Solaria: Temperature Characteristics of Silicon PV Modules

Microelectronics Packaging and Test Engineering Council
March 2011
2000-2010 Industry Growth

- 2010 ~$71B
- 2000 - 2010: 58% CAGR
- 2005 - 2010: 65% CAGR
- 1978 - 2010: 35% CAGR

Source: Navigant Consulting
2010 – Silicon PV Dominates

- 2010 Shipments - 87% Crystalline silicon based

Source: Navigant Consulting
Solaria

- Global manufacturer of competitive, low-cost silicon PV systems
- Breakthrough, low risk technology
- Proprietary manufacturing process
- Well-capitalized, backed by leading institutional investors
- Run by industry veterans and seasoned management team
- Worldwide operations in USA, Europe and India
# Experienced Team

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dan Shugar</td>
<td>CEO</td>
<td>SunPower</td>
</tr>
<tr>
<td>Suvi Sharma</td>
<td>President</td>
<td>Ivus, Inc</td>
</tr>
<tr>
<td>Kevin Gibson</td>
<td>CTO</td>
<td>Emerson Electric</td>
</tr>
<tr>
<td>Dr. Abhay Maheshwari</td>
<td>SVP Product Development</td>
<td>Xilinx</td>
</tr>
<tr>
<td>Ajay Marathe</td>
<td>SVP, Operations</td>
<td>AMD</td>
</tr>
<tr>
<td>Chris Dier</td>
<td>CFO</td>
<td>Veritas</td>
</tr>
<tr>
<td>Bruce Dickinson</td>
<td>VP Sales</td>
<td>Chevron Energy</td>
</tr>
<tr>
<td>David Hochschild</td>
<td>VP External Affairs</td>
<td>City of San Francisco</td>
</tr>
<tr>
<td>Stri Zulch</td>
<td>VP Marketing</td>
<td>Fotowatio Renewable Ventures</td>
</tr>
</tbody>
</table>

> 100 years of solar experience on executive team, plus deep semiconductor and manufacturing expertise
Early Company Tenets

- Replace expensive PV material with low cost optics
- Leverage other manufacturing processes to produce solar products
  - Backend Semiconductor Assembly and Packaging
- Crystalline Silicon PV is a good thing
  - Solar Thin Film is Semiconductor Thick Film
- The standard crystalline module has not changed in 20 years, there has to be a better way to make it
- Application specific PV designs can offer an advantage over generic designs
Solaria Module

- 230W – 1.65m²
- 14% area efficiency
- Standard form factor
- Thicker, robust glass
- Uses standard industry PV and materials
- TUV, UL, IEC Certified
- Framed and Frameless
- Shipping globally
All materials used in Solaria modules are industry standard and have been used for > 25 years in outdoor applications.

Leverage current industry supply chain:

- Industry standard glass
- Industry standard cells
- Industry standard EVA
- Industry standard ribbon
- Industry standard back-sheet
Reliable – Fully Tested

- Uses crystalline PV material – the standard for reliability
- Industry proven materials – 25+ years of field experience
- Proprietary, high strength glass – withstands 4x impact of other modules
- High wind tolerance and snow load: 7,200 Pascal
- Fully tested and certified:

**Underwriters Laboratories**
- UL-1703 certification
- Factory inspection

**TÜV**
- TUV-61215 certification
- Factory inspection

**Performance**
- Sandia National Labs
- PI-Berlin
Solaria’s focus is on the industrial and utility-scale market.

Industrial/Utility Projects
1-500 MW

Commercial Rooftop
10 kW – 1 MW

Residential
1-10 kW
What Matters to Customers

- **Price**: Dominant factor when combined with Performance
- **Performance**: Highest performing solutions doesn’t always win
- **Financing**: Controlling force
  - Hard to measure – Financing driven
Solaria Value Proposition

- Solaria modules:
  - Cost less than standard crystalline PV modules
  - Provide industry leading cost/performance
  - Have the intrinsic reliability of standard crystalline silicon modules
What is a Silicon PV Cell

- Silicon wafer – almost semi grade
  - Mono or multi-crystalline
  - ~180 microns thick
  - 156mm X 156mm

- Simple p-n Junction – It is a diode
  - One junction over entire area

- Texturing and AR coatings

- Front and back electrical contacts

- Cost: ~$4-$5/cell - 60 Cells/module
Why Thermal Management Matters

- **Performance**
  - For every 2°C junction temp rise 1% power is lost

- **Reliability**
  - Modules contain polymers.
  - Higher operating conditions = accelerated degradation
  - Stress reduction, solder bonds, fatigue

- **Safety**
  - Must safely handle temperatures of several hundred degrees C without fire or electrical shock hazard
Silicon PV = Diode

- Same IV curve as a Diode
- Shifted because it is producing power

Since the cell is generating power the convention is to invert the current axis.
Output voltage and power decrease with increasing temperature

Silicon Power Loss: -0.4%/°C to -0.5%/°C
Reality

**230Wp STC module on a sunny day, produces 190W**

Solaria 220W module
Tested in the Negev Desert
Israel by Dr. David Faiman

\[
y = 248.63 - 1.0001x \quad R^2 = 1.000
\]

\[
gamma(pp) = - 1.000 \text{ W/K}
\]

\[
P_{\text{max}(1000,25)} = 223.63 \text{ W}
\]
Module Temp Equations

- **Basic Form of Equation**
  \[ T_{module} = Irradiance \times e^{a+b \times \text{WindSpeed}} + T_{ambient} \]

- **Module to Cell Temperature**
  \[ T_{cell} = T_{Module} + \frac{G}{1000 \text{W/m}^2} \Delta T \]

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Mount</th>
<th>a</th>
<th>b</th>
<th>\Delta T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass/cell/glass</td>
<td>Open rack</td>
<td>-3.47</td>
<td>-0.0594</td>
<td>3</td>
</tr>
<tr>
<td>Glass/cell/glass</td>
<td>Close roof mount</td>
<td>-2.98</td>
<td>-0.0471</td>
<td>1</td>
</tr>
<tr>
<td>Glass/cell/polymer sheet</td>
<td>Open rack</td>
<td>-3.56</td>
<td>-0.0750</td>
<td>3</td>
</tr>
<tr>
<td>Glass/cell/polymer sheet</td>
<td>Insulated back</td>
<td>-2.81</td>
<td>-0.0455</td>
<td>0</td>
</tr>
<tr>
<td>Polymer/thin-film/steel</td>
<td>Open rack</td>
<td>-3.58</td>
<td>-0.113</td>
<td>3</td>
</tr>
<tr>
<td>22X Linear Concentrator</td>
<td>Tracker</td>
<td>-3.23</td>
<td>-0.130</td>
<td>13</td>
</tr>
</tbody>
</table>

Empirically determined

SAND2004-3535
Unlimited Release
Printed August 2004
Bad News - Good News – Bad News

Bad News
- Module Temperatures = Ambient + 30°C
- 10-20% losses due to module temperature
- Modules 14-16% efficient – Light energy converted to thermal
- Closed rooftop systems have highest module temperatures
- Open rack systems have more air movement
- Location matters: Riyadh and Phoenix different for San Jose

Good News
- Opportunity to use temp difference to cool PV junction temperature

Bad News
- Not easy to do
Financial Example

- 10MW_{ac} System = 11.5MW_{dc}
- 50,000 230 W_p – Standard Test Conditions (STC)
- Approximately 80 acres
- Produce 2100 kWhrs/kWp
- 483 kWhrs/Module
- Electricity value $0.15/kWhr
- $72.45/module of electricity produced per year
- Installed Cost - $3.25/W or $750/module
- 10.3 years to pay off
- IRR ~ 8.4% over 25 years
Thermal Management Opportunity

- Reduce Junction temperature by 2°C
  - 1% energy yield improvement

- 4.9 kWhrs/kWp improvement

- At $0.15/kWhr = $0.735/year/module

- 25 year life
  - ~ $18.1 per module cash
  - LCOE the proper way to do the calculation
  - $6.90 with TVM at 8.4% IRR
Challenge

- How to spend less than $6.90 per module to get a 2°C temperature drop
  - 1.6m² area to cover
  - Must provide benefit for 25+ years
  - Must be maintenance free
  - Has to survive extend temp. ranges -40 to +85°C
  - UV and moisture resistant
  - Electrically insulating
  - Survive manufacturing >150°C
  - Must be compatible with other module materials

- As modules and systems become cheaper, challenge increases
By focusing on proven science, Solaria is solving the economics of solar energy without reinventing the industry.
<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly-Competitive Product</td>
<td>Lower cost advantage over silicon modules, efficiency and reliability advantage over thin-film modules</td>
</tr>
<tr>
<td>Low Risk Technology</td>
<td>Uses industry-standard materials with 25+ years of proven durability</td>
</tr>
<tr>
<td>Capital Efficiency</td>
<td>Low CapEx ($0.15/W) with fabless business model enables rapid scale at low cost</td>
</tr>
<tr>
<td>Industry Leverage</td>
<td>Takes advantage of the solar industry’s trends toward lower costs and higher efficiencies</td>
</tr>
<tr>
<td>IP Protection</td>
<td>Protected by strong IP portfolio</td>
</tr>
<tr>
<td>Experienced Team</td>
<td>Seasoned team with 100+ years of solar experience</td>
</tr>
<tr>
<td>Set to Scale</td>
<td>Growth by meeting increased product demand.</td>
</tr>
</tbody>
</table>
Thank You

Kevin Gibson, CTO
kgibson@solaria.com