Shedding Light on Solar Energy

ORNL Sustainable Campus
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Curt Maxey
Shedding Light on Solar Energy

• Some perspectives on energy
• Direct uses of solar energy
• Photovoltaics
  – Why efficiency matters
  – Cells, modules, arrays, and systems
  – Solar resource tools
• Concentrating Solar Systems
The Earth contains enough water to hydrate all living beings and to grow crops on all arable land.

- Convert to useful form
- Transport where needed
- Deliver when needed
- Store as necessary

*Problem Solved!*
The Earth receives more energy from the sun in just one hour than humanity uses in a whole year

- Convert to useful form
- Transport where needed
- Deliver when needed
- Store as necessary

*Problem Solved!*
Getting Perspective on Energy Production
Bull Run Steam Plant

- 900 MW nameplate capacity
- Annual production 6,000,000 MWh
- About enough to power 545,000 average homes (11 MWh ea. per year)

http://www.tva.com/sites/bullrun.htm
http://www.eia.doe.gov/tools/faqs/faq.cfm?id=97&t=3
Getting Perspective on Energy Production
South Knoxville PV Array

• 1 MW nameplate capacity
• ~5 acres land area required
• 4.7 TN “sun-hours” per day
• ~80% DC to AC conv. efficiency
• Annual production 1,372 MWh
• About enough to power 125 average homes

Thus, a TN solar array to equal the annual production of Bull Run Steam Plant would require about 22,000 acres (35 square miles) of flat land area

~$18B, plus the cost of the land
Governing Principles for Any Energy Infrastructure Development Project

• 2nd Law of Thermodynamics
  – You can’t win, you can’t break even, and you can’t get out of the game

• Golden Rule of Engineering Economics
  – Nothing is ever cheap or easy

• Principle of Inter-Cooperative Non-Empowerment
  – Anything that is not mandatory is prohibited

• Regional Policy for Infrastructure Expansion
  – Not In My Back Yard (NIMBY)

• Global Policy for Infrastructure Expansion
  – Build Absolutely Nothing Anywhere Near Anything (BANANA)
How to build a hybrid solar/wind energy system with a payback period under one year

• Energy savings* ~33% as much as installing a 2.5 kW solar PV system (~$20,000) but typically costs between $10 and $100

• Prohibited in virtually all the locations that have the highest per capita ownership of hybrid (and soon all-electric) vehicles

*Assumes displacement of all electric clothes drying 1079 kWh per typical household
Direct uses of solar energy

- Clotheslines
- Skylights
- Space heating
- Water heating

When you convert sunlight to electricity, via any method, the conversion losses destroy most of the energy (up to 90%) and ... 
if you store it in batteries, you destroy much of the rest (up to 25%)
Lighting Uses the Most Energy in Commercial Buildings
(largely during daylight hours)

Typical Average Energy Usage for Commercial Buildings

Daylighting can provide high-quality light and reduced energy consumption

One Warehouse: Three Illumination Examples (before, during and after)

- Conventional T8 Fluorescent Illumination
- Fluorescents Off Open Roof Penetrations
- Fluorescents Off Prismatic Skylights Installed

Photos courtesy of Sunoptics
Architecturally integrated daylighting solutions are visually stimulating and save energy
Transpired Solar Air Collectors for Space Heating and Industrial Processes

Solar Water Heating

Pool Collectors

Concentrators

Flat Plates

Evacuated Tubes
Which collector is best depends on the temperature rise needed

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

Freeze Protected Solar Water Heater

- In most areas of the U.S. SHW systems will require an antifreeze system
- Food-grade propylene glycol is used as the anti-freeze
- Heat exchanger provides interface to potable water system
- Controls must ensure that the glycol does not “cook” during stagnant periods (vacation etc.)
Photovoltaics

- Why efficiency matters
- Cells, modules, arrays, and systems
- Solar resource tools
**Efficiency matters**

- 51 kW array installed using 18.7% efficient (Sunpower) modules – 288 feet long
- Same array if installed with more typical 13-14% efficient modules would have been 100 feet longer

Solar energy is free but real estate is not

- Are these single or multi-crystal cells?
- What is unusual about them?
Single and multicrystal silicon cells

early (1970s) round single crystal cell

modern semi-square single crystal cell

modern multicrystal cell

http://pvcdrom.pveducation.org
Cell efficiency: Shockley–Queisser limit
(theoretical limit for single-junction solar cell efficiency)

• First calculated by William Shockley and Hans Queisser at Shockley Semiconductor in 1961

• Simply stated, the theoretical limit for a single junction solar cell is about 30%

• Several factors limit the ability to achieve this maximum value
  – material imperfections
  – processing limitations
  – Fresnel reflection (surface reflection due to refractive index)
  – electrodes on surface

• Sunpower is routinely manufacturing cells with >22% efficiency and has demonstrated a full-scale prototype cell at 24.2%
But what about the 40+% efficient cells I’ve heard about? - Multilayer PV cells

- In multilayer cells, light is converted into electricity in successive layers: shortest wavelengths (UV and blue) in top layer, longest wavelengths (red and IR) in bottom layer.

- These cells are extraordinarily complex to manufacture and are orders of magnitude more expensive to produce than standard solar cells.

- They are cost-prohibitive for all but space applications and a few high-concentration CPV systems.

http://www.spectrolab.com
PV Module efficiency

- PV Modules are constructed with arrays of solar cells

- The spacing of the cells, the border around them to accommodate the frame, the reflections from the cover glass, and other factors reduce the module efficiency substantially below the cell efficiency

<table>
<thead>
<tr>
<th>Efficiency comparisons of common solar modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
</tr>
<tr>
<td>BP</td>
</tr>
<tr>
<td>REC</td>
</tr>
<tr>
<td>Sharp</td>
</tr>
<tr>
<td>Sanyo</td>
</tr>
<tr>
<td>Sunpower</td>
</tr>
</tbody>
</table>

BP 200W module 14% efficient
Multi-crystal Si front-surface electrodes

SunPower 305W module 18.7% efficient
Single-crystal Si rear-surface electrodes
Thin film PV technologies
Selected examples

Thin film PV offers flexibility, light weight, and potentially lower cost at the expense of efficiency

- Amorphous silicon: Well established technology with lots of installed product but relatively low efficiency (6-7%) modules

- CIGS: Copper Indium Gallium di-Selenide very exciting – 19.5% efficient cells have been achieved in the laboratory. Some commercial modules are emerging

- CdTe: First Solar leads this technology and is installing multi-megawatt arrays on multiple continents. Cell efficiency ~16%; Module efficiency ~10%

Limited availability of Indium and Tellurium may ultimately challenge the CIGS and CdTe technologies

Photovoltaic Array Efficiency

- Composed of multiple modules (20 – 60 VDC typ.)
- Modules arranged in series strings to achieve higher voltages (400 – 600 VDC typ)
- Multiple strings typically combined in parallel prior to connection to inverter
- Shading one module in a series string cuts the output of the entire string
- Inverter incorporates Maximum Power Point Tracking (MPPT) to optimize power output
Inverter (for conversion of DC to AC)

- Available in many sizes and voltage outputs
- Enables DC from solar array to be connected to AC power distribution system
- Micro-inverters may be used (one per PV module) to optimize output of each module
PV System efficiency considerations and tools

- Fixed tilt and tracking
- Suncharts and self-shading discussion
- DC to AC conversion losses
- Solar Redbook
- PV Watts Calculator
- IMBY (in my back yard) Calculator
- Solar Pathfinder instrument
PV System Efficiency
Effect of tilt and tracking on monthly energy

Average daily solar radiation (kWh/m²/day)

Data for Cleveland OH
A Sun chart shows the position throughout the year
Sample sun chart for Oak Ridge in solar (not local) time

To ensure effective performance at winter solstice the critical angle for shadowing is around 18°
**Large (unity aspect ratio) array tilt and fill factor**

- **Wa** = width of array
- **Ha** = height of array
- **Pa** = ground projection of array
- **Sa** = spacing of arrays
- **S** = winter solstice angle
- **T** = tilt of array
- **FF** = fill factor \((Wa/(Pa+Sa))\)

**Fill Factor vs Tilt Angle**
(for unity aspect ratio array at 35deg latitude)
**System Efficiency – DC to AC**

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**Calculator for Overall DC to AC Derate Factor**

<table>
<thead>
<tr>
<th>Component Derate Factors</th>
<th>Component Derate Values</th>
<th>Range of Acceptable Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV module nameplate DC rating</td>
<td>0.95</td>
<td>0.80 - 1.05</td>
</tr>
<tr>
<td>Inverter and Transformer</td>
<td>0.92</td>
<td>0.88 - 0.98</td>
</tr>
<tr>
<td>Mismatch</td>
<td>0.98</td>
<td>0.97 - 0.995</td>
</tr>
<tr>
<td>Diodes and connections</td>
<td>0.995</td>
<td>0.99 - 0.997</td>
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<tr>
<td>DC wiring</td>
<td>0.98</td>
<td>0.97 - 0.99</td>
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<tr>
<td>AC wiring</td>
<td>0.99</td>
<td>0.98 - 0.993</td>
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<tr>
<td>Soiling</td>
<td>0.95</td>
<td>0.30 - 0.995</td>
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<tr>
<td>System availability</td>
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<td>0.00 - 0.995</td>
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<tr>
<td>Shading</td>
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<td>0.00 - 1.00</td>
</tr>
<tr>
<td>Sun-tracking</td>
<td>1.00</td>
<td>0.95 - 1.00</td>
</tr>
<tr>
<td>Age</td>
<td>1.00</td>
<td>0.70 - 1.00</td>
</tr>
<tr>
<td>Overall DC to AC derate factor</td>
<td>0.77</td>
<td><em>(PVWATTS Default)</em></td>
</tr>
</tbody>
</table>
Peak solar intensity, “1 sun” is nominally 1000 W/m² The average kWh/m²/day is casually called the number of “sun hours” per day
# PVWatts Calculator - NREL (based on Redbook data)

## PV System Specifications:
- **DC Rating (kW):** 51
- **DC to AC Derate Factor:** 8
- **Array Type:** Fixed Tilt
- **Fixed Tilt or 1-Axis Tracking System:**
  - **Array Tilt (degrees):** 35 (Default = Latitude)
  - **Array Azimuth (degrees):** 150 (Default = South)

## Energy Data:
- **Cost of Electricity (cents/kWh):** Default = State Average

## Station Identification
- **City:** Knoxville
- **State:** Tennessee
- **Latitude:** 35.82° N
- **Longitude:** 83.98° W
- **Elevation:** 299 m

## PV System Specifications
- **DC Rating:** 51.0 kW
- **DC to AC Derate Factor:** 0.800
- **AC Rating:** 40.8 kW
- **Array Type:** Fixed Tilt
- **Array Tilt:** 35.0°
- **Array Azimuth:** 150.0°

## Energy Specifications
- **Cost of Electricity:** 6.9 ¢/kWh

## AC Energy & Cost Savings

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar Radiation (kWh/m²/day)</th>
<th>AC Energy (kWh)</th>
<th>Energy Value ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.05</td>
<td>3839</td>
<td>264.89</td>
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<tr>
<td>2</td>
<td>3.77</td>
<td>4230</td>
<td>291.87</td>
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<tr>
<td>3</td>
<td>4.67</td>
<td>5625</td>
<td>388.12</td>
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<tr>
<td>4</td>
<td>5.19</td>
<td>5889</td>
<td>406.34</td>
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<tr>
<td>5</td>
<td>5.30</td>
<td>6063</td>
<td>418.35</td>
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<tr>
<td>6</td>
<td>5.62</td>
<td>6085</td>
<td>418.49</td>
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<tr>
<td>7</td>
<td>5.61</td>
<td>6236</td>
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<tr>
<td>8</td>
<td>5.33</td>
<td>5931</td>
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<tr>
<td>9</td>
<td>4.81</td>
<td>5257</td>
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<tr>
<td>10</td>
<td>4.63</td>
<td>5445</td>
<td>375.70</td>
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<tr>
<td>11</td>
<td>3.42</td>
<td>3887</td>
<td>268.20</td>
</tr>
<tr>
<td>12</td>
<td>3.00</td>
<td>3659</td>
<td>252.47</td>
</tr>
<tr>
<td>Year</td>
<td>4.54</td>
<td>62124</td>
<td>4286.56</td>
</tr>
</tbody>
</table>
1. Enter address

2. Draw area of array and adjust inputs

3. Run simulation (automatically links to PVWatts)
Shading analysis instruments

Solar Site Analysis Tools

These can help you find the best location for your solar collector(s) by showing you where shading will occur from buildings, trees, or other objects. Several are available, from the lower-tech, but highly reliable, Solar Pathfinder ($255; or $319 with software interface) to Wiley Electronic’s ASSET, a digital camera, mount, and software package that crunches solar access data on your computer from a set of photos you shoot at your site ($699). Solmetric’s high-tech (and higher-priced) SunEye is a handheld digital tool that provides solar access and shading information with the touch of a button ($1,255).

www.homepower.com
## Sample Solar Pathfinder Report

### Solar Obstruction Data

<table>
<thead>
<tr>
<th>Month</th>
<th>Ideal Solar Rad w/o Shading Azimuth=180.0 Tilt=36.0° KWH/m²/day</th>
<th>Actual Solar Rad w/o Shading Azimuth=150.0 Tilt=36.1° KWH/m²/day</th>
<th>Actual Solar Rad w/ Shading Azimuth=150.0 Tilt=36.1° KWH/m²/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>3.23</td>
<td>3.06</td>
<td>2.82</td>
</tr>
<tr>
<td>February</td>
<td>3.94</td>
<td>3.78</td>
<td>3.59</td>
</tr>
<tr>
<td>March</td>
<td>4.83</td>
<td>4.67</td>
<td>4.44</td>
</tr>
<tr>
<td>April</td>
<td>5.34</td>
<td>5.16</td>
<td>4.85</td>
</tr>
<tr>
<td>May</td>
<td>5.28</td>
<td>5.27</td>
<td>4.95</td>
</tr>
<tr>
<td>June</td>
<td>5.56</td>
<td>5.58</td>
<td>5.20</td>
</tr>
<tr>
<td>July</td>
<td>5.56</td>
<td>5.57</td>
<td>5.20</td>
</tr>
<tr>
<td>August</td>
<td>5.32</td>
<td>5.31</td>
<td>4.94</td>
</tr>
<tr>
<td>September</td>
<td>4.96</td>
<td>4.80</td>
<td>4.59</td>
</tr>
<tr>
<td>October</td>
<td>4.91</td>
<td>4.64</td>
<td>4.51</td>
</tr>
<tr>
<td>November</td>
<td>3.65</td>
<td>3.44</td>
<td>3.29</td>
</tr>
<tr>
<td>December</td>
<td>3.22</td>
<td>3.02</td>
<td>2.85</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>55.82</strong></td>
<td><strong>54.29</strong></td>
<td><strong>51.26</strong></td>
</tr>
</tbody>
</table>

Effect: 100%  Effect: 97.26%  Effect: 91.83%
Sun Hrs: 4.65  Sun Hrs: 4.52  Sun Hrs: 4.27
Concentrator Photovoltaics (CPV)

Concept: use lenses and/or mirrors to concentrate sunlight so smaller solar cells can be used

- Fresnel lens
- Aspheric mirrors
- Planar mirrors
Concentrator Photovoltaics (CPV)

CPV systems are emerging
As an important sector of
The solar market

Amonix – Fresnel lens concentrator
http://i.n.com/i/ne/p/2007/Amonix_550x363.jpg

Solfocus – aspheric mirror concentrator

JX Crystals – Low concentration
flat mirror concentrator
Concentrating Solar Thermal

• General wisdom is that the installed cost per kW is less than PV and the potential for energy storage (even for a few hours) is a significant advantage

• Power towers, parabolic troughs, and parabolic dishes

• Working fluids range from water, to oil, to molten salt

• Stirling engines for direct conversion to electricity have historically been problematic but are still a contender
Nevada Solar 1 – Boulder City

- ~300 acres of concentrating collectors online June 2007
- Largest CSP plant
- 64 MW output capacity
- $266 M to build
- $4.15 per watt
- 71:1 concentration ratio
- Working fluid – oil
- No thermal storage
PS 10/20 – Seville Spain

- PS 20 – Seville Spain
  - Abengoa Solar

- Working fluid, water (steam)

- Short term (50 minutes at 50% power) thermal storage
Solar1/Solar2 – Mojave Desert, Barstow, CA

- Solar 2: 10MW, molten salt (40% KNO$_3$, 60% NaNO$_3$) working fluid
- Energy storage of a few hours
Summary - Solar energy is an important component of our energy future

- Direct use of solar affords the greatest efficiency
- Crystalline silicon PV is the most efficient means for direct conversion of sunlight to electricity
- Emerging thin film products (especially CdTe and CIGS) will be a significant player in the global energy scenario
- Solar thermal (where applicable) is the optimum solution for large-scale utilities, in terms of installed costs and the ability to provide energy storage