Solar Energy – Capturing and Using Power and Heat from the Sun

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NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC
Topics

• Solar Resource Overview

• Solar Hot Water Systems

• Solar Photovoltaic Systems

• Concentrating Solar Power Systems
Clear Sky

Solar Irradiance Measurements
Golden, Colorado 9 April 2003

- Direct (Beam)
- Global (Total)
- Diffuse (Sky)

Irradiance [Watts/sq meter]

Mountain Standard Time

0 200 400 600 800 1000
5:00 6:00 7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Partly Cloudy Sky

Solar Irradiance Measurements
Golden, Colorado 3 July 2004
The Renewable Resource Data Center (RReDC) provides access to an extensive collection of renewable energy resource data, maps, and tools. Biomass, geothermal, solar, and wind resource data for locations throughout the United States can be found through the RReDC.

Almost every area of the country can take advantage of renewable energy technologies, but some technologies are better suited for particular areas than others. Knowing the resources of a region, state, city, or neighborhood is therefore critical to renewable energy planning and siting.

RReDC provides detailed resource information through tools, reports, maps, and data collections. Additional resource data can be found on the NREL Dynamic Maps, GIS Data, and Analysis Tools Web site.

The Renewable Resource Data Center is maintained by NREL's Electricity, Resources, and Building Systems Integration Center.

Learn more about your solar resource by exploring these Web sites:
- SMARTS
- PV Watts
- NREL Measurement and Instrumentation Data Center
- NREL Solar Radiation Research.
Topics

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- Solar Photovoltaic Systems

- Concentrating Solar Power Systems
Building Hot Water Energy Use
average 125 kbtu/sf/year

Energy for Water Heating
kBtu/sf/year

Office 8.7
Mercantile 5.1
Education 17.4
Health Care 63.0
Lodging 51.4
Pub Assembly 17.5
Food Service 27.5
Warehouse 2.0
Food sales 9.1
Public Safety 23.4
Other 15.3
All Buildings 13.8
Solar Water Heating Is Not New!

Before the advent of gas pipelines and electric utilities, the technology gained footholds in Florida and California before the 1920’s.

Over 1,000,000 systems are in use in American homes and business.

The technology is in widespread use in:
- Caribbean basin
- Israel
- Japan
- China
- Greece
- Australia
Technical And Economic Viability Depends Upon

- Amount of annual sunshine
- Capital cost of the solar system
- Prices of conventional fuels
- Solar system annual O&M cost
- Annual energy requirement and energy use profile
- Temperature and amount of hot water (kWh produced)
- Rate at which conventional fuels are escalating in price
- Other (e.g. legislative mandates, tax credits)
Solar Thermal Applications

Low Temperature (> 30C)
  – Swimming pool heating
  – Ventilation air preheating

Medium Temperature (30C – 100C)
  – Domestic water and space heating
  – Commercial cafeterias, laundries, hotels
  – Industrial process heating

High Temperature (> 100C)
  – Industrial process heating
  – Electricity generation

Solar thermal and photovoltaics working together
Which collector is best depends on the temperature...

Efficiency = % of solar captured by collector

- Unglazed are best for ~0 to 10°C above ambient
- Flat-plate are best for ~10°C to 50°C above ambient
- Evacuated tubes are best for more than 50°C above ambient

Temperature above ambient (°C)

Solar radiation (W/m²)
Solar Rating and Certification Corp.

Contact information
Solar Rating and Certification Corporation
c/o FSEC, 1679 Clearlake Road
Cocoa, FL 32922-5703
Voice (321)638-1537
Fax (321)638-1010
E-mail: srcc@fsec.ucf.edu

- An independent nonprofit organization that tests performance and certifies almost every solar heater on the market today.
- Reports efficiency and annual performance for different climates and temperature uses.
Typical Low Temperature Application
Low Temperature Example:

Barnes Field House, Fort Huachuca, AZ

2,000 square feet of unglazed collectors
3,500 square feet indoor pool
Installed cost of $35,000
Meets 49% of pool heating load
Saves 835 million Btu/year of natural gas
Annual savings of $5,400
Installed by the Army in June, 1980.
Passive, Integral Collector Storage (ICS)

Direct System

- Moderate freeze protection (pipes at risk)
- Minimal hard water tolerance
- Very low maintenance requirements
Passive, Thermosyphon, Direct System

- Auxiliary element can also be in tank above collector, eliminating the auxiliary tank altogether.
- No freeze protection
- Minimal hard water tolerance
- Low maintenance requirements
Active, Open-loop, Pumped Direct System

- No freeze protection
- Minimal hard water tolerance
- High maintenance requirements
Active, Closed-loop (antifreeze), Indirect System

- Excellent freeze protection
- Good hard water tolerance
- High maintenance requirements
Tempering Valve to Prevent Scalding: Extremely Important for Safety!
Mid-Temperature Example:

Chickasaw National Recreation Area, OK

Small Comfort Stations
- 195 square feet of flat plate collectors
- 500 gallon storage volume
- Cost $7,804
- Delivers 9,394 kWh/year
- Saves $867 / year

Large Comfort Stations
- 484 square feet of flat plate collectors
- 1000 gallon storage volume
- Cost $16,100
- Delivers 18,194 kWh/year
- Saves $1,789 / year
High Temperature Example:

Phoenix Federal Correctional Institution

- 17,040 square feet of parabolic trough collectors
- 23,000 gallon storage tank
- Installed cost of $650,000
- Delivered 87.1% of the water heating load in 1999.
- Saved $77,805 in 1999 Utility Costs.
- The prison pays IST for energy delivered by the solar system at a rate equal to 90% of the utility rate (10% guaranteed savings), over 20 years.
Resources and References

American Society of Heating, Air Conditioning and Refrigeration Engineers, Inc.

- ASHRAE 90003 -- Active Solar Heating Design Manual
- ASHRAE 90336 -- Guidance for Preparing Active Solar Heating Systems Operation and Maintenance Manuals

Solar Rating and Certification Corporation

- SRCC-OG-300-91 -- Operating Guidelines and Minimum Standards for Certifying Solar Water Heating Systems
Topics

- Solar Resource Overview
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- Solar Photovoltaic Systems
- Concentrating Solar Power Systems
Solar Electric Technologies

- Photovoltaics (PV)
- Concentrating Solar Power (CSP)
- Distributed Generation - on-site or near point of use -
- Centralized Generation - large users or utilities -

Market Transformation
Grid Integration

DOE SETP
A typical solar cell (10cm x 10cm) generates about 1W at about 0.5V.
Individual cells are connected in series (increases the voltage) and in parallel (increases the current) into a module.
“Czochralski” Technology
Cast Polycrystalline Technology
“Sheet” Technologies

Edge-defined Film-fed Growth (EFG)

“Thin film” Silicon
Thin Film Technologies On Glass
Thin Film Technologies
On Flexible Substrates
Concentrating PV Systems

Point Focus 100-1000X

Line Focus 30-50X
Photovoltaic Markets: Very diverse > Large (GWs) Market Potential
Building-Integrated PV (BIPV)
A Plot of Land, 100 Miles on a side, in Nevada could provide all the kWh consumed by the U.S.
0.01%-0.1% of electricity now comes from PV - extrapolates to > 5% in 2020 competitive with conventional electricity for 0.1% - 1% of market; more in future
Challenges for Photovoltaics

Continue to drive down costs and develop sufficient product diversity to address and maximize all market segments.

Ensure adequate supply chain for a large and rapidly growing industry.

Continue to provide reliable products with 30 yr lifetimes (both actual and perceived).
Fundamental Targets Leading to U.S. PV Deployment Success

### Module
- $1/Wp

### System
- $2 to 3/Wp
  - Manufacturing Scale Up
    - Supply Chain (gigawatt scale).
    - Meeting efficiency & $/m² cost targets.
    - Maintain Performance/Quality.
    - Energy Payback & Environmental.

### Electric Power Source
- $cents/kWhr
  - System Installation Costs
  - Grid Integration
  - 20 to 30 yr. lifetime/reliability
  - 1 to 2% Degradation
  - Low Operating Costs
Photovoltaic (PV) technologies

- **CPV**
  - Market: Ground Mounted, Rooftop Mounted

- **Thin Films**
  - Material: Amorphous Silicon, CdTe / CIGS, Organic

- **Crystalline Silicon**
  - Structure: Multi-Crystalline, Mono-Crystalline

**Examples:**
- 20x-100x
- 500x
- Cu(In,Ga)Se$_2$ ~ 1-2 um
- c-Si ~ 180 um
Costs have been dramatically reduced across vastly different technologies

Historical and Projected Experience Curve for PV Modules

Public data from SEC, analysts, etc.
Currently PV is financially competitive where there is some combination of high electricity prices, excellent irradiance and/or state/local incentives.

Assumptions: For the price of electricity, the average electricity price for the 1000 largest utilities in the U.S. based on EIA data for 2006 (except CA, where existing tiered rates structures were used). The installed system price is set at $8.5/Wp in the current case and is assumed to be financed with a home equity loan (i.e., interest is tax deductible), with a 10% down payment, 6% interest rate, with the owner in the 28% tax bracket, and a 30 year loan/30 year evaluation period. Incentives included are the Federal ITC worth $500/kW due to $2000 cap and individual state incentives as of December 2007.
PV is less expensive in 250 of 1,000 largest utilities, which provide ~37% of U.S. residential electricity sales.

85% of sales (in nearly 870 utilities) are projected to have a price difference of less than 5¢/kWh between PV and grid electricity.

Notes: The installed system price is set at $3.3/Wp.
The realistic forecast - 2015 residential installations without incentives and aggressive (2.5% PA) increases in real electricity prices

PV is less expensive in 450 of the 1,000 largest utilities, which provide ~50% of U.S. residential electricity sales.

91% of sales (in nearly 950 utilities) have a price difference of less than 5¢/kWh between PV and grid electricity.

Notes: The installed system price is set at $3.3/Wp.
PV can provide peak shaving in many parts of U.S.

**PV Energy kWh/kW-yr**

**Effective Load Carrying Capacity**

Source: Christy Herig (NREL) and Richard Perez (SUNY/Albany)
Technical Challenges for High-Penetration PV

Ensure safe and reliable two-way electricity flow

Develop smart grid interoperability

Develop advanced communication and control functionalities of inverters

Integrate renewable systems models into power system planning and operation tools

Integrate with energy storage, load management, and demand response to enhance system flexibility

Understand high-penetration limiting conditions

Understand how various climates and cloud transients affect system reliability
Topics

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CSP Technologies and Market Sectors

CSP w/ Storage* (Dispatchable)
– Parabolic trough
– Power tower
– Linear Fresnel
*for non-steam heat transfer fluids

CSP w/o Storage (Non-Dispatchable)
– Dish/Engine
Value of Dispatchable Power?
Meets Utility Peak Power Demands

- **Storage provides**
  - higher value because power production can match utility needs
  - lower energy costs if storage is less expensive than incremental turbine costs

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Solar Resource

Hourly Load

Generation w/ Thermal Storage

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Innovation for Our Energy Future
Concentrating Solar Power: Dispatchable Power

Parabolic Troughs: Commercial, utility-scale deployments

Central Receiver: Pre-commercial, pilot-scale deployments

- Up to 250MW plants (or multiple plants in power parks) for intermediate and baseload power
- Moderate solar-to-electric efficiency
- Thermal storage offers load following and capacity factors up to 70%
Parabolic Trough Power Plant
w/ 2-Tank Indirect Molten Salt Thermal Storage
Parabolic Trough
Molten Salt Power Towers

Hot Salt

Cold Salt

Steam Generator

Condenser

Conventional steam turbine & generator

Heliostat Field

565°C

288°C

National Renewable Energy Laboratory

Innovation for Our Energy Future
Power Tower (Central Receiver)

Different design approaches:

• Direct Steam Generation
  – Abengoa PS10 (Spain)
  – Abengoa PS20 (Spain)
  – BrightSource (USA/Israel)
  – eSolar (USA)

• Molten Salt
  – Gemasolar (Spain)
  – SolarReserve (USA)

• Air Receiver
  • Jülich (Germany)
Concentrating Solar Power: Non-Dispatchable Central Station/Distributed Power

Dish/Stirling: Pre-commercial, pilot-scale deployments

Concentrating PV: Commercial and pre-commercial pilot-scale deployments

- Modular (3-25kW)
- High solar-to-electric efficiency
- Capacity factors limited to 25% due to lack of storage capability
CSP Market Goals

– Competitive in southwest intermediate load power markets ($0.12/kwh nominal LCOE) by 2015

– Expand access to include carbon constrained baseload power markets ($0.10/kwh nominal LCOE) by 2020
2015 Cost Target Analysis

2015 Electric Generation Costs (no CO2 capture)

- CEC advanced
- EPRI 2015
- NETL

2007 dollars unless noted.

Intermediate Load Target

Nominal LCOE ($/MWh)

Supercrit PC | IGCC | GTCC | GTCC (40%CF) | Nuclear

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U.S. Southwest GIS Screening Analysis for CSP Generation

Screening Approach

- Initial solar resource and GIS screening analysis used to identify regions most economically favorable to construction of large-scale CSP systems

- GIS analysis used in conjunction with transmission and market analysis to identify favorable regions in the southwest
1. Start with direct normal solar resource estimates derived from 10 km satellite data.

2. Eliminate locations with less than 6.0 kWh/m²/day.

3. Exclude environmentally sensitive lands, major urban areas, and water features.

4. Remove land areas with greater than 1% (and 3%) average land slope.

5. Eliminate areas with a minimum contiguous area of less than 1 square kilometers.
GIS Solar Resource Screening Analysis

Unfiltered Resource

Solar > 6.0 kwh/m²-day

Land Exclusions

Slope Exclusions
Resulting CSP Resource Potential

<table>
<thead>
<tr>
<th>State</th>
<th>Land Area (mi²)</th>
<th>Solar Capacity (MW)</th>
<th>Solar Generation Capacity (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ</td>
<td>13,613</td>
<td>1,742,461</td>
<td>4,121,268</td>
</tr>
<tr>
<td>CA</td>
<td>6,278</td>
<td>803,647</td>
<td>1,900,786</td>
</tr>
<tr>
<td>CO</td>
<td>6,232</td>
<td>797,758</td>
<td>1,886,858</td>
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<tr>
<td>NV</td>
<td>11,090</td>
<td>1,419,480</td>
<td>3,357,355</td>
</tr>
<tr>
<td>NM</td>
<td>20,356</td>
<td>2,605,585</td>
<td>6,162,729</td>
</tr>
<tr>
<td>TX</td>
<td>6,374</td>
<td>815,880</td>
<td>1,929,719</td>
</tr>
<tr>
<td>UT</td>
<td>23,288</td>
<td>2,980,823</td>
<td>7,050,242</td>
</tr>
<tr>
<td>Total</td>
<td>87,232</td>
<td>11,165,633</td>
<td>26,408,956</td>
</tr>
</tbody>
</table>

The table and map represent land that has no primary use today, exclude land with slope > 1%, and do not count sensitive lands.

Current total nameplate capacity in the U.S. is 1,000GW w/ resulting annual generation of 4,000,000 GWh.
Optimal CSP Sites from CSP Capacity Supply Curves
354 MW Luz Solar Electric Generating Systems (SEGS)
Nine Plants built 1984 - 1991
1-MW Arizona Trough Plant, Tucson, AZ
50 MW AndaSol One and Two
Parabolic Trough Plant w/ 7-hr Storage, Andalucía
Abengoa 50MW Trough Plants
Seville, Spain
50 MW Iberdrola Energía Solar de Puertollano
Puertollano (Ciudad Real)
Abengoa PS10 and PS 20
Seville, Spain
Power Tower Pilot Plants

5 MWe eSolar
California, USA

6 MW_{thermal} BrightSource
Negev Desert, Israel
1MW Dish Demonstration – Phoenix, AZ
Questions?

SunEdison 8MW, San Louis Valley, CO