The Status of PV in 2008 and a Look Ahead

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Outline

1. Survey of photovoltaic materials and small cells
2. Three generations of PV
3. Manufacturing technology for solar modules and systems -- thin films rising…
4. Commercial growth of PV in the U.S. and the world
5. Long-term potential for PV (>20% ?)
Champion Cell Efficiencies

Best Research-Cell Efficiencies

Efficiency (%)

- Multi-junction Concentrators
  - Three-junction (2-terminal, monolithic)
  - Two-junction (2-terminal, monolithic)

- Single-Junction GaAs
  - Single crystal
  - Concentrator
  - Thin film

- Crystalline Si Cells
  - Single crystal
  - Multicrystalline
  - Thick Si film

- Thin-Film Technologies
  - Cu(In,Ga)Se₂
  - CdTe
  - Amorphous Si:H (stabilized)
  - Nano-, micro-, poly-Si
  - Multijunction polycrystalline

- Emerging PV
  - Dye-sensitized cells
  - Organic cells
    - (various technologies)

- Companies and Institutions
  - ARCO
  - Westinghouse
  - No. Carolina State Univ.
  - Solaris
  - ARCO
  - Boeing
  - Kodak
  - Monosolar
  - University of Maine
  - RCA
  - EPFL
  - University of Linz
  - Siemens
  - NREL
  - Sharp

- Efficiency Milestones
  - Varian (216x conc.)
  - Stanford (140x conc.)
  - Spire
  - Stanford
  - NREL
  - Sharp
  - Georgia Tech
  - UNSW
  - NREL
  - NREL
  - NREL
  - Sharp (large-area)
  - University of Stuttgart (45 μm thin-film transfer)
  - NREL
  - NREL
  - NREL
  - NREL
  - NREL
  - NREL
  - FhG-ISE
  - FhG-ISE
  - FhG-ISE

- Dates and Categories
  - Boeing Spectrolab (metamorphic)
  - NREL (inverted, metamorphic)
  - Amonix (92x conc.)

From 5/28/08 presentation at U. Toledo by L. Kazmerski, Dir. NCPV, U.S. DOE
actual and attainable single junction cell efficiencies
(inorganic materials)

Attainable cell efficiencies for AM0 (solid line) and AM1.5 spectra (dashed line) and best efficiencies achieved for several materials as single junctions. (Kazmerski 2006)
First generation: wafer silicon modules

Three types of commercial silicon wafer cells as described in the text. From Kazmerski 2006. a) Sun Power, b) BP Solar, c) Sanyo HIT cell
Second generation (thin-film) cells

CdS/CdTe

Glass
TCO
HRT
CdS
CdTe
ZnTe
grid

CdS/CIGS

grid
ZnO:Al
ZnO
n-CdS
p-CIGS
Mo
glass
(sodalime)

a-Si triple junction
Grain boundaries: the challenge of polycrystalline thin-film cells.

Fig. 4.2 Structure of the polycrystalline CIGS and CdTe cells. From Noufi 2006.
Third generation concepts

- multijunction III-V
- organic
- dye sensitized
- hybrid cells
Fig. 17. Cross-sections of triple-junction, high-efficiency solar cells: (a) lattice-matched design, (b) lattice-mismatched (metamorphic), and (c) lattice-mismatched, thin, inverted structure. ARC is the antireflection coating.
concentrators:
derrestrial implementation of high efficiency cells
Device representation of a dye-sensitized solar cell

- Conducting glass electrode
- Pt mirror
- Electrolyte with redox mediator ($I^- / I_3^-$)
- TiO$_2$ with adsorbed dye
- TCO glass electrode

Sunlight
Band diagram and processes for polymer organic solar cells
PV modules

- solar resource (U.S.)
- history of cost reductions
- manufacturing technology
PV Energy kWh/kW-yr
(for any flat solar module)
assembly from smaller cells

monolithic integration

from cell to module--series integration

First Solar, 40 MW, Brandis, Germany

nonconducting substrate
First Solar—the largest U.S. module producer
(Began as Solar Cells Inc on the U.T. campus)

Module Production Capacity:
Ramped the first 25MW module production line in Perrysburg, Ohio to its steady state volume in 2005

Added two additional 25MW production lines in the U.S. in 2006

Annual Capacity = 75MW by end 2006 (raised to 90 MW in 2007)
Xunlight Corp.
flexible PV products
Top 15 Global Producers of PV in 2007

1. Q-Cells (DE) - 375 MW
2. Sharp (JP) - 230 MW
3. Suntech (CH) - 300 MW
Tie 4. Kyocera (JP) - 200 MW
Tie 4. First Solar - 200 MW
6. Motech (TW) - 150 MW
7. Sanyo (JP) - 150 MW
8. SunPower (PH) - 100 MW
9. Baoding Yingli (CH) - 100 MW
10. SolarWorld - 75 MW
11. BP Solar - 75 MW
12. Mitsubishi (JP) - 50 MW
13. JA Solar (CH) - 50 MW
14. Solarfun (CH) - 30 MW
15. Isofoton (ES) - 30 MW

3/08 data from PVNews
# Production of solar modules in the U.S.

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*First Solar (Perrysburg, OH), UniSolar (Auburn Hills, MI) and Global Solar (Az) are exclusively thin-film PV mfgs.

(3/08 data from PVNews)
Electricity price convergence – 5 to 6 years
(Source: Deutsche Bank 2007)

Solar PV industry outlook

Definitions:
First Generation PV: bulk crystalline silicon (monocrystalline, multicrystalline)
Second Generation PV: inorganic thin films (CdTe, a-Si:H, nc-Si:H, CIGS)
Third Generation PV: nanostructures, organic/hybrid, advanced concepts
PV Module Production Experience (or "Learning") Curve

Based on discovery and progress in new technologies

* Future-year markers are based on 25% annual growth rates (expect >>25% in this scenario)

Cumulative Production (MWp)

PV Module Price (2002$/Wp)

1976 $3/W_p

2002

2013*

2023*

thin films

unknown!

90%

80%

70%

(First Solar module production cost Q4 2007 = $1.13/W_p)

From Tom Surek & Robt Margolis, Third World Conf. on PV Energy Conversion, Osaka, May, 2003
PV produces electricity just when it is most needed! electricity usage (NY State) vs. time of day

source:  http://currentenergy.lbl.gov/ny/
...and sometimes grid electricity fails!

Sunday, August 08, 2004 Cleveland Plain Dealer--
About 50 million people were affected, and the economic impact was estimated at more than $6 billion in lost business and damages.
...and sometimes grid electricity fails!

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About 50 million people were affected, and the economic impact was estimated at more than $6 billion in lost business and damages.
PV at the workplace + plug-in electric vehicles = off-peak power for the home

Not only is the e-truck charged with solar, it can power up the house for emergencies...

Exeltech inverters with transfer switch and subpanel circuits for:
- furnace,
- water heater,
- sump pump,
- kitchen,
- master bedroom
PV, Wind and the Smart Grid

• Sensors and controls together with a communications backbone can support bi-directional power flow and help to reduce the need for base-load power generation and dispatchable power.

• The smart grid can increase the penetration of solar and wind and enable a lower carbon grid.

• Navigant Consulting is engaged in a major study of the potential for and impacts of a PV smart grid to be completed in October, 2008, involving:
  • Electric utilities
  • Equipment manufacturers and installers
  • Service providers
  • Lenders and investors
PHEVs and Vehicle-to-Grid
(with either wind or solar)

Figure 4: Wind Penetration with PHEVs
from: Short and Denholm, NREL
A Solar Grand Plan
Ken Zweibel, James Mason, Vasilis Fthenakis
Scientific American, Dec. 16, 2007

• PV farms in the U.S. Southwest
  [can use high efficiency, concentrating PV (CPV)]

• High Voltage Direct Current (HVDC) long-distance transmission lines throughout the U.S. deliver power to regional AC grid

• Compressed air storage (1100 psi) in natural gas reservoirs across the U.S.

• Natural gas turbines w/ compressed air used for off-peak power
recent developments

**Battery storage**--Xcel Energy has signed a contract to purchase a battery from NGK Insulators Ltd. The 20 50-kilowatt NaS battery modules will be able to store about 7.2 megawatt-hours of electricity, with a charge/discharge power of one megawatt. The project will take place in Luverne, Minn., about 30 miles east of Sioux Falls, S.D., with the battery installation beginning this spring adjacent and connected to a nearby 11-megawatt wind farm owned by Minwind Energy, LLC. The battery is expected to go on-line in October 2008.

- **IBM** announced Monday a joint venture with Tokyo Ohka Kogyo to produce CIGS solar modules
- Miasolé, Nanosolar, HelioVolt and Global Solar Energy also are developing CIGS modules
- **GE Energy** last week announced it had raised its stake to a controlling interest in PrimeStar Solar developing CdTe modules
- other CdTe module developers: AVA, Calyxo
Energy payback time for various PV materials

Reaping the environmental benefits of solar energy requires spending energy to make the PV system. But as this graphic shows, the investment is small. Assuming a 30-year system life, PV systems will provide a net gain of 26 to 29 years of pollution-free and greenhouse-gas-free electrical generation.

Ribbon Si growth techniques

Upper: edge fed growth (EFG)
Lower: string ribbon (SR)

Upper: ribbon growth on substrate (RGS)
Lower: molded wafer (RST)
self-assembled multijunctions

Figure 8 Structure for high-efficiency (50%) organic PV cell based on a nanostructured substrate onto which thin layers of molecular multi-junctions are grown and anchored onto the nanostructure surface. The red circle denotes an electron acceptor; the blue square, an electron donor; and the yellow circle, a metal nanoparticle.