Solar Energy Technologies: Research, Applications and Opportunities

Presentation to DOE/National Association of State Universities and Land Grant Colleges (NASULGC)

August 3, 2004

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Electronic Materials and Devices
Solar Technology Programs

- Photovoltaics (PV)
- Concentrated Solar Power (CSP)
- Solar Thermal
- Solar Lighting
Solar Lighting

Estimated Itemized Cost in Small (~500 units) Quantities
- Primary/secondary mirror - $200.00
- Balance of roof-mounted system - $1,000.00
- Light Distribution - $1,200.00
- Hybrid Luminaires/Controls - $600.00
- Building Preparation - $500.00
- Installation/Alignment/Calibration - $500.00
- Total - ~$4,000.00 per m² of collection area

Estimated Levelized Cost 0.12 $/kWh

Each 3 mm fiber carries 350 lumens
Low-Cost Solar Water Heaters

Unpressurized, Integral Collector Storage (UPICS) Schematic

- Immersed heat exchanger
- Glazing(s)
- Insulation
- Thin-walled polymer vessel of water
- Supply/Return Piping
Low-Cost Solar Water Heaters

**Status:**
- Mild climates: $0.08 - $0.10/kWh in 2003
- Cold climates: $0.12 - $0.14/kWh in 2003

**Technical Challenges:**
- **Polymer durability** – the key technical challenge
- **System performance**
  - Overheating protection
  - Heat exchanger sizing and placement
- **Building code issues**
  - Use of plastics, e.g., flammability
  - Structural concerns, e.g., roof weight, wind loading
- **Manufacturing process design**
  - Thermoforming and rotomolding tolerances and temperature limits
Concentrating Solar Power

- Power Tower
- Concentrating Photovoltaics
- Parabolic Trough
- Dish/Stirling
SW Solar Energy Potential

<table>
<thead>
<tr>
<th>State</th>
<th>Solar Capacity (MW)</th>
<th>Land Area (Sq Mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ</td>
<td>3,267,456</td>
<td>25,527</td>
</tr>
<tr>
<td>CA</td>
<td>821,888</td>
<td>6,421</td>
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<tr>
<td>NV</td>
<td>743,296</td>
<td>5,807</td>
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<tr>
<td>NM</td>
<td>3,025,920</td>
<td>23,640</td>
</tr>
<tr>
<td>Total</td>
<td>7,858,560</td>
<td>61,395</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.

Solar Energy Resource ≥ 7.0 kWhr/m²/day (includes only excellent and premium resource)

Current total generation in the four states is over 100,000 MW.

Planned additions in four states over the next 3 – 5 years are 37,099 MW of which 87.6% is natural gas.

1000 MW of CSP requires 7.7 mi².
Concentrating Solar Parabolic Trough Systems

**Current Advances**
- 20% improvement in receiver efficiency
- Development of lower-cost concentrator designs
- Reduction in LEC from $.16/kWh to $.10/kWh

**Projected Advances**
- Integration w/ low-cost thermal storage
- Improved efficiency through advanced receivers and high temperature operation
- Cost reductions through plant scale-up
- Reduction in LEC from $.10/kWh to $.04-$0.06/kWh
Parabolic Trough Development Activities

- Trough R&D
  - Low-cost concentrator designs
  - Near- and long-term thermal storage
  - Advanced receiver designs
  - Alternative power cycles
1000 MW Initiative

• In 2001 Congress asked DOE to determine what would be required to deploy 1000 MW of Concentrating Solar Power in the Southwest U. S.

• DOE and CSP industry approached the Western Governors’ Association through the Western Interstate Energy Board to explore implementation.

• A number of Southwestern States have high solar potential and some have renewable energy portfolio standards (particularly, AZ, CA, NM, and NV) and the potential to gain from development of their solar energy resources.

• Western Governors’ likely to create Southwest Solar Task Force to investigate mechanisms for implementing regional initiative
World PV Cell/Module Production (MW)

Source: PV News, March 2004
PV Manufacturing R&D Cost/Capacity

- **Actual** and **Projected** trends shown for 'Average' Module Manufacturing Cost ($/Wp) vs. Total PV Manufacturing Capacity (MW/yr).

- Data from **2003 Data** (13 PV Manufacturing R&D participants with active manufacturing lines in 2003) and direct module manufacturing cost only (2003 Dollars).


- Source: National Renewable Energy Laboratory (NREL).
Reduction in Module Price versus Cumulative Shipments

Experience Curve

25% reduction in price for every doubling of cumulative shipments

Source: Paul Maycock

Reduction in Module Price vs Cumulative Shipments

$[\text{1999}]/\text{Wp}$
PV System vs. Electricity Costs

Capacity Factor = 0.2
(U.S. Average)

Capacity Factor = 0.25
(South West U.S.)

Japanese Retail Rate

German Retail Rate

Pennsylvania Retail Rate

California Retail Rate

Additional Assumptions:
System Lifetime = 20 years
Real Interest Rate = 6%
O&M = 0.1 cent per kWh

Note: In Japan with subsidy set at 33-48% and system cost of $7/Wp, COE is 18-23 cents/kWh. In 2000 Germany had 40% subsidy and 51 cents/kWh buy-back rate.

R. M. Margolis, NREL Presentation, March 24, 2003, page 15
PV Market Sectors

2000 Actual  0.3 GW

Consumer  Communication
Off Grid  Hybrid/Commercial
Grid Connected BIPV  Utility Scale

2010 Projected  4.5 GW
**Key companies:** Shell Solar, BP Solar, GE, Sharp, Kyocera, Sanyo, Motech, Cypress-SunPower

- ~85% of today's market
- ~800 MW capacity (to double in near-term)
- Proven products, 20-25 year warranties
- Large ingots: 100 kg CZ, 250 kg casting
- Multiple ingot growth with melt replenishment
- Wire saw: < 250 µm wafers, < 200 µm kerf

**Efficiency Status**

<table>
<thead>
<tr>
<th></th>
<th>Cells</th>
<th>Modules</th>
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</thead>
<tbody>
<tr>
<td>Float-zone</td>
<td>24.7</td>
<td>22.7*</td>
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<tr>
<td>Czochralski</td>
<td>22.0</td>
<td>13–17</td>
</tr>
<tr>
<td>Cast poly</td>
<td>19.8</td>
<td>10–16</td>
</tr>
</tbody>
</table>

- Batch/continuous processing
- High-efficiency devices in production
- Well-developed technology base--new understanding of defects/impurities

* Best prototype
**Key companies:** RWE Schott Solar, Evergreen Solar, GE, Pacific Solar, Kaneka

- Status varies from prototype modules to pilot production to commercial products (many MW)
- Proven products (~ 6% of market)
- Capacity increases underway—many tens of MW in near term
- Improved performance from defect/impurity and passivation studies
- Increasing interest in thin silicon growth

**Efficiency Status**

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</tr>
</thead>
<tbody>
<tr>
<td>EFG</td>
<td>14–16</td>
</tr>
<tr>
<td>String ribbon</td>
<td>14–16</td>
</tr>
<tr>
<td>Thick Si/substrate</td>
<td>16.6</td>
</tr>
<tr>
<td>Thin Si/substrate</td>
<td>5-12*</td>
</tr>
</tbody>
</table>

*Depends on process (some efficiencies not verified)

**Best prototype**
Ink Jet Printing of Ag and Cu contacts for Si Solar Cells 8% Cells on Si$_3$N$_4$

Line thickness: 15 µm
Line width: 250µm
Dep. temperature: 180 °C
Ann. temperature: 850 °C
Substrates from Evergreen Solar
Building Higher Efficiency onto the Expanding Infrastructure for Silicon PV

**Heterojunction a-Si/c-Si cell**
Potential >20% Efficient

<table>
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<tr>
<th>Material</th>
<th>Description</th>
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<tr>
<td>ITO</td>
<td>a-Si n-type emitter</td>
</tr>
<tr>
<td>a-Si intrinsic thin layer</td>
<td></td>
</tr>
<tr>
<td>p-type crystal-Si wafer</td>
<td></td>
</tr>
<tr>
<td>Al-Si alloyed p+-type back-surface field</td>
<td>Al</td>
</tr>
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14.17 %
Best $V_{oc}$ = 628 mV (p-type CZ cell record)

**GaNP on Si Tandem**
Potential >30% Efficient

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<td>Al</td>
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$GaN_{0.02}P_{0.98}$
Conventional PV Installations
Breakout of Installed Price of a Residential PV System by %

Total System Price: $9/Wp

2.7 kWp, Grid-tied Residential PV System
Based on one of the Million Solar Roofs Installations

Total Labor = 28%
Total Materials = 72%

Roadmap: 2010 Target; $3.50/Wp

Price Elements (L = labor; M = Materials):
- Design (L): 3%
- Electrical (L): 13%
- Mounting (L): 13%
- Modules (M): 12%
- Inverter (M): 7%
- Rack (M): 2%
Powerlight Roof Integrated PV System

Advances in PV System Design Can Also Achieve Cost Advantages

United Solar Shingles

Combines PV Power with Energy Saving from Insulation
**Efficiency status:**

- **Cell:** 12-19
- **Submodule:** 10-12
- **Module:** 7-11
- **Commercial:** 5-10

- Understanding of film growth, microstructures, defects, and device physics
- Reproducible high-efficiency processes
- Multiple junctions

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**Key companies:** United Solar/ ECD, Shell Solar, EPV, Global Solar/ITN, First Solar, Iowa Thin Films, HelioVolt, Wurth Solar, Showa-Shell, DayStar, Miasolé

- Multi-MW/year in consumer products
- 5 and 10 MW plants operational; few tens of MW in near term
- Unique products for building integration
CIGS Performance Across the Entire Compositional Range for Tandem Cells

Efficiency (%) vs. Absorber band gap (eV)

- 19.3%
- 14.5%
- 14.5%
- 10.2%

Open Circuit voltage (V) vs. Absorber band gap (eV)

- 0.9
- 0.8
- 0.7
- 0.6
- 0.5
Polycrystalline Thin Film Tandem Solar Cell

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
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<tbody>
<tr>
<td>7059 Corning glass</td>
<td>CTO</td>
</tr>
<tr>
<td>CTO</td>
<td>ZTO</td>
</tr>
<tr>
<td>ZTO</td>
<td>S-CdS:O</td>
</tr>
<tr>
<td>S-CdS:O</td>
<td>CdTe</td>
</tr>
<tr>
<td>CdTe</td>
<td>Cu_x Te back-contact</td>
</tr>
<tr>
<td>Cu_x Te back-contact</td>
<td>ITO</td>
</tr>
<tr>
<td>ITO</td>
<td>Ni/Al grids</td>
</tr>
<tr>
<td>Ni/Al grids</td>
<td>In contact</td>
</tr>
<tr>
<td>In contact</td>
<td>c-ZTO / i-ZnO</td>
</tr>
<tr>
<td>c-ZTO / i-ZnO</td>
<td>CBD-CdS</td>
</tr>
<tr>
<td>CBD-CdS</td>
<td>CIS</td>
</tr>
<tr>
<td>CIS</td>
<td>Mo</td>
</tr>
<tr>
<td>Mo</td>
<td>Soda-lime glass</td>
</tr>
</tbody>
</table>

CdTe top cell
Achieved 50% transmission, 12.7% efficiency

CIS bottom cell
Achieved 14.5% efficiency

FY06 milestone: 15% efficient 4-terminal device will be met one year early.
Accomplishments: High Throughput Methods

Developing Capabilities for Combinatorial Materials Science at NREL

Combinatorial, Focused-Beam X-ray Diffraction

Equations:
- \( \text{Ga}_2\text{O}_3 \)
- \( \text{In}_2\text{O}_3 \)
- \( \text{SnO}_2 \)
- \( \text{CdO} \)
- \( \text{ZnO} \)
High Throughput Research Methods

TCO Combi at NREL

Research Time Compressed to one week

Conductivity (Ω cm)$^{-1}$

%In for Zn (as-measured by EPMA)

Mobility (cm$^2$/V s)

Carrier Concentration x 10$^{19}$ (#/cm$^3$)

Library 2
%In: 15 → 50

Library 3
%In: 34 → 75%

Library 4
%In: 62 → 95

Research Time Compressed to one week
**Key companies:** Amonix, Spectrolab, Emcore, Sunpower, ENTECH; Solar Systems Ltd

- Manufacturability demonstrated
  - Low-concentration, line focus
  - High-concentration, point focus
  - High efficiency cells (Si, GaAs, multijunctions) in production
- Limited applications in today's markets
  - Hydrogen generation may be well matched

**Efficiencies:**

- Si (up to 400X) 27
- GaAs (up to 1000X) 28
- GaInP$_2$/GaAs (1X) 30.3
- GaInP$_2$/GaAs (180X) 30.2
- GaInP$_2$/GaAs/Ge (40–600X) 36.9

- Module efficiencies: 15-17% (Si); best prototypes: >20% (Si), >24% (GaAs), 28% (GaInP$_2$/GaAs/Ge, 10X)
- Large space markets drive GaInP$_2$/GaAs and GaInP$_2$/GaAs/Ge commercial cell production
Solar Tracking Provides Energy Benefits

- Tracking systems provide 15 to 20% more energy than fixed PV
- Up to 40% more than fixed horizontal systems
Novel Concepts, Excitonic Devices and New Materials

- Key Companies: GE, Kodak, Konarka, NanoSolar, NanoSys, Luna, UltraDots ...

- Dye-sensitized TiO₂ photochemical cells
- Potential for very low cost
- Nanocrystalline TiO₂, with monolayer dye sensitizer, in liquid electrolyte
- 11%-efficient cell; scale-up for consumer products underway
- Dye stability issue
- Gel or solid-state electrolytes in research
- Photoelectrochromic window (with WO₃)
Accomplishments: Discovery

Organic Solar Cells
Nanostructured Oxides – Polymer Composites

2-d slice of a nanostructured device concept:

- Anode
- Donor Polymer
- Adsorbate
- Structured oxide
- TCO

Multistep charge transfer at interface:

1) polymer* + adsorbate → polymer* + adsorbate-
2) adsorbate* + oxide → adsorbate + oxide*

Strengths:
- Long optical path-length
- Short carrier-to-electrode path-length
- Higher electron mobility
- No isolated clusters, guaranteed percolation
- Better adhesion between layers, mechanical durability

Weaknesses:
Controlled Nucleation Layers for Nanocomposite Organic Solar Cells

The Goal

ZnO Nanofibrils

Wetted with P3HT
Best Research-Cell Efficiencies

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

Crystalline Si Cells
- Single crystal
- Multicrystalline
- Thin Si

Thin Film Technologies
- Cu(In,Ga)Se₂
- CdTe
- Amorphous Si:H (stabilized)

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

Flowchart showing efficiency (%) over time from 1975 to 2005 with various research institutions and technologies, including Crystalline Si Cells, Thin Film Technologies, and Emerging PV technologies.
Solar Technologies Research and Applications

- Solar technologies maintain an aggressive learning curve and are cost competitive as alternative energy sources in a growing number of markets
  - Approaching retail electricity rates in Japan and Europe
- Low retail energy costs in the U.S. discourage manufacturing and deployment of new technologies
- Projected technology improvements can bring solar electricity generating costs to U.S. retail electric levels
Changing Energy Landscape

- Natural Gas Shortage
- Transmission and Distribution Limitations
- CEO’s Call for National Energy Strategy
  - With Balance
- International Pressure on Global Climate Change
- State and Local Initiatives for Renewable Energy
From: Nathan Lewis, Global Energy Perspective

Energy Reserves and Resources

<table>
<thead>
<tr>
<th>Resource</th>
<th>Reserves/(1998 Consumption/yr)</th>
<th>Resource Base/(1998 Consumption/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>40 - 78</td>
<td>51 - 151</td>
</tr>
<tr>
<td>Gas</td>
<td>68 - 176</td>
<td>207 - 590</td>
</tr>
<tr>
<td>Coal</td>
<td>224</td>
<td>2160</td>
</tr>
</tbody>
</table>

Rsv = Reserves
Res = Resources

(Unconv)
Mean Global Energy Consumption, 1998

Total: 12.8 TW
U.S.: 3.3 TW (99 Quads)

From: Nathan Lewis, Global Energy Perspective
Sources of Carbon-Free Power

• Nuclear (fission and fusion)
  • 10 TW = 10,000 new 1 GW reactors
  • i.e., a new reactor every other day for the next 50 years
    → 2.3 million tonnes proven reserves; 1 TW-hr requires 22 tonnes of U
    → Hence at 10 TW provides 1 year of energy
    → Terrestrial resource base provides 10 years of energy
    → Would need to mine U from seawater (700 x terrestrial resource base)

• Carbon sequestration

• Renewables

From: Nathan Lewis, Global Energy Perspective
From: Paul B. Weisz, Physics Today, July 2004
Solar Land Area Requirements

From: Nathan Lewis, Global Energy Perspective
<table>
<thead>
<tr>
<th>Country</th>
<th>Energy consumed per year*</th>
<th>Land area</th>
<th>Approximate solar cell area needed</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Quads per 10^6 people</td>
<td>10^3 km^2</td>
<td>10^3 km^2</td>
</tr>
<tr>
<td>US</td>
<td>0.36</td>
<td>9,591</td>
<td>263</td>
</tr>
<tr>
<td>Belgium</td>
<td>0.27</td>
<td>30</td>
<td>7</td>
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<tr>
<td>Australia</td>
<td>0.19</td>
<td>7,580</td>
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<tr>
<td>Russia</td>
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<td>16,981</td>
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<td>Egypt</td>
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<td>996</td>
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</table>


From: Paul B. Weisz, Physics Today, July 2004
The Need to Produce Fuel

“Power Park Concept”

Fuel Production

Stationary Generation

Fuel Processor or Electrolyzer

Distribution

Storage

Fuel Cell

From: Nathan Lewis, Global Energy Perspective
Energy Costs

Coal
Oil
Biomass
Elect

$0.05/kW-hr

www.undp.org/seed/eap/activities/wea
Low Cost Processes

Large-Area Optical and Electronic Materials

$\$/M^2 versus Million M^2 per Year

FPD

Fuel Cell

Bipolar plate

PV

Coated Glass

Solar Fuels Electrode

Glass

Paint

NREL National Renewable Energy Laboratory
Solar Technology Opportunities

• Source of Carbon Free Power

• Solar energy is the only currently practical primary source in sufficient abundance to sustain growing energy demand for centuries to come.

• Massive change to energy infrastructure requires decades to implement, along with massive investment.