Solar PV Manufacturing Cost Analysis: U.S. Competitiveness in a Global Industry

Stanford University: Precourt Institute for Energy

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Si Solar Manufacturing Supply Chain

Also...

- Capital equipment
- Raw materials
- Intermediate products

PV Module Trade Flows

Solar PV Market Developments
Global U.S. Position Ceded to China & Taiwan

- Between 2000 and 2010 global shipments grew 53% (CAGR)
- U.S. market share slipped from 30% to 7% (30% CAGR)
- China/Taiwan grew from <2% to 54% (115% CAGR)

China Solar PV: Export Driven

- Meager domestic demand belies China’s dominant production
- $9.3 \text{ GW}_\text{P,DC}$ shipments vs. $0.5 \text{ GW}_\text{P,DC}$ installed

China’s Focused Growth: (4) Key Players, All Si

Growth enabled by access to low cost debt, technology diffusion

U.S. Diversity vs. China Manufacturing Scale

- U.S. private investors encourage technology differentiation – opportunities for producers of innovative Thin Film PV technologies
- China’s government-backed investors fund more mature technologies – opportunities for w-Si technologies (quick scale-up; wages, exports)

2009 ARRA Manufacturing Tax Credit (section 48C):
• "...have the greatest potential for technological innovation and commercial deployment."

• "...employ new or significantly improved technologies as compared to commercial technologies."

• Amended EPAct §1703; Expired September 30, 2011.

“The (Loan Guarantee) program was designed to provide support to these cutting edge industries, which have great potential to create jobs in whatever country wins the clean energy race, but also involve technology and market risks that private sector lenders often cannot or will not underwrite.”
— Jonathan Silver, Executive Director LPO, U.S. DOE

Sources: Graphic – Bloomberg NEF (4/9/10, 4/16/10, 11/8/10, & 3/16/11); J. Silver Testimony before the Subcommittee on Oversight and Investigations Committee on Energy and Commerce, U.S. House of Representatives (September 14, 2011)
• Single junction wafer Si approaching practical performance limit
• Challenge facing thin films: closing the gap between laboratory and production devices
Private Investors Value Thin Film PV Potential

Thin Film PV technologies seek to close the gap: innovative, disruptive
- Startups raise capital based on defensible, disruptive IP position

Installed Solar PV System Price
Sensitivity to module efficiency, rack mounted, standard installation methods, national average labor rates

η = 12%; Leading commercial Thin Film PV module (2011)
η = 20%; Leading commercial wafer Si PV module (2011)
Lab CIGS cell: >20%
Lab Si cell: ~25%

International Investment Risk
### Other Investment Risk Considerations

| Country | Political and economic stability  
| Status, procedures, and maturity of legal system  
| Transparency of business dealings |
| Economic | Expected inflation  
| Local regulation |
| Currency | High cost and reliability of derivatives and other hedging instruments, particularly in emerging markets |
| Security | IP protection  
| Property ownership, including the ability of creditors to repossess assets |
| Financial | Interest rates  
| Insurance (business interruption) |

Only *Economic, Financial* risks quantified in this analysis

Other factors partially considered by Global $K_E$ approach

- **Security** risk factors related to IP, property ownership particularly important (innovative startup); binary considerations
- Access to subsidized China debt generally limits foreign ownership to minority stake, e.g., Evergreen-Jiawei JV
Expected Inflation by Country

- Delta between U.S. and China as high as 470 bps
- China labor rates rose nearly 50% in 2010. Some expect 2011 China inflation 20%.

Recent and Expected Inflation: by Country

Impact of Inflation on capital budgeting decisions [2]:
- Revenues
- Costs (non-depreciation)
- Cost of debt capital ($K_D^{Nominal}$)
- Increased demand for Investments in non-financial assets.
- Decreased supply of Regulators seek to limit growth

Sources: www.tradingeconomics.com
NREL private conversations with agent from leading Chinese Si PV manufacturer, January 2011
Inflation and Chinese Wages

Jiangsu province (Suntech) +5%, Jiangxi province (LDK) -26%

Manufacturing Laborers, National Average

Source: National Bureau of Statistics of China, Federal Reserve Bank of St. Louis
Market Volatility in the Global Equity Market

Specific market volatility measured as $\beta_{\text{Country}}$

- Covariance of target country index & ACWI, divided by variance of ACWI


Global CAPM Overview

\[ W.A.C.C. = [(D/V) \times K_D \times (1 - \tau_C)] + [(E/V) \times K_E] \]

**Levered, Nominal Cost of Debt \((K_D)\):**
\[ K_D = [(1 + R_f) \times (1 + i) - 1] + \text{levered corporate bond spread} \]

**Levered Cost of Equity \((K_E)\):**
\[ K_E = K_{E \text{Unlevered}} + [(D/E) \times (K_{E \text{Unlevered}} - K_D)] \]

Where, unlevered \(K_E\) is determined by unlevering \(R_E\):
\[ R_E = (K_D \& \ CRP) + (\beta_{\text{Equity}} \times \ EMRP_{\text{Global}}) \]

Country Risk Premium (CRP):
\[ \text{CRP} = R_{F \text{Country}} - R_{F \text{Global}} \]

Equity Market Risk Premium (EMRP):
\[ \text{EMRP}_{\text{Global}} = \text{EMRP}_{\text{Country}} / \beta_{\text{Country}} \]

- Levered corporate bond spread estimated based on current (Q3 2011) U.S. bond spreads, estimate of best (unlevered) Solar PV bond rating (B for established player, low gearing)
- \(\beta_{\text{Equity}}\) estimated based on private conversations with VCs, PE firms, banks. Solar PV industry: 2.0. Startup, e.g., company profiled in the following case study: 3.5

## Manufacturing Subsidies by Country

<table>
<thead>
<tr>
<th></th>
<th>U.S. Loan Guarantee, Manufacturing Tax Credit</th>
<th>U.S. State Subsidies</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic proprietorship required?</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Sales/Value Added Tax waiver?</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Property tax credits</td>
<td>100%</td>
<td>100%</td>
<td>N/A</td>
</tr>
<tr>
<td>Subsidized cost of debt</td>
<td>4.0%</td>
<td>3.0%</td>
<td>3.0-4.5%</td>
</tr>
<tr>
<td>Subsidized debt limit (D/ D+E)</td>
<td>60%</td>
<td>60%</td>
<td>80%</td>
</tr>
<tr>
<td>delay in processing subsidized debt</td>
<td>2 years</td>
<td>&lt;1 year</td>
<td>&lt;1 year</td>
</tr>
<tr>
<td>Facilities grant</td>
<td>100%</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Land grant</td>
<td></td>
<td></td>
<td>Discount purchase (land use rights)</td>
</tr>
<tr>
<td>Training grant (millions USD)</td>
<td>$0.5-4.5</td>
<td>$0.5-4.5</td>
<td></td>
</tr>
<tr>
<td>Effective Corporate income tax rate</td>
<td>28%</td>
<td>28%</td>
<td>21%</td>
</tr>
<tr>
<td>Income tax credits</td>
<td></td>
<td>30% MTC</td>
<td>Cash Grant in lieu</td>
</tr>
<tr>
<td></td>
<td></td>
<td>State: 5-7 year holiday</td>
<td>20 year holiday</td>
</tr>
</tbody>
</table>

**Sources:**
- Private conversations with solar PV manufacturers who are investigating potential production sites in U.S. and non-U.S. locations.
- U.S. Energy Information Administration
Solar PV Module Technologies

Disaggregate supply chain
• Multiple players, some vertically integrated
• Intermediate products are relatively cheap to ship
• Wide range of automation levels
• Relatively mature, less tech. differentiation than TF PV

Many flavors of TF PV
• Many opportunities for tech. differentiation
• Monolithically integrated
• Single factory: glass & gas in, modules out
• No intermediate products (shipping costs)
• Automation does not vary, regionally

Photos left to right: NREL/PIX 19248; NREL/PIX 15377; NREL/PIX 13859; NREL/PIX 13569
The Case for Foreign Direct Investment

China based c-Si PV manufacturer,
U.S. customer (end market)
Silicon Cell & Module Manufacturing

- **Direct labor content varies from <1.0 job/MWP DC to 4.0 jobs/MWP DC**
  - Suntech automation strategy (~1.4 jobs/MWP DC) reflects inflation risk, not cost benefits
- **Relative to low cost labor regions, automation requires:**
  - 80% less direct labor content, 33% additional investment (automation)

<table>
<thead>
<tr>
<th>500 MW_p DC c-Si Cell &amp; Module Facility</th>
<th>US</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cells</td>
<td>Modules</td>
</tr>
<tr>
<td>No. of Direct Laborers (all shifts)</td>
<td>296</td>
<td>104</td>
</tr>
<tr>
<td>Unskilled Labor rate ($ per hour)</td>
<td></td>
<td>$13.33</td>
</tr>
<tr>
<td>Manufacturing Engineer ($ per year)</td>
<td></td>
<td>$75,110</td>
</tr>
<tr>
<td>Total facility Capex ($/W_p)</td>
<td>$0.49</td>
<td>$0.19</td>
</tr>
</tbody>
</table>

China’s Comparative Advantage: Si Cells

Is China’s comparative advantage sustainable?

National average labor rates assumed for U.S., China scenarios. “Discount materials”: 10%.
“Discount equipment”: 50% for wet benches, screen printer lines, co-firing furnace operations only.
“Core Costs” include direct labor, materials, energy, depreciation expenses, but exclude: shipping costs, cost of capital, taxes.
Si Module Shipping Costs

- Costs including fees, insurance are significant, total: ~$0.05/W_{P\text{ DC}}
- Cost of capital excluded (Shanghai to Los Angeles: 30 day transit time)
- Cost of breakage excluded
- Shanghai to Hamburg, Newark to Hamburg costs roughly the same

Regional Benchmarking Analysis: Direct Si PV Module Core Costs

- China-direct (module) manufacturing cost benefits, excluding shipping: 1-2%
- Including shipping to U.S., China suffers a 5% cost disadvantage
  - Above Direct Costs analysis excludes other regional factors: direct government subsidies, income taxes, global economic instability (inflation), and investment risk factors

Note 1: Cost structures that are heavily comprised of variable costs, including shipping costs are more sensitive to inflation.
- Expected inflation:
  - China: 6.5%
  - U.S.: 3.6%

Note 2: Based on one global wafer and cell prices (e.g. Chinese tier 1 module manufacturer can ship cells to U.S. module-assembly location for little cost).

## Cost of Capital (Global CAPM): Tier 1 Si company

<table>
<thead>
<tr>
<th>Facility location</th>
<th>U.S.</th>
<th>U.S. Loan Guarantee (LG)</th>
<th>U.S. LG, 30% MTC grant</th>
<th>U.S. State Subsidies</th>
<th>China</th>
<th>China Subsidized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsidy program, if any.</td>
<td>Debt percent (book D / book V)(^1)</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>Nominal Cost of Debt ((K_D^{\text{Nominal}}))(^6)</td>
<td>6.4%(^{13})</td>
<td>4.0%</td>
<td>4.0%</td>
<td>3.0%</td>
<td>10.2%</td>
</tr>
<tr>
<td></td>
<td>Loan Terms(^4)</td>
<td></td>
<td>2 year delay, $2.5 million application costs</td>
<td>2 year delay, $2.5 million application costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Expected Inflation ((i))(^5)</td>
<td></td>
<td></td>
<td></td>
<td>3.6%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Real Cost of Debt ((K_D^{\text{Real}}))(^3)</td>
<td>2.7%</td>
<td>0.4%</td>
<td>0.4%</td>
<td>-0.6%</td>
<td>3.8%</td>
</tr>
<tr>
<td></td>
<td>Expected Market Return ((R_m))</td>
<td></td>
<td></td>
<td></td>
<td>10.8%(^7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Country Beta ((\beta_{\text{country}}))(^9)</td>
<td></td>
<td></td>
<td></td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nominal EMRP(_{\text{Global}})^(^{10})</td>
<td></td>
<td></td>
<td></td>
<td>11.0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Country Risk Premium (CRP)</td>
<td></td>
<td></td>
<td></td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Company’s Equity Beta ((\beta_{\text{E Company}}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Levered (Global) Cost of Equity ((K_{E \text{Levered}}))(^{12})</td>
<td></td>
<td></td>
<td></td>
<td>38.1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Effective Corporate Tax Rate ((T_c))(^{15})</td>
<td></td>
<td></td>
<td></td>
<td>28%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Global CAPM (WACC) or Hurdle Rate(^{16})</td>
<td></td>
<td></td>
<td></td>
<td>16.4%</td>
<td>15.4%</td>
</tr>
</tbody>
</table>

See next slide for footnotes
Cost of Capital (Global CAPM): Tier 1 Si company

Footnotes
1. Based on Suntech Corporation book value of total debt divided by book value of total assets (as of 10/06/11).
2. 30% Manufacturing Tax Credit (MTC) monetized in year 1, effectively reducing depreciation expenses.
3. $D_{real} = R_T + Debt Margin; R_T = Global risk free rate (10 year U.S. T-bill), Debt Margin = corporate bond spread estimated based on company leverage.
4. U.S. LG award delay: 2 years, application cost: $2.5 million; Low cost China debt subsidized based on condition that foreign ownership is limited to minority stake (≤49%)
5. Average rate of inflation (i) since Jan-2008 for U.S. and China, as reported by “Trading Economics” (www.tradingeconomics.com).
6. Based on Fisher equation: $D_{nominal} = (1 + D_{real})*(1 + i) – 1$
8. Expected market return ($R_m China$): MSCI AWCI Broad China.
9. Country Beta ($\beta_{Country}$) = Covariance (Country Index, MSCI AWCI) / Variance (MSCI AWCI).
10. Nominal Equity Market Risk Premium (EMRP) = ($R_m - D_{nominal})/B_{Country}$
11. Company’s Equity Beta ($\beta_{Company}$) based on Suntech Corporation, as reported by yahoo.finance.com (10/6/11).
12. $K_{E Levered} = K_{E Unlevered} + [(D/E)*(K_{E Unlevered} - D_{nominal})]$
14. 20 year China corporate tax holiday.
16. $WACC = [(E/V)*K_{E Levered}] + [(D/V)*K_{D nominal}*(1 – T_C)]
Regional Benchmarking Analysis: Minimum Sustainable Si PV Module Price

- Chinese Si PV manufacturers should consider regional module production strategy
- Regional module manufacturing facilities located near end markets reduce glass shipping costs and mitigate impact of China’s inflation on product costs

NREL internal DCF (2011), including Global CAPM analysis and country based incentives (private conversations with PV companies)
Capitalizing on U.S. Innovation

U.S.–based thin film (CIGS) PV startup, U.S. customer (end market)
CIGS Module Shipping Costs

Costs including fees, insurance are significant, total: \$0.05/W_{P\,DC}

Cost of capital excluded (Shanghai to Los Angeles: 30 day transit time)

Cost of breakage excluded

Shanghai to Hamburg, Newark to Hamburg costs roughly the same

Maersk online shipping calculator, NREL private conversation with Maersk sales representatives. 2011
Bunker Adjustment Factor as of (March 31, 2011)
Fuel surcharge based on $3.96-$3.99/gallon gas price. Average DOE diesel fuel surcharge. (March 2011)
Regional CIGS Module Costs

- CIGS direct labor content assumed not to vary by region: \( \sim 0.9 \) job/MW<sub>DC</sub>

### 600 MW<sub>DC</sub> CIGS Module Facility
(near term target module efficiency = 16.6%)

<table>
<thead>
<tr>
<th></th>
<th>US</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Direct Laborers (all shifts)</td>
<td>540</td>
<td>540</td>
</tr>
<tr>
<td>Unskilled Labor rate ($ per hour)</td>
<td>$13.33</td>
<td>$2.13</td>
</tr>
<tr>
<td>Manufacturing Engineer ($ per year)</td>
<td>$75,110</td>
<td>$8,171</td>
</tr>
<tr>
<td>Total facility Capex ($/W&lt;sub&gt;p&lt;/sub&gt;)</td>
<td>$0.40</td>
<td>$0.33</td>
</tr>
</tbody>
</table>

Regional Benchmarking Analysis:
Direct CIGS PV Module Core Costs

- China-direct manufacturing cost benefits, excluding shipping: 10%
- Including shipping to U.S., China advantage reduced to -3%

Direct Costs analysis excludes other regional factors: direct government subsidies, income taxes, global economic instability (inflation), investment risk factors

# Cost of Capital (Global CAPM): CIGS start-up

<table>
<thead>
<tr>
<th>Facility location</th>
<th>U.S.</th>
<th>U.S. Loan Guarantee (LG)</th>
<th>U.S. LG, 30% MTC grant²</th>
<th>U.S. State Subsidies</th>
<th>China Subsidized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debt percent (book D / book V)¹</td>
<td>65%</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
<td>50%</td>
</tr>
<tr>
<td>Nominal Cost of Debt (K_D Nominal)⁶</td>
<td>8.9%</td>
<td>4.0%</td>
<td>4.0%</td>
<td>3.0%</td>
<td>9.5%</td>
</tr>
<tr>
<td>Loan Terms⁴</td>
<td>2-year delay, $2.5 million application costs</td>
<td>2-year delay, $2.5 million application costs</td>
<td>Foreign ownership limited to minority stake</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected Inflation (i)⁵</td>
<td>3.6%</td>
<td></td>
<td></td>
<td></td>
<td>6.5%</td>
</tr>
<tr>
<td>Real Cost of Debt (K_D Real)³</td>
<td>5.1%</td>
<td>0.4%</td>
<td>0.4%</td>
<td>-0.6%</td>
<td>3.1%</td>
</tr>
<tr>
<td>Expected Market Return(R_m)</td>
<td>10.8%</td>
<td></td>
<td></td>
<td></td>
<td>18.1%</td>
</tr>
<tr>
<td>Country Beta (β_country)⁹</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
<td>1.34</td>
</tr>
<tr>
<td>Nominal EMRP_{Global}¹⁰</td>
<td>11.0%</td>
<td></td>
<td></td>
<td></td>
<td>10.1%</td>
</tr>
<tr>
<td>Country Risk Premium (CRP)</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
<td>3.8%</td>
</tr>
<tr>
<td>Company’s Equity Beta (β_E Company)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.5¹¹</td>
</tr>
<tr>
<td>Levered (Global) Cost of Equity (K_E Levered)¹²</td>
<td>39.2%</td>
<td>37.0%</td>
<td>37.0%</td>
<td>37.0%</td>
<td>43.7%</td>
</tr>
<tr>
<td>Effective Corporate Tax Rate (T_c)¹⁵</td>
<td>28%</td>
<td></td>
<td></td>
<td></td>
<td>21%</td>
</tr>
<tr>
<td>Global CAPM (WACC) or Hurdle Rate:¹⁶</td>
<td>17.9%</td>
<td>16.6%</td>
<td>16.6%</td>
<td>16.1%</td>
<td>25.6%</td>
</tr>
</tbody>
</table>

See next slide for footnotes
Cost of Capital (Global CAPM): CIGS start-up

Footnotes

1. Based on Suntech Corporation book value of total debt divided by book value of total assets (as of 10/06/11).
2. 30% Manufacturing Tax Credit (MTC) monetized in year 1, effectively reducing depreciation expenses.
3. \( K_{D\text{ real}} = R_f + \text{Debt Margin} \); \( R_f = \text{Global risk free rate (10 year U.S. T-bill)} \), Debt Margin = corporate bond spread estimated based on company leverage.
4. U.S. LG award delay: 2 years, application cost: $2.5 million; Low cost China debt subsidized based on condition that foreign ownership is limited to minority stake (≤49%)
5. Average rate of inflation (i) since Jan-2008 for U.S. and China, as reported by “Trading Economics” (www.tradingeconomics.com)
6. Based on Fisher equation: \( K_{D\text{ nominal}} = (1 + K_{D\text{ real}})*(1 + i) – 1 \)
7. Expected market return (\( R_{m\text{ U.S.}} \): S&P 500. 50 years: 1961 to present (September 2011).
8. Expected market return (\( R_{m\text{ China}} \): MSCI AWCI Broad China.
9. Country Beta (\( \beta_{\text{Country}} \)) = Covariance (Country Index, MSCI AWCI) / Variance (MSCI AWCI).
10. Nominal Equity Market Risk Premium (EMRP) = \( (R_{m} – K_{D\text{ nominal}})/\beta_{\text{Country}} \)
11. Hypothetical company beta based on conversations with firms that have experience investing in solar PV start-ups.
12. \( K_{E\text{ Levered}} = K_{E\text{ Unlevered}} + [(D/E)*(K_{E\text{ Unlevered}} – K_{D\text{ nominal}})] \)
13. As reported by PV start-ups investigating potential facility locations (2010).
14. 20 year China corporate tax holiday.
16. \( WACC = [(E/V)*K_{E\text{ Levered}}] + [(D/V)*K_{D\text{ nominal}}*(1 – T_C)] \)
Regional Benchmarking Analysis
Minimum Sustainable CIGS PV Module Price

- The cost of China’s subsidies (domestic proprietorship requirement, impact of significant government ownership on cost of equity) is largely left un-quantified in this analysis.
- Over past 2-3 years, the “U.S.” (unsubsidized) case has largely been unavailable to innovative thin film startups. Unsubsidized access to capital in United States has been limited.

NREL internal DCF (2011), including Global CAPM analysis and country based incentives (private conversations with PV companies)
Summary

• China is the world’s leader in global production (55% market share)
  • 95% of production is exported; no domestic demand

• The U.S. is a leader in early stage technology investments that have disruptive potential

• Shipping costs offset China’s core cost advantage
  • c-Si module advantage reduced from 1% to -5%
  • CIGS advantage reduced from 10% to -3%

• Access to low cost capital is needed to offset investment risk in emerging markets
  • Cost of capital: China (26%) with subsidy (18%), vs. U.S. (18%)
  • Inflation and changes in value of currency are significant
Conclusions

• China advantage may not be sustainable
  • Inflation
  • Growing importance of shipping costs
  • Reliance on massive government subsidies
  • Lack of technology diversification
    • Risk of being supplanted by disruptive non-Si technology

• U.S. incentives can level the playing field
  • The scale of Chinese incentives dwarf U.S. efforts
  • Access to capital is a critical compliment to the United States’ capacity to innovate
U.S. Solar PV Opportunities and Challenges

Comparative advantages

- Low cost electricity (hydro power and poly Si)
- Complimentary industries
  - Specialty chemicals, non-woven films (Dow, DuPont, 3m, Eastman Chemical, etc.)
- Institutional capacity for R&D (innovation)
- Private capital
- Demand potential

Risk factors

- Material resource availability
- Policy uncertainty (R&D funding, industrial incentives)
- Inflation
Acknowledgements

Colleagues at NREL who have contributed through both formal and informal discussions. Special thanks to David Feldman, Robert Margolis, and Rommel Noufi.

Many industrial collaborators for their willingness to share data and provide invaluable external review.
c-Si Wafer Costs: 2011 Benchmark

- China’s ingot and wafering advantage (~$0.14/WP DC)
- Labor intensive, and difficult to fully automate.
Regional c-Si Wafer Manufacturing Cost Benefits

Quantifying the China-advantage. Cell efficiency: 16.7%.
Source: NREL internal cost model.

2011 USD/Wp,DC

- Margin
- Overhead Labor
- Maintenance
- Building
- Tooling
- Equipment
- Utility
- Direct Labor
- Other Materials
- Saw Slurry
- Saw Wire
- Polysilicon

U.S.  Labor  Scale  Supply chain  Cost of capital  China
c-Si Cell Costs: 2011 Benchmark

- Little difference in regional costs, but negligible shipping costs and manufacturing scale benefits (regional supply chain)
- Low cost Chinese equipment vendors (wet-benches, screen-printers, firing)
- Regional-differences in automation

**c-Si Cell Manufacturing**

Standard (Industry Median) Cell Efficiency (16.7%)

Source: NREL internal cost models (polysilicon feedstock, ingots and wafers, cells)
$U.S. 1/W_{P_{DC}}$ Chinese w-Si Panels: Unsustainable

- Recent module price reductions driven by poly price, manufacturer scale, and level of vertical integration
- Can U.S. w-Si manufacturers survive latest price wars?

**c-Si PV Module Cost and Price Trends**

*Standard (Industry Median) Module Efficiency*

*Source: NREL internal cost models (polysilicon feedstock, wafer, cell, modules)*

- PS price/kg: contract ($75) + spot ($364) + blend ($230)
- 170 μm wafer thickness
- Module efficiency: 13.6%
- 500 MWe equivalent annual production capacity
- Prices based on sustainable 25% total cost of capital

<table>
<thead>
<tr>
<th>Year</th>
<th>China</th>
<th>U.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>$3.25</td>
<td>$1.62</td>
</tr>
<tr>
<td>2011</td>
<td>$1.14</td>
<td>$1.62</td>
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</tbody>
</table>

**Key Components:**
- Module margin
- Module cost
- Cell margin
- Cell cost
- Wafer margin
- Wafer cost
- Polysilicon Price

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