The Silicon Photovoltaic Roadmap

The Stanford Energy Seminar
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President Emeritus, SunPower
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SunPower 2011

- 2010: Revenue $2.23B
- 5,500+ Employees
- 550+ MW 2010 production
- >1.5 GW solar PV deployed

- World-leading solar conversion efficiency
- Diversified portfolio: roofs to power plants
- 1,500 dealer partners, #1 R&C USA
- 5 GW power plant pipeline

Residential  
Commercial  
Power Plants
SunPower vs. Conventional c-Si Cell

**SUNPOWER SOLAR CELL 22% EFFICIENCY**

- **Lightly doped front diffusion**
  - Reduces recombination loss
- **Texture + ARC**
- **Backside Mirror**
  - Reduces back light absorption & causes light trapping
- **Localized Contacts**
  - Reduces contact recombination loss
- **Passivating SiO₂ layer**
  - Reduces surface recombination loss
- **Backside Gridlines**
  - Eliminates shadowing
  - High-coverage metal reduces resistance loss

**CONVENTIONAL SOLAR CELL 15% EFFICIENCY**

- **Texture + ARC**
- **Gridlines**
- **N-Type diffused junction**
- **Silver Paste Pad**
- **P-Type multi-crystalline silicon**
- **Aluminum paste**
Alamosa 19 MW: Xcel
Alamosa County, CO
Swiss Alps Alpine Hut
Talk Outline

- Where we have come from in PV
- Where we are now
- Where we are going
- How we are going to get there
Situation in 1975

Wafered Silicon Process

- Polysilicon: $300/kg
- Ingot: 3 inches in diameter
- Wafer: Sawn one at a time
- Solar Cell: 0.5 watts each
- Solar Module: $100/watt
- Systems: $200/watt
Historical PV Learning Curve (ca. 2002)

- 1979: $33.44/W
- 2002: $3.65/W
- 2010: $2.20/W
- 2013: $1.74/W
After Silicon Shortage

- 1979: $33.44/W
- 2010: $1.81/W
- 2010: $2.20/W

Module Price ($/W) vs. Cumulative Production (MW)
If the original learning curve were followed, consumers would have spent $83B to get to 40GW of cumulative modules.
Consumers actually spent $17B (20%) more (0.43/W)
Zooming in on Recent Times

The graph illustrates the trend in Module ASP ($2010/W) against Cumulative Production (MW) from 2005 to 2020. Key points include:

- **2005**: Module ASP was $3.00/W.
- **2011**: Module ASP dropped to $1.32/W.
- **2015**: Module ASP further decreased to $0.99/W and $0.75/W.
- **2020**: Module ASP reached $0.50/W.

The projections show a continued decline, with a target price of $1.12/W by 2020, as required by ITC.
PV Power Plants Are Cost Competitive Today
2012 LCOE by Resource $/MWh: 2010 USD

<table>
<thead>
<tr>
<th>Resource</th>
<th>Levelized Cost ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable Solar PV</td>
<td>$73 ground – 192 roof</td>
</tr>
<tr>
<td>Solar Thermal</td>
<td>$120 - 198</td>
</tr>
<tr>
<td>Wind</td>
<td>$38 - 79</td>
</tr>
<tr>
<td>Offshore Wind</td>
<td>$164 off-shore</td>
</tr>
<tr>
<td>Conventional Gas Peaking</td>
<td>$211- 242</td>
</tr>
<tr>
<td>Gas CC</td>
<td>$69-97</td>
</tr>
<tr>
<td>Nuclear</td>
<td>$77-113</td>
</tr>
<tr>
<td>Coal</td>
<td>$70-152</td>
</tr>
</tbody>
</table>

Prices include federal incentives
Not as Pretty Without ITC

2012 LCOE by Resource $/MWh: 2010 USD

Renewables

- Solar PV: $104 ground – 274 roof
- Solar Thermal: $171 - 283
- Wind: $54 - 113, $234 off-shore

Conventional

- Gas Peaking: $211- 242
- Gas CC: $69-97
- Nuclear: $77-113
- Coal: $70-152

Prices include federal incentives
Regional PV Market

Source: EPIA
4.2 GW PV in 2009…10+ GW in 2010

European 2009 New Installed and Retired Capacity (MW)

Source: EWEA, February 2010
German Feed-in Tariff will be less than retail in 2012!

Source: Deutsche Bank
Grid parity in Europe 2010
PAST COST PROJECTIONS CAME TRUE
2002 NREL Workshop
Wafer Thickness Roadmap

SunPower Actuals

Wafer Thickness (um)

2002 NREL Workshop

Year
Module Cost ($/W)

2010 Actual (2002$)
2012 $1.00/W
Incremental Improvements in Silicon Technology will Continue to Drive Solar Panel Price Reduction.

- 1980: $21.83/W
- 1990: $6.07/W
- 2000: $3.89/W
- 2010: $1.82/W
- 2013: $1.44/W

Retail Parity: 2010 Actual $1.81/W
SunPower UPP LCOE Competitive with CA MPR

Notes: LCOE = delivered electricity price to utility via PPA; MPR=25-yr Market Price Referent , 30% ITC /MACRS included
unlevered return range for plant owner 7.5%-8.5%, sunlight range included

End of ITC, 2016
Schleicher-Tappeser (Jan 2011)

Grid parity in Europe 2016

Diagram showing the average price of electricity in EUR/kWh against annual irradiation on module in kWh/(m²·y) for various countries in Europe.
HOW DO WE GO FORWARD?
Conventional Wafered Silicon Value Chain:

Rough percentages for conventional c-Si:

- Polysilicon: 12%
- Ingot: 6%
- Wafer: 9%
- Solar Cell: 14%
- Solar Panel: 25%
- System: 34%

Total Cost: $2.63/W_{ac}
SunPower cell efficiency history

- **Laboratory Prototyping Results**
- **Production median**

### Gen 1
- 2003: 20.6%
- 2004: 20.6%
- 2005: 20.6%
- 2006: 22.0%

### Gen 2
- 2007: 22.4%
- 2008: 23.4%

### Gen 3
- 2009: 24.2%
## Generation 3 Modules Status – 20.9%

- Engineering scale production of Generation 3
- Module performance continues to improve
- 96-Cell module presently achieving 20.9%*

<table>
<thead>
<tr>
<th></th>
<th>Area (m²)</th>
<th>Voc (V)</th>
<th>Isc (A)</th>
<th>FF (%)</th>
<th>Pmax (W)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>96-Cell Module</strong></td>
<td>1.63</td>
<td>69.02</td>
<td>6.38</td>
<td>77.4</td>
<td>341W</td>
<td>20.9%*</td>
</tr>
</tbody>
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*Unconfirmed
Cost Reduction: Silicon Utilization

SunPower’s Cell Ideal for Thin Silicon

SunPower’s cell architecture maintains performance as silicon thickness reduces.
### Intrinsic cost of silicon ingot is not an issue

<table>
<thead>
<tr>
<th></th>
<th>Ingot cost</th>
<th>Silicon use</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Today</td>
<td>$100/kg</td>
<td>5g/W*</td>
<td>$0.50/W</td>
</tr>
<tr>
<td>Possible</td>
<td>$50/kg</td>
<td>1g/W**</td>
<td>$0.05/W</td>
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*Approximate SunPower today
**100 um thick, 23% cell, kerfless wafering
2014 SunPower Panel Cost Reduction Roadmap

$/W

Q407 $3.01
Q408 $2.38
Q409 $1.91
Q410 $1.71
Q411
Q412
Q413
Q414

- $-

Fab 3 Ramp
135 um wafers
Lean Fab Mngt
Material Red’n

Gen 3 Ramp

Step Red’n
DW Sawing

$1.00

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Next Steps: Glass superstrates???

High Efficiency SunPower Cell + 23%

Less than 100 µm thick

Glass

Si – n-type
Passivated Contacts
Front Surface Field Passivation
Optimized Diffusion & SiNx
Rear Dielectric
Optimized for Passivation
High Lifetime Silicon Point Contacts
Small Contacts through Dielectric
Rear Mirror
Excellent Light trapping

SUNPOWER™
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Technology Development central to Cost Roadmap

- $0.6/W c-Si Module is conceivable
- 25% cell performance practical
- Optimized process sequence
  - Back-contact process is immature (< 8 yrs old)
    - New process-steps and materials
- Reduced Silicon Usage
  - Ultra-thin Wafers (<100um), reduced Kerf or Kerfless
- No end in sight for learning curve for c-Si back contact solar cells
DOE Sunshot Goal: Make PV the lowest cost electric energy option
Near theoretical limits: ~24% efficient cells; low ($32/kg) silicon price, 80 micron kerfless wafers

Value of 24% Efficiency plus Tracking

Source: DOE $1/W Whitepaper
Solaicx Continuous Ingot Growth

**Key Activities:**
- Continuous Cz ingot growth
- Low-oxygen, high-lifetime material
- Development of hot zone for N-type material
- FBR polysilicon process development and implementation
- Crucible durability

**Participants:**
Solaicx, Santa Clara, CA
SiGen Direct Cleave Process

Direct Cleave Process

Cleaved Wafers

Silicon Ingot

Same material → 2X to 3X more wafers

- c-Si lifetime
- Excellent Edges/Surface
- High strength

Kerf-Free 50 μm c-Si wafer
Other Kerf-less Approaches

- **Pealed Wafer**
  - AstroWatt
  - Crystal Solar

- **Epitaxial Deposition and Lift-Off**
  - SOLEXEL®
BOS innovation is equally important

Figure 7: Highly automated agriculture equipment revolutionized harvesting of crops.

Source: DOE $1/W Whitepaper
WHAT CAN STOP US, AND WHAT CAN YOU DO?
Average US natural gas well
Area covered: 19.6 square miles
Power density: 287.5 hp/acre
(53 watts/square meter)

Biomass-fueled power plant
Area covered: 2,606 square miles
Power density: 2.1 hp/acre
(0.4 watts/square meter)

Wind
Area covered: 869 square miles
Power density: 6.4 hp/acre
(1.2 watts/square meter)

Solar PV
Area covered: 156 square miles
Power density: 36 hp/acre
(6.7 watts/square meter)

South Texas Project Nuclear Plant
Area covered: 18.75 square miles
Power density: 300 hp/acre
(56 watts/square meter)
“A brutal, brilliant exploration…unsentimental, unsparing, and impassioned…[P]recisely the kind of journalism we need to hold truth to power.”
--Wall Street Journal

“Should be mandatory reading for U.S. policymakers”
--National Review

<table>
<thead>
<tr>
<th>Solar PV</th>
<th>South Texas Project Nuclear Plant</th>
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<tr>
<td>Area covered: 156 square miles</td>
<td>Area covered: 18.75 square miles</td>
</tr>
<tr>
<td>Power density: 36 hp/acre</td>
<td>Power density: 300 hp/acre</td>
</tr>
<tr>
<td></td>
<td>(6.7 watts/square meter)</td>
</tr>
<tr>
<td></td>
<td>(56 watts/square meter)</td>
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</table>
Myths you must refute

- PV is too small to matter…and always will be
- PV is too expensive…and will require massive subsidies
- PV takes up too much valuable land
- PV will make grid unstable
- Green jobs are a myth
THANK YOU