Manufacturing Challenges for PV in the 21st Century

NSF Workshop – Arlington, VA, March 24-5, 2009
Topics

- Introduction to PV manufacturing
- Manufacturing Roadmap
- Implementation/Policy
# PV Technologies and Commercialization Status for power generation markets

<table>
<thead>
<tr>
<th>Technology</th>
<th>Commercialization Status</th>
</tr>
</thead>
</table>
| Crystalline Silicon (C-Si) | Mature (commodity)*  
-> 90% of installed market  
-> 25 years track record     |
| Thin Films (TF)     | Mature/Emerging *   
-a-Si, <5 % of installed market  
-- >20 years track record  
- CdTe, CIGS, < 5% of installed market  
- <5 years track record |
| Concentrator PV (CSP) | Piloting  
- Mainly R&D  
- some pilot field installations (< 2-3 y) |
| Organics            | R&D and piloting – current module/cell designs not suitable for power generation |

* "Track record" estimates here give the years that latest module designs and manufacturing methods have been placed in high voltage field installations.
PV Products: C-Si (CZ, mc) vs Thin Films (CdTe, a-Si) – 2008 total 5458 MWp, market about 86% Si (Navigant)

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<tbody>
<tr>
<td>1</td>
<td>Sharp Solar</td>
<td>375.2</td>
<td>Sharp Solar</td>
<td>434.7</td>
<td>Sharp Solar</td>
<td>363.0</td>
<td>Q-Cells</td>
<td>547.2</td>
<td>Cz</td>
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<td>2</td>
<td>Kyocera</td>
<td>142.0</td>
<td>Q-Cells</td>
<td>240.4</td>
<td>Q-Cells</td>
<td>344.1</td>
<td>Suntech</td>
<td>497.5</td>
<td>Cz</td>
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<tr>
<td>3</td>
<td>Q-Cells</td>
<td>131.2</td>
<td>Kyocera</td>
<td>180.0</td>
<td>Suntech</td>
<td>309.0</td>
<td>Sharp</td>
<td>458.0</td>
<td>Cz/a-Si</td>
</tr>
<tr>
<td>4</td>
<td>Schott Solar</td>
<td>95.0</td>
<td>Suntech</td>
<td>152.0</td>
<td>Kyocera</td>
<td>207.0</td>
<td>First Solar</td>
<td>434.7</td>
<td>CdTe</td>
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<tr>
<td>5</td>
<td>BP Solar</td>
<td>85.8</td>
<td>Sanyo</td>
<td>120.5</td>
<td>First Solar</td>
<td>186.0</td>
<td>Kyocera</td>
<td>290.0</td>
<td>Cz</td>
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</tbody>
</table>
Cost Breakdown for C-Si Technologies (Applied Materials)

Driving Down Cost per Watt

- Current: $2.04
- Technology Improvement: $1.67
- Materials Reduction: $1.55
- Advanced Automation: $1.47

Assumes fixed silicon costs at $55/kg
Cost Schematic for a-Si Technology (Applied Materials)

SunFab Module Installation Benefits

Projected Installed Cost 2010

- c-Si: $1.69, $1.26
- CdTe: $0.90, $1.62
- Applied SunFab TJ Single Line: $1.00, $1.36
- Applied SunFab GW Scale: $0.85, $1.36

BoS Costs: $2.95, $2.52, $2.36, $2.21
Module Production Cost: $0.75, $0.90, $1.00, $0.85

SunFab enables the lowest installed cost per watt

Sources: Companies’ announcements, Deutsche Bank, Photon, Applied Materials
Assumptions: Applied TJ at 10% eff., CdTe at 12% eff, c-Si at 18% eff.

Gay - Photon, Munich 2009
The Reality - US PV installations by American Capital Energy on commercial rooftops

- **Rocklin CA – (Sacramento area)**
  - 1.2 MWp DC, 1 MWp AC
  - 16,200 m² (175,000 ft²)
  - 70 Wp/m² (7 Wp/ft²)

- **Atlantic City Convention Center**
  - largest rooftop array in US today
  - 2.36 MWp on 8 acres
  - 90 W/m² (9 W/ft²)
USA: “Best in Class” at American Capital Energy – 1.2 MW DC (1 MWp AC)
- refrigerated warehouse roof of United Natural Foods, Rocklin, CA;
- no storage, ca 50% max of building peak energy use; Density: ca. 7 Wp/ft².
“Best in Class” at SunPower: Blundin, Photon, Munich 2009

SunPower: 628 kW
Conventional: 410 kW
Thin Film: 204 kW

Area: 4650 m² (50,000 ft²)
SunPower power density: 12.5 Wp/ft²
Scale of 0.25 TWp, with capacity factor of 25% this is 5% US electric needs in 2020; area: 50kmx50km

Rooftop Segment Potential

- 3 Billion m2 of commercial roof tops
- 0.3 TWp at 100 W/m2 practical area coverage

Reality

- 400 MWp total/250p MW commercial, ’08 US market
- As of 2009, only two projects in US > 10 MWp, both ground mount (10 MWp CdTe, 14 MWp c-Si)
- 0.3 TWp = > 125,000 projects of Atlantic City scale
- Time Scale: 6 mo. for Atlantic City, 4-5 years sand to module
The Solution To Storage – The Hydrogen Economy

Water                      Hydrogen                      Electricity
PV              Electrolizer             Fuel Cell

6 h/day (x5 Wp)                        24 h/day

This manufacturing group has one challenge:
Show how to build one multi-kW or -MW unit per sec.

- Processes/Equipment definition
- Process controls
- Investments for scale up
- Technology Diversity
- Infrastructure
- Standard Products/Testing
- Long Range Strategies/equipment set of the future
Manufacturing Needs (US PV Roadmap – 1999)

- Develop high volume/throughput processes
- Develop process control
- Common industry objectives (consortia)
- Low cost packaging (module assembly) and testing
- New process development
- Balance of Systems
State-of-the-art “best-in-show” c-Si factory concept

Grid Parity Factory

PV system cost

- 0.90 €/Wp BOS (Balance Of System Cost)
- 0.35 €/Wp 25% margin
- 0.13 €/Wp 10% overhead
- 1.26 €/Wp module manufacturing cost

2.60 €/Wp PV system cost

Grid Parity: for roof top systems in Southern Italy at 0.30 €/kWh grid electricity

Module manufacturing target cost

- Canada
  - Silicon: 0.21 €/Wp
  - Ingot: 0.14 €/Wp
  - Wafer: 0.18 €/Wp
  - Cell: 0.23 €/Wp
  - Module: 1.45 €/Wp

- Germany
  - Silicon: 0.21 €/Wp
  - Ingot: 0.14 €/Wp
  - Wafer: 0.18 €/Wp
  - Cell: 0.23 €/Wp
  - Module: 1.45 €/Wp

1.26 €/Wp

Parameters Grid Parity Factory

- Poly Si (TCS / "Siemens"): 2500 t
- Multi ingot: 2273 t
- Multi wafer: 97.2 million wafer
- Cell: 93.8 million cells
- Module: 347 MW
- CAPEX ~720 Mio €
Integrated Manufacturing Thin Films Example – <800 m2 for 100 MW CIGS factory

Centrotherm – Photon, Munich 2009
**Scale of PV Challenge (PV capacity factor: 25%)**

US electricity use = $\frac{1}{4}$ of total energy of 4 TW

<table>
<thead>
<tr>
<th>Year</th>
<th>Volume (Capacity)</th>
<th>Si Feedstock</th>
<th>Cost</th>
<th>Manufacturing lines</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>5 GW (10 gW)</td>
<td>50,000 mT</td>
<td></td>
<td>100 mfg lines</td>
<td>$5 B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10g/W</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>2g/W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>10 GW</td>
<td>100,000</td>
<td>$7.5 B</td>
<td>10</td>
<td>$50 B</td>
</tr>
<tr>
<td>2015</td>
<td>50 GW</td>
<td>500,000</td>
<td>$7.5 B</td>
<td>50</td>
<td>$250 B</td>
</tr>
<tr>
<td>2020</td>
<td>250 GW</td>
<td>2,500,000</td>
<td>$37.5 B</td>
<td>250</td>
<td>$1.25 T</td>
</tr>
<tr>
<td>2024</td>
<td>1 TW</td>
<td>10,000,000</td>
<td>$150 B</td>
<td>1,000</td>
<td>$5 T</td>
</tr>
</tbody>
</table>

**50% Thin Films Manufacturing**

<table>
<thead>
<tr>
<th>Year</th>
<th>Capacity</th>
<th>Si Feedstock</th>
<th>Cost</th>
<th>CAGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>0.5 GW</td>
<td>Rare metals</td>
<td>$1 B</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>16 GW</td>
<td>Cd, Ga, In, Se</td>
<td>$32 B</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>125 GW</td>
<td>Silane</td>
<td>$250 B</td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td>500 GW</td>
<td>NF3</td>
<td></td>
<td></td>
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</table>
Roadmap: Manufacturing Parameters

- Material purity – silicon, metals and gases
  - Growth (C-Si)/deposition rates (TF)
  - Yield/Information systems
  - Module performance/cell, absorber efficiency

- Equipment cost and factory area/automation
  - Throughput (piece rate, deposition rate)
  - Thin wafers (c-Si)
  - Yield/Information systems
Roadmap: Throughput
Common Issue for both c-Si and TF

Crystal growth limitations

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Desired:

- Higher growth speed (c-Si melt)
- Higher deposition rates (gas phase)

lower quality
Roadmap: c-Si Barriers

- Large wafers: 156 → 210 sq mm
- Wafer thickness reduction: 200 → 50 μm
- Wafer handling: low stress grippers
- High speed transfers: 2,400 → 3,600 parts/h
- Low cost dedicated robotics
Module Production Line Robotics
– Heller, Schmid, Photon, Munich 2009

Module Production Line

Glass Loader
<table>
<thead>
<tr>
<th>Leadership Area</th>
<th>Existing Semis Strategy</th>
<th>Proposed PV Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>University-Industry Partnership</td>
<td>SRC</td>
<td>University Centers of Excellence and NREL</td>
</tr>
<tr>
<td>Industry Consortia</td>
<td>SEMI, SMTA, INEMI, IPC</td>
<td>Industry alliances with equipment manufacturers</td>
</tr>
</tbody>
</table>
Reference Slides
Baseline – PV Technology Market Shares in 2008 (Navigant)

2008 Total Shipments 5455.8-MWp
Example on Diversity Issue - Solar Cell Concepts

- Solar Cells
  - Silicon
    - Crystalline wafers
      - Poly
      - Mono
    - Thin Film
      - aSi/μcSi
    - GaAs (conc)
  - Compound Semiconductor
    - Chalcopyrite CIGSSe
    - CdTe
  - Dye cells
  - Organic
  - New Concepts

Based on M. Powalla, ZSW
C-Si Solar Cell Manufacturing Costs

- Solar cell manufacturing cost per Wp determined:
  - Cell efficiency
  - Wafer cost (thickness, wafer quality)
  - Consumable cost
  - Yield
  - Utilization of factory (uptime, capacity usage)
Example of specialty metals used in CIGS thin film PV modules

<table>
<thead>
<tr>
<th></th>
<th>g/m²</th>
<th>$/g</th>
<th>$/m²</th>
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<tbody>
<tr>
<td>Cu</td>
<td>2.53</td>
<td>0.12</td>
<td>$0.5</td>
</tr>
<tr>
<td>In</td>
<td>3.16</td>
<td>0.8</td>
<td>$3-5</td>
</tr>
<tr>
<td>Ga</td>
<td>0.76</td>
<td>0.7</td>
<td>$0.65-1</td>
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</table>
P(lasma)VD Cost Analysis for TCO in scaling up to Gen 8.5 or 5.7 m² glass substrates

<table>
<thead>
<tr>
<th>Costs</th>
<th>PIAnova Gen5</th>
<th>PIAnova Gen8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invest</td>
<td>1.00 %</td>
<td>0.50 %</td>
</tr>
<tr>
<td>Maintenance</td>
<td>0.20 %</td>
<td>0.10 %</td>
</tr>
<tr>
<td>Manpower</td>
<td>0.40 %</td>
<td>0.15 %</td>
</tr>
<tr>
<td>Energy</td>
<td>0.90 %</td>
<td>0.60 %</td>
</tr>
<tr>
<td>Target material</td>
<td>2.90 %</td>
<td>2.10 %</td>
</tr>
<tr>
<td>Total</td>
<td>5.40 Euro / m²</td>
<td>3.45 Euro / m²</td>
</tr>
</tbody>
</table>

[Image of equipment for TCO production]
## TCO Demand – 1 GW Fab

<table>
<thead>
<tr>
<th></th>
<th>a-Si a-Si/μc-Si</th>
<th>a-Si a-Si/μc-Si</th>
<th>CdTe</th>
<th>CIGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical substrate size (example)</td>
<td>1,3 m x 1,1 m</td>
<td>2,6 m x 2,2 m</td>
<td>0.6 m x 1.2 m</td>
<td>0.6 m x 1.2 m</td>
</tr>
<tr>
<td>Typical efficiency (example)</td>
<td>7%</td>
<td>7%</td>
<td>9%</td>
<td>11%</td>
</tr>
<tr>
<td>Required total module surface</td>
<td>14.4 million m²</td>
<td>14.4 million m²</td>
<td>11.2 million m²</td>
<td>9.2 million m²</td>
</tr>
<tr>
<td>Number of modules</td>
<td>10.1 million</td>
<td>2.5 million</td>
<td>15.6 million</td>
<td>12.8 million</td>
</tr>
<tr>
<td>Number of coating machines @ 60 sec cycle time</td>
<td>22</td>
<td>6</td>
<td>18</td>
<td>15</td>
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</tbody>
</table>
Cost Targets for TCO

Cost Reduction per m²

35% or 1,95 €/m² cost reduction by scaling from 1.4 m² to 5.7 m² coating surface:

- Target costs 0,80 EUR
- Invest costs 0,50 EUR
- Maintenance costs 0,10 EUR
- Energy costs 0,30 EUR
- Manpower costs 0,25 EUR
Thin CIGS Film cost breakdown
- Dimmler, Wurth Solar

- Material: 45-55%
- Equipment: 20-25%
- Energy: 5-8%
- Labour: 10-15%
New Thin Film Tandem Cell Based on Silicon

µc-Si + a-Si \rightarrow \text{an « ideal » combination}

- IMT pioneered in 1994 the µc-Si:H/a-Si:H or « micromorph » tandem
- Today, stabilized cell efficiencies of 11 to 12 % can be obtained with these tandems

\rightarrow \text{In such a micromorph tandem, the solar spectrum is ideally shared between top (a-Si:H) and bottom (µc-Si:H) cell}
Baseline - Vertically Integrated Manufacturing c-Si Example (86% of market in 2008)
### Roadmap: Materials used in current PV Manufacturing

<table>
<thead>
<tr>
<th>Materials - Specialty</th>
<th>Crystalline Silicon</th>
<th>Thin Films</th>
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<tbody>
<tr>
<td>Feedstock</td>
<td>Semi grade</td>
<td>Metals (often gas phase)</td>
</tr>
<tr>
<td></td>
<td>Solar grade</td>
<td>-Cd, Te, In, Se, Ga</td>
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<tr>
<td></td>
<td>Metallurgical grade</td>
<td>Gases</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Silane, SF6, F1,</td>
</tr>
<tr>
<td>Materials - Common</td>
<td>Glass</td>
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<tr>
<td></td>
<td>Encapsulant (EVA)</td>
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<tr>
<td></td>
<td>Electrodes: Ag, Al, Cu</td>
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Roadmap: Barriers
Common Issues for all Thin Film Solar Cells

- Volume ramp up, achieve the projected yield
- Thinner absorber layers
- Better TCO
- Better/cheaper encapsulation materials
- Lifetime
- Market acceptance/track record
- Next generation equipment (R2R), simplified production processes