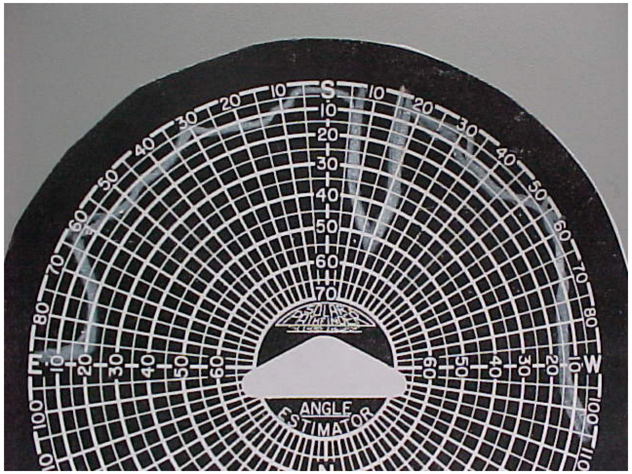
- Solar Resource
- Land
- Water
- Transmission Access/Interconnection
- Road Access
- Environmental requirements
- Financial Aspects

PV Deployment Issues

- Solar Resource
  - 6.0 kWh/m^2-day or higher
    - Global Solar for Flat Plate PV
    - Direct Normal Insolation for Concentrating PV
  - Increasing solar resource assessments
    - Install pyrometer, temperature, and wind anemometer for 1 year data collection prior to financing



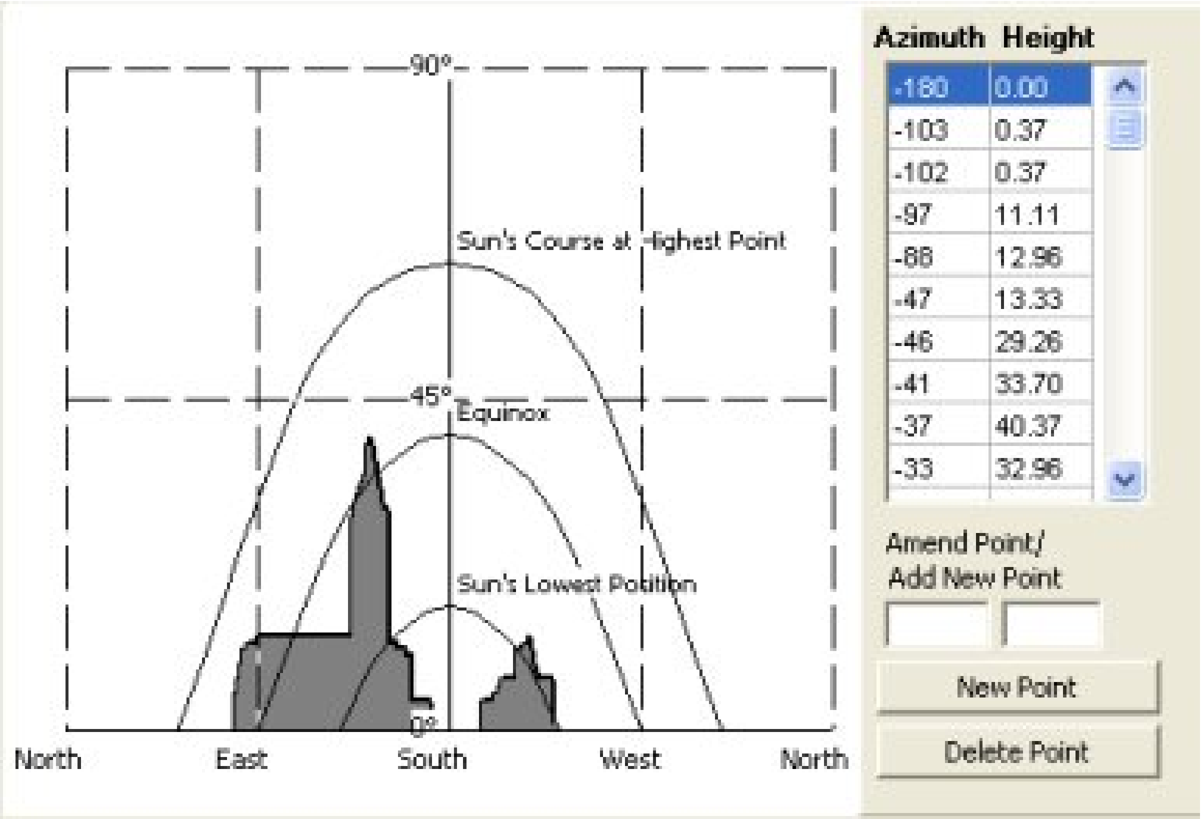
Shading: horizon profile



Solar Pathfinder

Solmetric Suneye

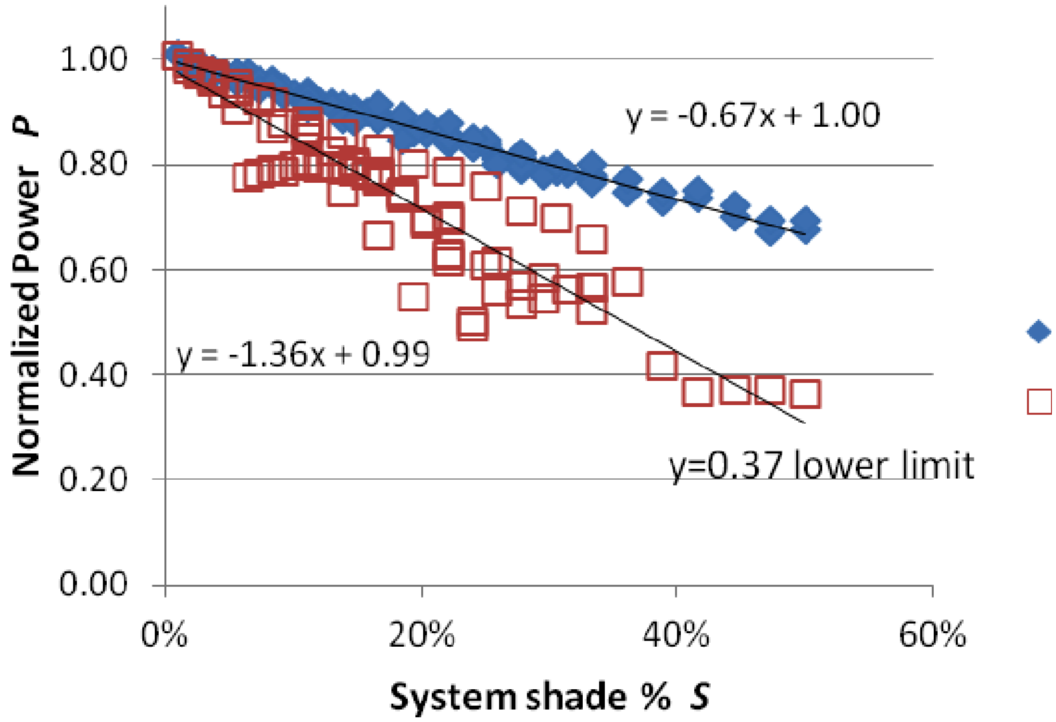
Shading Analysis



SolarDesignPro

Shading Effects on Performance

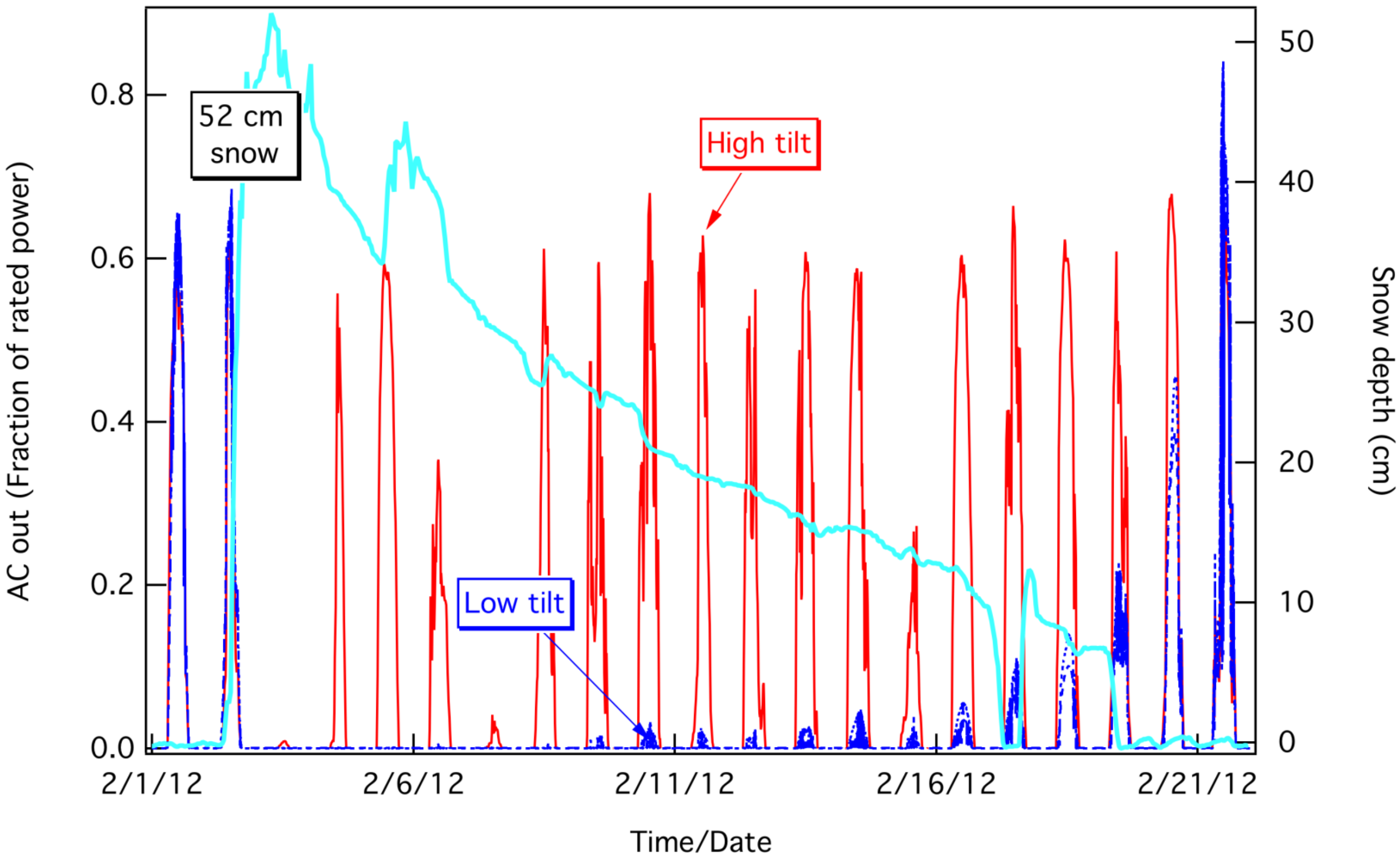
- Losses may be mitigated by using module-level electronics
- Small amount of shade = large decrease in output

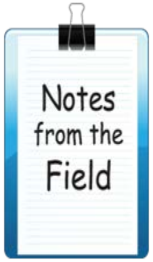


Blue: Individual Inverter on each Module

Red: Central inverter on string of modules

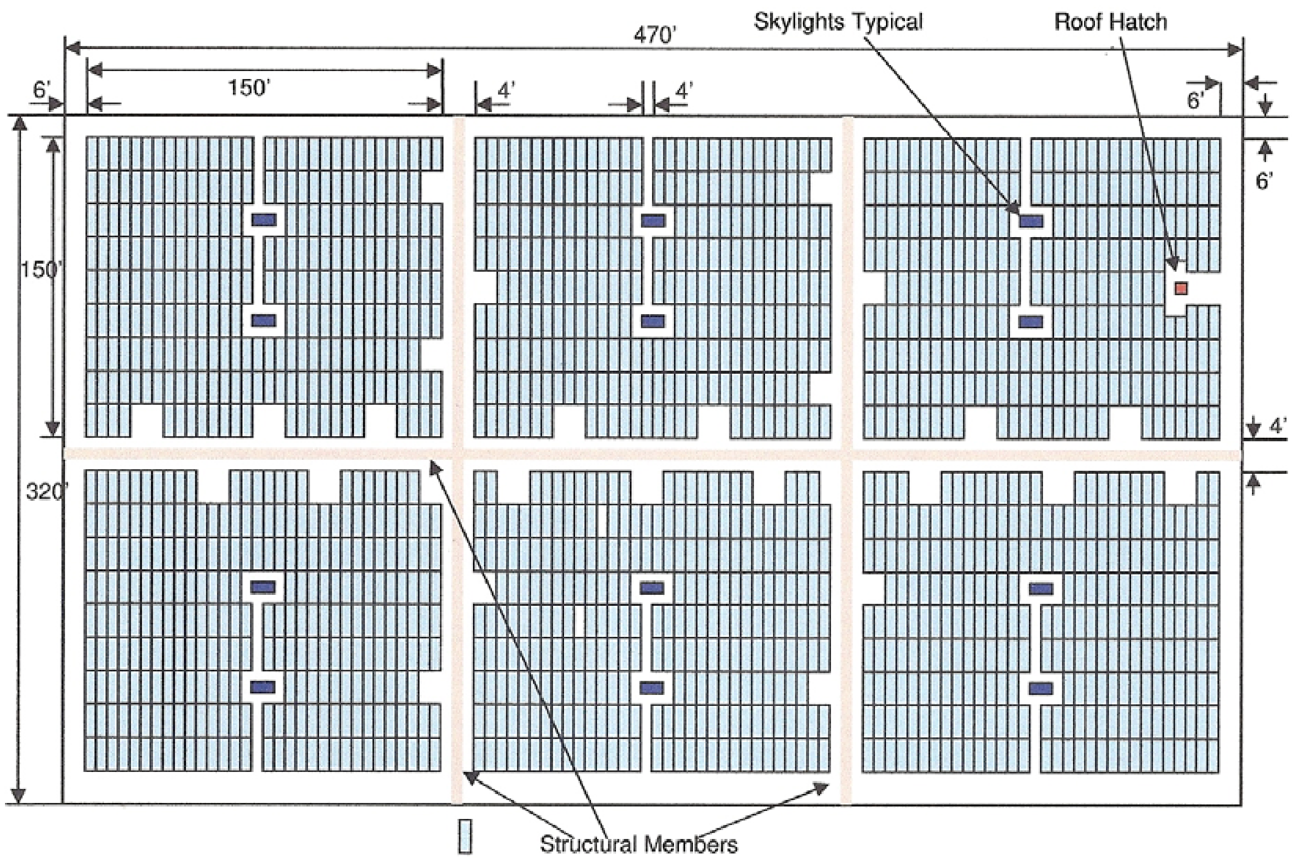
Snow Effects on Performance





PV Deployment Issues

Site Feasibility: Rooftop Layout

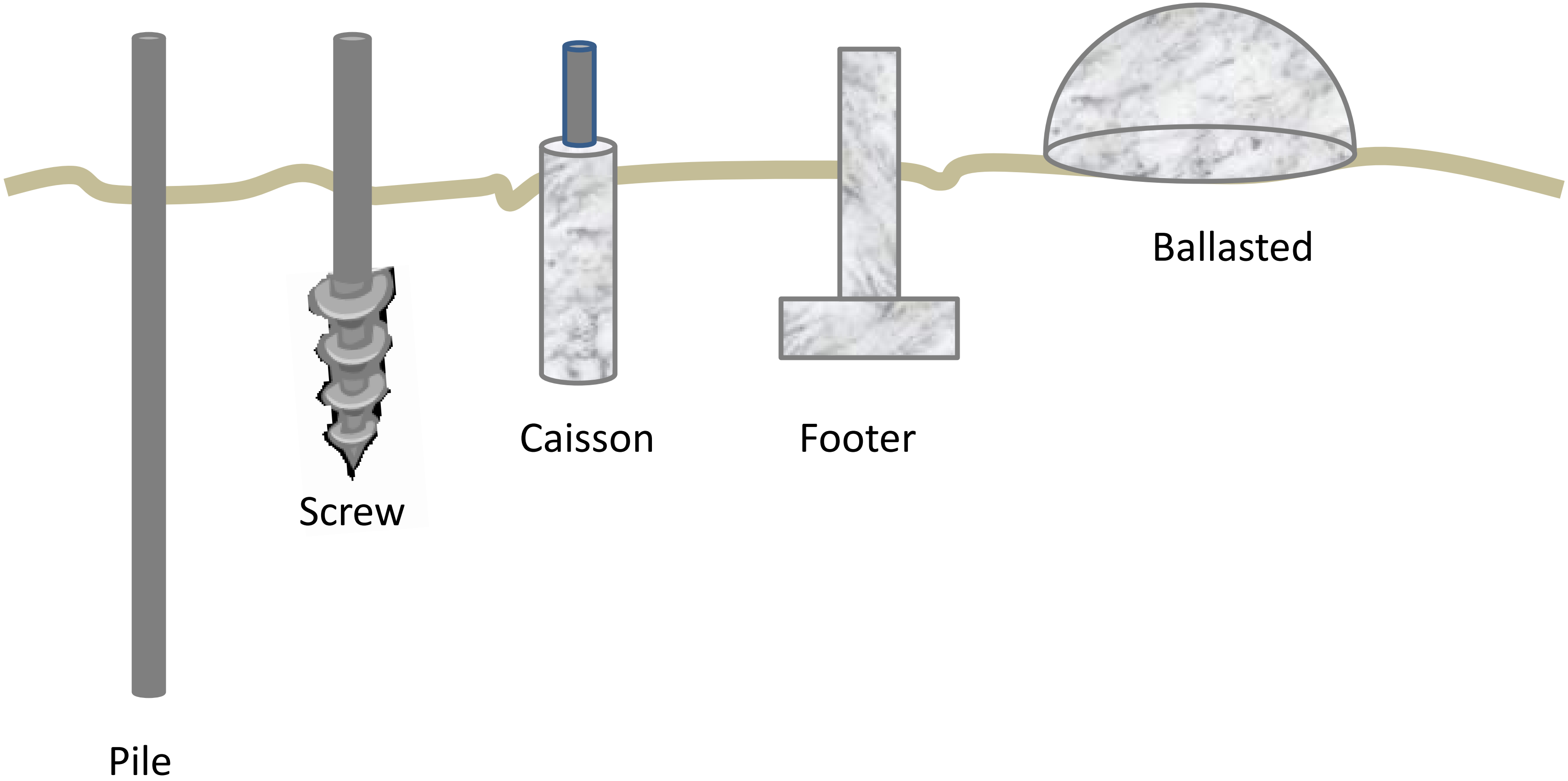


Large Commercial Building (Axis > 250 ft)
4 ft Walkways
8 ft x 4 ft Lay-Down and Venting Opportunities Every 20 ft Along Walkway

PV Deployment Issues

- Land
  - 5 to 10 Acres per MW (average over 6)
    - Row spacing or array spacing varies for fixed flat plate and Concentrating PV
      - Mitigate shading
    - Increased spacing for single or dual axis tracking
  - Slope
    - Ideally 1%, 3% feasible for flat plate fixed
    - Higher slope up to 5% for pole mounted

Ground-Mounted Systems



PV Deployment Issues

- Land
  - Site Preparation (Land disturbance variable)
    - PV can be mounted on monopoles to limit surface disturbance
    - Simple to grade for solar field
    - Systems include spacing between rows of panels/receivers for cleaning and maintenance
  - Expect wind monitoring for tall PV systems

PV Deployment Issues

- Water
  - Limited water use (2-5 gallons per MWh)
    - Washing down panels and receivers
    - Some installations may not need cleaning
      - Cost trade off: production versus cleaning cost
    - Water trucks with pressurized water between rows of PV panels and Receivers

PV Deployment Issues

- Transmission Access/Interconnection
  - Adjacent to existing substation is ideal
  - Distance and Access to Transmission major factor in site selection
  - Land Lease of right of entry critical for Interconnection Applications

Deployment Issues

- Road Access
  - Typical road access for any major construction project
  - Conventional sized vehicles for material delivery and construction equipment
  - On site access – paths between rows of panels/receiverss

PV Deployment Issues

- Environmental requirements
  - Site Specific
    - Threatened & Endangered Species mitigation
    - Erosion control;
    - Example: limit development in Areas of Critical Environmental Concern
    - Habitat disturbance

PV Deployment Issues

- Archeological/Cultural Resources
  – Viewshed
  – Underground artifacts, etc.
    - Surveys, investigations
    - Non-penetrating systems

PV Deployment Issues

- Financial Aspects
  - Power Purchase Agreement
  - Land rights linked w/PPA to accessing financing
  - Land Lease Costs
  - On site construction/operations personnel
  - O&M, Service Contracts, Debt Service
  - System disposition at end of PPA or useful life

Module Performance: Testing Organizations

- **ASTM - American Society for Testing and Materials.**
  >Performance Testing

- **IEC - International Electrotechnical Commission.**
  >Compliance and Performance Testing

- **IEEE - Institute of Electrical and Electronic Engineers.**
  >Performance Testing

- **NFPA - National Fire Protection Association.**
  >National Electric Code; Fire Safety Testing

- **TUV Rheinland - European.**
  >Safety Certification

- **UL - Underwriters Laboratories.**
  >Safety Certification

- **CE - European Conformity.**
  >Performance Certification

- **CSPC – Consumer Product Safety Commission.**
  >Safety certification.

Other Requirements

- Building codes - UBC, SBC, BOCA, local codes
- Local covenants regarding appearance
- National Historic Preservation Act

PV Operation and Maintenance

- Cleaning
  - Most rely on rain to keep the array clean.
  - Cleaning in Sacramento improved output by 6%
  - Depend on local sources of dirt (diesel soot, dust, construction, etc)
- Annual inspection: tighten all electrical connections, remove any insect nests from boxes, clean any persistent soiling from PV array.
- Unscheduled maintenance includes inverter replacement (most have 10 year warranty), replacement of boxes that have rusted (recommend plastic boxes), and repair of damage caused by theft, vandalism or animals that have gotten into enclosures.

PV Operation and Maintenance

Table II. Maintenance cost as a percentage of capital investment

Year	Scheduled (%)	Unscheduled (%)	Total (%)
2002	0 08	0 01	0 09
2003	0 07	0 22	0 29
2004	0 06	0 04	0 10
2005	0 06	0 01	0 07
2006	0 04	0 03	0 07

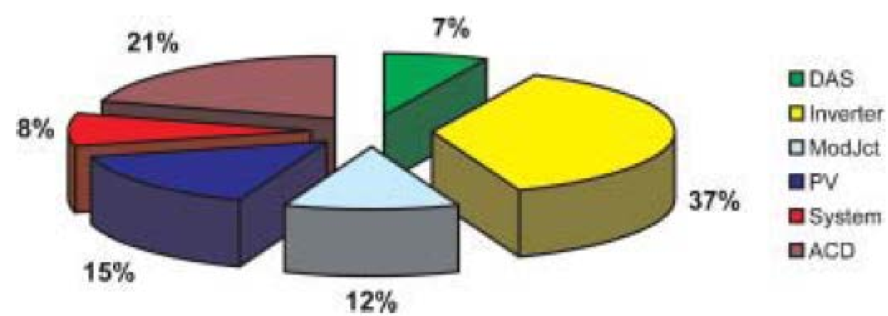


Figure 7. Unscheduled maintenance events by component

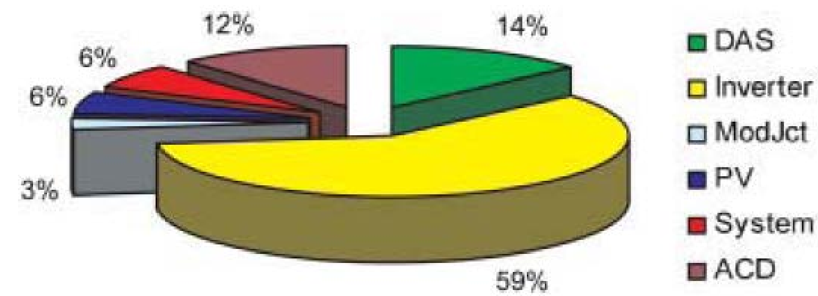


Figure 8. Unscheduled maintenance costs by category

Tuscon Electric Power Data PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2008; 16:249–259
Published online 3 December 2007 in Wiley InterScience (www.interscience.wiley.com) DOI: 10.1002/pip.800

Operation and Maintenance, cont.

- Another estimate estimates Operation and Maintenance of PV systems at $40/kW, including inverter replacement [Tracking the Sun II", Lawence Berkeley National Laboratory, October 2009]

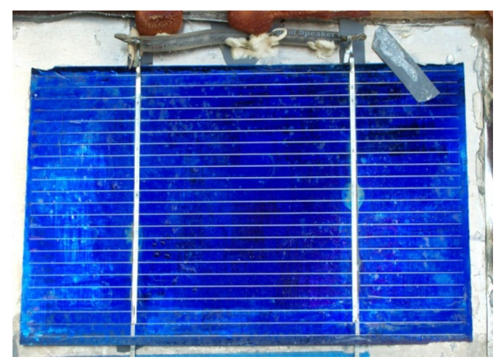
Degradation over time

Modules degrade slowly, but some defects can cause immediate performance reductions. These include:

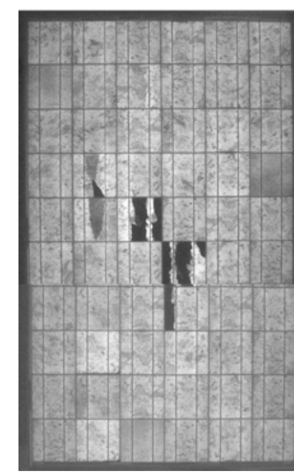
- Thermal Fatigue
- Discoloration
- Cracking

Thermal Fatigue

Reference: Degraff presentation

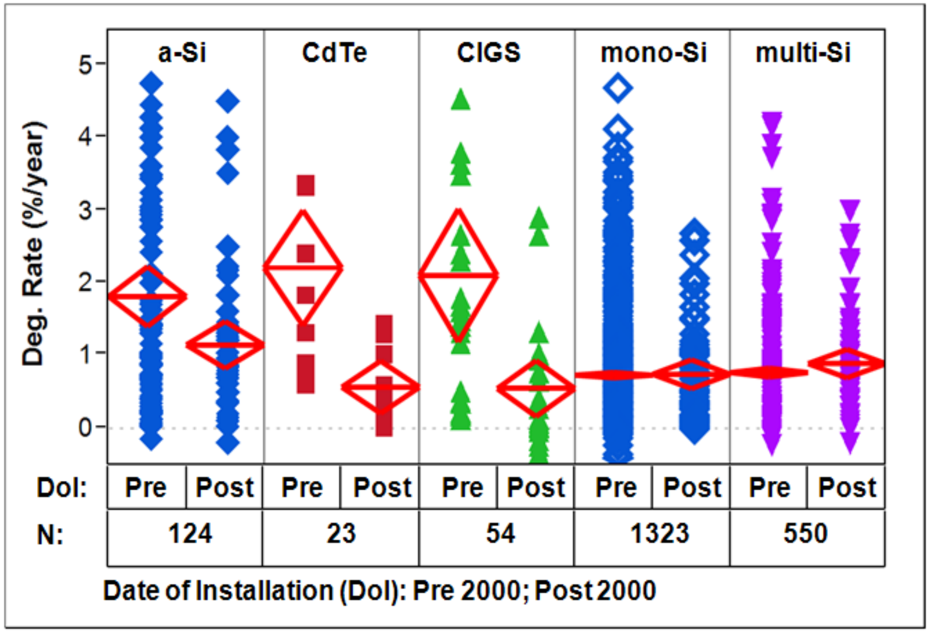


Discoloration



Cracking

Module Degradation



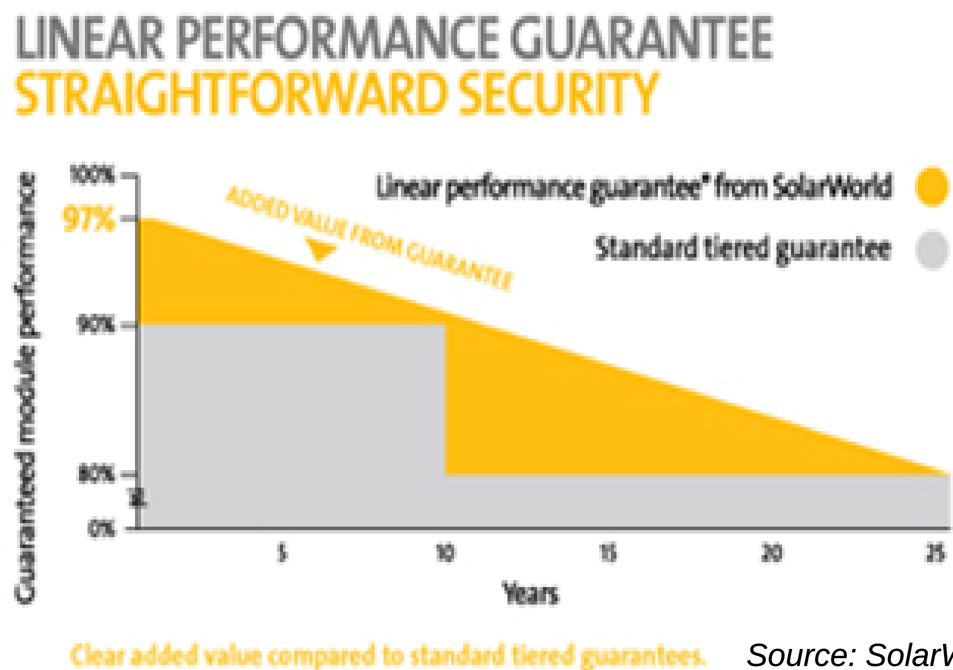
Reference: Dirk Jordan Prog. In PV, WREF, Euro PVSEC

- Modules degrade slowly with time
- A median degradation rate of 0.5%/year implies 90% of original after 20 years.
- Modules showing more than 1% per year degradation will fail most warranties

Types of Warranties

Stepped Warranty
- •90% power warranty for 12 years
- •80% power warranty for 25 years.

Linear Warranty
- •Starts at 97% in year one
- •Maximum annual degradation rate is ~ 0.5% to 0.7%/year



Source: SolarWorld

PV Acceptance Testing

- Standard Test Procedures:
  - IEC 62446-Commissioning grid tied PV systems (an IEC standard that covers commissioning of grid tied PV systems)
- Acceptance testing: Depends on contractual agreements
  - Power Purchase Agreement (PPA)--$/kWh delivered: No real acceptance testing needed since paying only for kWh delivered.
  - PPA with stipulation of minimum kWh/yr delivered: No real acceptance testing needed (could be based on actual measured solar data or some minimum that is a percentage of modeled production using TMY weather).
  - Purchase of plant: could be based on actual measured solar data

Due Diligence for PV Plants

- Legal due diligence: real property, utility agreements, operating, maintenance and insurance contracts.
- Tax due diligence: income tax, trade tax, value added tax, tax on dividends, real property tax and land transfer tax, tax incentives and depreciations.
- Technical due diligence: yield forecast, plant layout, module orientation, ground survey, specification of components, order placement, installation, quality management, guarantees and warranties, theft and vandalism protection, maintenance and land management.
- Financial due diligence: required investment, property cost and future value, revenues from solar delivery, operation and maintenance costs, reserves, insurance, bonding, costs for disposition of the plant after the end of its life span, taxes, debt service, profitability.

PV Financing Issues

- Challenges:
  - Market tight after recent financial crisis, tax equity investors have no tax liability following losses
  - Uncertainty about subsidies
  - Availability of cheaper renewable sources, such as wind
- Strategic investors and private equity companies providing financing
- PV module and CSP construction costs continue to decline
- Cost-based feed-in tariffs remove revenue risk for investors
- Climate legislation makes coal more expensive
- Removal of subsidies for fossil fuel

PV Analysis Tools

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 Perform
- 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
- SAM

Resources

- Solar Energy Resources
  - NREL http://www.nrel.gov/rredc/
  - Firstlook: http://firstlook.3tiergroup.com/
  - TMY or Weather Data
    http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

- State and Utility Incentives and Utility Policies
  - http://www.dsireusa.org

- Solar PV Analytical Tools
  - Solar Advisor Model (SAM): https://www.nrel.gov/analysis/sam/
  - HOMER: https://analysis.nrel.gov/homer/
  - PVWatts: http://www.nrel.gov/rredc/pvwatts/
  - RETScreen: http://www.retscreen.net/
  - IMBY: http://www.nrel.gov/eis/imby/