The Terrestrial Solar Resource

Solar Energy Resource Base
1.5x10^{18} \text{kWh/year}
1.7x10^5 \text{TW}_{\text{ave}}

Wind Energy Resource Base
6x10^{14} \text{kWh/year}
72 \text{TW}_{\text{ave}}

Human Energy Use (2050 estimate)
4x10^{14} \text{kWh/year}
50 \text{TW}_{\text{ave}}
Solar Resource is VAST!

Solar Energy Resource Base
1.5x10^{18} kWh/year
1.7x10^5 \text{ TW}_{ave}

Solar Resource on Earth’s Surface
5.5x10^{17} kWh/year
3.6x10^4 \text{ TW}_{ave}

Wind Energy Resource Base
6x10^{14} kWh/year
72 \text{ TW}_{ave}

Human Energy Use (mid- to late-century)
4x10^{14} kWh/year
50 \text{ TW}_{ave}

Solar constant: 1368 W/m^2
Surface, 30 – 50% less
Solar constant: 1 kW/m^2
x 0 – 8 hours/day, or
An average of
4 kWh/m^2/day
Energy resources compared

Solar
40,000 TW-yrs per year

Wind
23

OTEC
11

Biomass
6

Hydro
4

Geothermal
2

Waves
0.5

Tides
0.3

Petroleum
170

Natural Gas
70

Uranium
220

Total reserve
900

World Energy Use
15 TW-yrs per year
PV Land Area Requirements

6 Boxes at 3.3 TW Each
Evolution of U. S. deployment
Solar Thermal
The World’s Largest Solar Thermal Power Plant (Parabolic Trough)

Solar Energy Generating System (SEGS)
310 MW
San Bernardino County, CA
The World’s Largest Solar Thermal Power Plant (Tower)

Ivanpah Solar Thermal Project
370MW
San Bernardino County, CA
PV Supply and Demand

Figure 2-2. 2010 Global PV Supply and Demand

Supply 2010 Shipped From

- Rest of World: 14%
- Europe: 15%
- Japan: 12%
- U.S.: 6%
- China and Taiwan: 53%

Demand 2010 Shipped To

- Europe: 80%
- U.S.: 8%
- Japan: 6%
- Rest of World: 6%

Source: Mints (2011a) and Mints (2011b)

Goodrich, Margolis, et al, NREL
Solar Price Drops Mirror High Tech Consumer Goods

Driven by Innovation, Automation, and Scale

Digital Cameras

- 1990 1.3 MP: $13,000
- 1994 Apple: $800
- 1996 Casio QV-10: $650
- 2011 Canon 14MP HD: $179

Cell Phones

- 1982 Motorola: $3,995
- 1996 StarTAC: $1,000
- 2004 Treo: $399
- 2010 iPhone 3G: $49
- 2011 Palm Pixi with plan: $0

DVD Players

- 1997: $840
- 1998: $571
- 1999: $467
- 2000: $345
- 2011: $40
Annual installed PV power in key countries

Based on data from IEA, EPIA, BSW-Solar, GSE, China PV Development Report, etc.
Nomenclature

- Ingot
- Wafer
- Solar Cell
- Module (Panel)
- Solar Array
- Tempered Glass
- Clear laminate
- Solar cells
- Clear laminate
- Plastic backing
- Junction box
- Aluminum frame
P-N Junction

- The electric potential barrier between the two semiconductors of a solar cell
- Creates a low resistance path for excited electrons to flow through
- “Loose” electrons flow from the rich end to the poor one creating a direct current

*This is called the photovoltaic effect and explains why the true name for solar cells are PV cells

http://express.howstuffworks.com/exp-solar-power1.htm
PV Device Types

• Single-crystal silicon
  – 15+% efficient, typically
  – expensive to make (grown as big crystal)

• Poly-crystalline silicon
  – 10–12% efficient
  – cheaper to make (cast in ingots)

• Amorphous silicon (non-crystalline)
  – 4–6% efficient
  – cheapest per Watt
  – called “thin film”, easily deposited on a wide range of surface types
PV Device Types

Monocrystalline PV

Amorphous Silicon PV

[Image of Monocrystalline PV]
[Image of Amorphous Silicon PV]

http://www.arisetech.com/

http://www.energyalternatives.ca/

Polycrystalline PV

CIGS Thin Film PV

[Image of Polycrystalline PV]
[Image of CIGS Thin Film PV]

http://img.alibaba.com/

http://www.cnn.com/
First generation cells

More Si than for ICs

Materials Issues
- thinner cells
- simpler Si purification

UNSW

Photovoltaics - Electricity from Sunlight
Second Generation: thin-film

**Thin-film Technologies**
- **Silicon**
  - amorphous
  - microcrystalline
  - polycrystalline
- **Chalcogenide** (polycrystalline)
  - CIS, CIGS \([Cu (In, Ga) (Se, S)_2]\)
  - CdTe
- **Dye sensitised, Organics**

**Advantages**
- low materials cost
- large manufacturing unit
- fully integrated modules
- aesthetics, ruggedness?

UNSW
Module cost breakdown - $/W based on Multi crystalline silicon technology (30 MW factory)

Total cost - $ 2.09/W
The Learning Curve … again

- Photovoltaics (learning rate ~ 20%)
  - USA
  - Japan
- Windmills (USA) (learning rate ~ 20%)
- Gas turbines (USA) (learning rate ~ 20%, ~10%)

Cumulative MW installed

US(1990)$/kW
Factors Driving Past Cost Reduction

- Poly silicon price: $300/kg → $30/kg
- Wire sawing: now < $0.25/W
- Larger wafers: 3” → 6”
- Thinner wafers: 15 mil → 10 mil
- Improved efficiency: 10% → 16%
- Volume manufacturing: 1MW → 1000MW
- Increased automation: none → some
- Improved manufacturing processes
Quantifying the benefits of R&D

R&D Funding → Technological change → Efficiency

50% increase in PV efficiency occurs immediately after unprecedented >$1b global investment in PV R&D (1978-85)...

Si-based PV Production: From Sand to Systems

Module Fab

Cost breakdown

Source: H. Aulich, PV Crystalox Solar, 2007
**Crystalline silicon**

*Single crystalline silicon*

- FZ, CZ

*Multicrystalline silicon*

- Cast, ribbon, sheet techniques

Each silicon atom is bonded to four neighbouring atoms.

The grain size in multicrystalline silicon is from several microns to several millimeters or even centimeters. The fundamental physical properties such as bandgap and absorption properties are similar. The difference between c-Si and mc-Si is primarily the density of defects and impurities – and **cost, cost, cost**.

Slide from A.A. Istratov, Siltronic
The Evolving Solar Energy Economy

A. Annual PV installations (GW)
- U.S.

B. Annual PV installations (GW)
- China

C. Patent, Market, Manufacturing
- Japan

D. Germany

China Racing Ahead of U.S. in the Drive to Go Solar

By KEITH BRADSHHER
Published: August 24, 2009
US has twice the German solar insolation resource
German FIT

Strong demand in periods before the feed-in tariff was reduced
PV feed-in tariff for modules ≤ 30 kW, module prices and weekly installations for systems ≤ 30 kW

Modules ≤ 30 kW have accounted for 44% and 38% of total installations in 2009 and 2010 respectively.
The Sample Represents a Large Fraction of All U.S. PV Capacity through 2011

- DoE federal data, after all data cleaning was completed, consists of 152,311 PV systems totaling 3,022 MW, including 2,224 MW of residential and commercial PV and 798 MW of utility-scale PV.

- The sample represents approximately 76% of cumulative grid-connected PV capacity installed in the United States through 2011, and 69% of annual capacity additions in 2011.

*Data source for U.S. grid-connected PV capacity additions: Larry Sherwood (Interstate Renewable Energy Council)*
Residential & Commercial PV Data Sample: Distribution Across States and by System Size

Distribution of Capacity Across States (1998-2011)

- CA represents the majority of cumulative installed capacity in the data sample, though 2011 capacity additions are more evenly distributed across states.

- The vast majority of systems are relatively small (<10 kW), though the sample capacity is evenly distributed across system sizes.

Distribution of Capacity Across States (2011)
Over time, an increasing portion of residential and commercial PV capacity has consisted of relatively large systems.
Data for California Show That Installed Prices Continued to Fall into 2012

Median installed prices for ≤10 kW and 10-100 kW systems fell by roughly $0.4/W (6-7%) in the CSI program during the first half of 2012, relative to 2011 (the slight increase for >100 kW systems is due to shift towards smaller systems within that size range from 2011 to H1 2012)

<table>
<thead>
<tr>
<th></th>
<th>2011 $/W_{DC}</th>
<th>2012 (H1) $/W_{DC}</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤10 kW</td>
<td>$6.4</td>
<td>$5.9</td>
</tr>
<tr>
<td>10-100 kW</td>
<td>$5.8</td>
<td>$5.4</td>
</tr>
<tr>
<td>&gt;100 kW</td>
<td>$5.0</td>
<td>$5.1</td>
</tr>
</tbody>
</table>

Recent Installed Price Declines Primarily Reflect Falling Module Prices

Global average module prices began a steep decline in 2008, falling by $2.1/W from 2008-2011, with movements in total installed price appearing to lag behind; implied non-module costs have fallen by $2.0/W since 1998, but have remained relatively flat in recent years.

Notes: The Global Module Price Index is Navigant Consulting’s module price index for large-quantity buyers (Mints, 2012). "Implied Non-Module Costs" are simply a residual term, equal to the Total Installed Price minus the Global Module Price Index.
Renewable Energy Portfolio Standards
(30 states + Washington, DC)

- **State Goal**
  - PA: 18% by 2020
  - NJ: 22.5% by 2021
  - CT: 23% by 2020
  - WI: requirement varies by utility; 10% by 2015 goal
  - MO: 11% by 2020
  - IL: 25% by 2025
  - MA: 4% by 2009 + 1% annual increase
  - ME: 30% by 2000
  - HI: 20% by 2020
  - CA: 20% by 2010; 33% by 2020
  - NV: 20% by 2015
  - AZ: 15% by 2025
  - CO: 20% by 2020 (IOUs)
  - NM: 20% by 2020 (IOUs)
  - NC: 12.5% by 2021 (IOUs)
  - ND: 10% by 2015
  - MT: 15% by 2015
  - TX: 5,880 MW by 2015
  - MD: 9.5% in 2022
  - NH: 23.8% in 2025
  - NY: 24% by 2013
  - NJ: 22.5% by 2021
  - PA: 48% by 2020
  - VA: 12% by 2022
  - MD: 9.5% in 2022
  - DC: 11% by 2022
  - ME: 30% by 2000
  - WI: 10% by 2015 goal

- **State RPS**

- **Solar water heating eligible**

- **Minimum solar or customer-sited RE requirement**
  - Increased credit for solar or customer-sited RE

- **Special Cases**
  - PA: 8% Tier I / 10% Tier II (includes non-renewables)
  - WA: 15% by 2020
  - OR: 25% by 2025 (large utilities)
  - HI: 20% by 2020

- **March 2012**
1 SREC 1,000 kWh of solar electricity = 1 MWh of solar electricity

Recall: 1 kWh/m$^2$ yields an average of 4 kWh/m$^2$/day x 365 days/yr = 1460 kWh/m$^2$/yr

So 10 kW solar capacity = ~14 SRECs per year

The SREC is sold separately and represents the "solar" aspect of the electricity. The value of an SREC is determined by the market subject to supply and demand constraints. SRECs can be sold to electricity suppliers needing to meet their solar RPS requirement. The market is typically capped by a fine or solar alternative compliance payment (SACP) paid by any electricity suppliers for every SREC they fall short of the requirement. The sale of SRECs is intended to promote the growth of distributed solar by shortening the time it takes to earn a return on the investment.
SREC Prices in Many Markets Have Also Declined Significantly

Solar renewable energy certificate (SREC) prices fell precipitously in most markets during 2011 and into 2012 as a result of oversupply in states with RPS solar set-asides, with spot prices and long-term contract prices in several major markets dropping to $100-$200/MWh (or lower).

Sources: Spectron, SRECTrade, and Flett Exchange (data averaged across available sources). Plotted values represent SREC prices for the current or nearest future compliance year traded in each month. Long-term contract prices, if available, may be either higher or lower than contemporaneous spot-market prices, depending on the particular state.
German total additions more than 5x US
Germany’s 2011 additions nearly 4x US market
German residential market less defined than US residential market

PV Additions (# of systems)

kW

USA 2009  USA 2010  USA 2011
Germany 2009  Germany 2010  Germany 2011
German cumulative installations 3.6x US
German cumulative installations/capita 14x US

Cumulative residential PV installations

![Graph showing cumulative residential PV installations for CA, USA, and Germany from 2010 to 2011. The graph compares the total MW and W/capita for the three regions, highlighting Germany's significantly greater installations and installations/capita compared to the US and CA.]
Price discrepancy growing since 2005

PV prices for systems ≤10 kW
(annual averages)

- US system prices
- German system prices
- US installer module costs
- German installer module costs
- Module factory prices
US vs. Germany: Prices drop in both markets by $1.3, but maintain their difference
German residential systems are on average 1-2kW larger than US systems

PV Additions (# of systems)
Shift of average size from 5 to 7kW would reduce US prices by $0.4/W.
US soft costs make up most of the difference

Residential PV cost comparison

USA 2011

- Module: 1.96
- Inverter: 0.41
- Other hardware: 0.47
- Profit: 0.35
- Total: $6.44

Germany 2011

- Module: 1.82
- Inverter: 0.33
- Other hardware: 0.28
- Profit: 0.33
- Total: $3.00

$2011/W

profit
soft BoS
other hardware
inverter
module
Build-up of the $3.30 price difference

Additional Costs in US systems

- Module: 0.08
- Inverter: 0.54
- Other hardware: 0.10
- Installation labor: 0.20
- System design engineering: 0.32
- Customer acquisition: 0.12
- Marketing and...: 0.09
- P11: 0.07
- Permitting fee: 1.40
- Profit: 0.00
- Overhead: 1.00

$ 2011/W
Share of module manufacturers for <10kW systems in 2010 by country of HQ

**US Top 25**

- Japan: 33%
- USA: 21%
- China+Taiwan: 14%
- Germany: 12%
- Rest of Europe: 0%

**Germany Top 50**

- Germany: 23%
- Japan: 7%
- USA: 5%
- China+Taiwan: 3%
- Rest of Europe: 3%
- Other: 4%
Residential New Construction

• All new residential construction in California will be zero net energy by 2020.
Commercial New Construction

• All new commercial construction in California will be zero net energy by 2030.

• Leverage opportunities from emerging technologies initiatives, incentive programs, and local initiatives targeting commercial building/property developers.
The World’s Largest Silicon PV Project

Antelope Valley Solar Project
579 MW
San Luis Obisbo County, CA
Almost 80% of the California RPS is Projected to Be Met by Solar & Wind by 2020

Source: CPUC RPS Report
CA Leads in New Solar Home Construction

Over 8000 New Solar Homes Installed in CA.
12,000 more under way.

Rocklin Zero Energy Community
Future Applications

• Constant trend of increasing efficiencies across all forms of solar cells

• Inventive methods currently being considered include
  * solar panels on satellites which beam the energy back to earth in the form of microwaves
  * desert spanning solar farms
  * laser sunlight collectors to focus sun rays right at the solar cells

http://pneumaticaddict.wordpress.com/page/25/

Technological and Entrepreneurial Opportunity: Lighting Africa

rael.berkeley.edu
Insights from what technology can do

Systems Approach to Household Energy

Microinverter
Per-module DC to AC power conversion

Communications Gateway
Collects system information over the power line

Software
Web-based monitoring
Microinverters: A device-level subtle revolution

Traditional Inverter System

Enphase Microinverter System

Utility

Web-based Management

Communication Gateway
Micro-inverters versus traditional designs

Energy Advantage: 10.24%
- SMA SB6000US (95.5%) - Blue
- Enphase – Red
- Location: Petaluma, CA
- Date: November 2007

Energy Advantage: 33.63%
- Xantrex GT3 (94.5%) - Blue
- Enphase – Red
- Location: Grass Valley, CA
- Date: December 2007