Photovoltaics – Challenges and Opportunities in Materials, Machines and Manufacturing

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What’s Your Mindset?

“Tough Guy”

“The energy content of all the crude oil left in the ground = 15 hours of sunlight hitting the earth
Who’s the “girly man” now?”

“Tree Hugger”

From: Brent Nelson - NREL
Driving forces for Solar

1. Increasing costs of conventional energy - Oil > $110/barrel; top tier pricing for electricity in the PG&E territory today - > 30 cents/kwh

2. Climate change, environmental issues - CO2 emissions

3. Energy security - political instabilities in oil producing regions, terrorism

4. Increasing demand for energy from China, India and other emerging economies

5. Increasing levels of government support – feed in tariffs, tax credits
What is needed to make solar happen?

• Government Policies
  – Active promotion of this energy source
  – Incentives, tax breaks, legislative initiatives- give solar the same advantages as have been given to carbon/nuclear/hydro based energy generation options

• Education, public awareness, sustained political will
  – Avoid irrational response to fluctuating oil prices
  – Sustained policies over decades
  – Invest in education

• Science/Technology/Manufacturing
  – Very large scale manufacture – GW scale factories
  – Highly automated, efficient manufacturing capability – machines, processes, factory automation, ---
  – Continuing and accelerating research in materials, processes, devices, machines –
All Path’s Lead to Solar

Pure Economist’s Path: Use what’s cheapest, no environmental concern

Low CO₂ Path: Invest in the future now

Invest in Solar before it’s too Late:
- Intelligent Solar Investment Now
- Education: public & future techies

From: Brent Nelson - NREL
Global crystalline silicon solar cell production


Year

MW

15 to 25 GW

2010 – 2012
Area of silicon used per year

Billions of square inches of silicon

- Photovoltaics
- ICs

Year

Polysilicon Capacity

Metric Tons (X 1000)

Year

Polysilicon Pricing

$/Kg

Direct selling price
Indirect selling price

Year

Projection by Photon International
Key market inflection point is coming

US Residential $/kWh

PV Costs/Watt falling
- Efficiency improvements
- Learning Curve
- Scale manufacturing

Utility Rates Increasing
- Modeled at 25 yr CAGR of 2.4%
- Additional upward bias from external factors
- PG&E service territory
  - Time of use rates as high as $0.40/kWh
  - Top pricing tier at $0.32/kWh

Average Price Parity Coming
- Crossover in US: ~3-10 yrs
- Crossover in Europe; 6-8 yrs
- Crossover in Japan: Now

Until crossover, subsidy bridges gap between PV and Utility cost

PV increasingly cost competitive with residential utility power
Today: Production Cost of Electricity

(in the U.S. in 2002)

Cost, $/kW-hr

- Coal: 1-4¢
- Gas: 2.3-5.0¢
- Oil: 6-8¢
- Wind: 5-7¢
- Nuclear: 6-7¢
- Solar: 25-50¢
Scale manufacturing and cost reduction

Module Cost ($/W)

Cumulative Volume (MW)

1980 $21.83/W
1985 $11.20/W
1990 $6.07/W
1995 $4.90/W
2000 $3.89/W
2005 $2.70/W

Historical
Projected

Scale to Enable Learning Curve

Production line size (Megawatts per Year):
- 0.5 (1980)
- 5 (2000)
- 50 (2005)
- 100 (2010)

Lines Per Factory:
- 2
- 3
- 4
- 10

2002 Dollars
Source: Navigant Consulting

Solar Business Group
The ratio between single crystal and multicrystal may change as we go forward:

- In favor of single crystal as higher efficiency cell processing concepts can be more easily implemented with single crystal silicon and advances, such as silicon recharging between ingot growth runs, may further shrink the cost differential between multicrystal and single crystal silicon.

- In favor of multicrystalline ingots if quality improvements narrow efficiency gap with Cz and further cost reductions are achieved as cast ingot technology is easier to scale and easier to wafer (no OD grinding-less waste and time)
Crystalline Silicon PV manufacturing Value Chain Summary

Definitions

- **Polysilicon manufacture**
- **Ingot manufacture**
- **Wafering**
- **Cell manufacture**
- **Laminate**
- **Module and BoS**
- **Installation**

Materials Production

- **Poly Silicon**
- **Ingots**
- **Wafering**

Materials Processing

- **Cell Production / Manufacture**
  - Saw Damage/Texture etch
  - Emitter Formation
  - Passivation/AR coating
  - Metallization

Cell interconnect/Laminate

Module

Installation

Packaging

Deployment
Module cost breakdown - $/W based on multicrystalline silicon technology (Current)

- **Total cost** - $2.09/W

- **Materials**
  - $1.37 (65%)

- **Depreciation**
  - $0.06

- **Labor**
  - $0.15

- **Oh**
  - $0.15

- **Interest**
  - $0.15

- **S&G&A**
  - $0.06

- **Wafers**
  - $0.73/W (53%)

- **Modules**
  - $0.4/W (30%)

- **Cells**
  - $0.23/W (17%)
Czochralski process intrinsically limited to ~250 mm (for solar) and, perhaps, 300 mm for ICs. Cast ingot approach not limited in size due to fundamentally different method of heat extraction during crystal growth.

- **Czochralski**

- **300 mm ingot**

- **Heat Extraction**

- **600 mm square ingot**

- **Cast ingots**

- **Heat Exchanger method**

- **Cast Ingots – Heat exchanger method**

- **~200 mm square “bricks”**
Efficiency calculations of n+p c-Si solar cell vs. wafer thickness at different rear surface recombination velocities. $L_n$ is diffusion length.

Crystalline Silicon

- Junction/surface lifetime/recombination dominated
- Bulk lifetime dominated

**a-Si:H/μc-Si:H Cell Spectral**

- Relative External Quantum Efficiency, %
- Number of Sunlight Photons (m²·s-1·micron⁻1) E+19
- Wavelength, microns

- a-Si:H junction
- μc-Si:H junction
- AM 1.5 global spectrum
Efficiency loss mechanisms

1. Thermalisation losses - photo excited pairs lose energy in excess of band gap - low energy photons pass through the device without doing useful work - limits efficiency to ~ 44%

2. Junction and contact voltage losses

3. Recombination of photo excited electron - hole pairs
   - Bulk recombination
   - Surface recombination

4. Theoretical upper efficiency limit of a silicon solar cell ~ 33%
Materials and Cell efficiency – where are we today?

Attributes of Silicon:
- Availability
- Efficiency
- Cost
- Reliability
- Non-toxicity
- Manufacturability

Lab cells – not in production
Production cells
Best c-Si Cell efficiencies—Impact of materials quality and device design (Data from NREL)

Crystalline Si Cells
- Single crystal
- Multicrystalline

Large area (> 140 cm²)
- Single crystal
- Multicrystalline

Rear junction/interdigitated device
- Inter-digitated contacts to inter-digitated junctions

Homojunction device
- Grain boundaries
- N+ P P+

Hetrojunction device
- n-type, high lifetime, single crystal silicon


Efficiency (%)
Efficiency! - Extrapolations, Exaggerations and Downright lies!!

Device structures that take advantage of the higher quality of single crystal silicon

Best reported cell efficiencies

Reported conversion efficiency numbers are all over the map!

Not everyone follows a standardized test method*

Best cell efficiencies reported at technical and trade conferences do not translate into production module efficiencies

Module efficiencies, based on volume manufacturing, are substantially lower than the best reported cell efficiencies

Large gap between R&D and manufacturing

* For example see - IEEE Spectrum – April 2008 – p 37


Selected PV manufacturers

Thin Films

Crystalline Silicon

PV industry today is characterized by:

- Small volume (50 to ~ 200 MW/year) factories

- Crystalline silicon (wafer based) technology has not changed substantially for over 30 years (with some notable exceptions)

- Non silicon thin film technologies (E.G. CdTe, CIGS, etc.) are characterized by proprietary processes with “home built/one of a kind” tools, practiced by a few, mostly single, companies

- Thin film silicon (α-Si, tandem structures) beginning to emerge with integrated, turn key factories – AMAT Sunfab Thin Film Lines

- Very high efficiency concepts based on single crystal compound semiconductors and complex multijunction structures are even further away from volume manufacturing
Benchmarking?

• C-Si PV industry today
  – No standards, no industry road map
  – Low volume factories
  – Minimal inter-tool automation
  – Little factory automation (software)
  – No SPC
  – Low yields, large bin splits
  – Large companies integrating individual tools purchased from different tool manufacturers
  – Small and new companies getting state of the art turnkey lines from several manufacturers

• Contrast with the Semiconductor industry
  – Industry standards (SEMI)
  – Industry road maps (ITRS)
  – Common tools – differentiation in design, integration, applications, markets
  – Very high yields
  – Very complex materials systems and processes
  – Sophisticated, automated mega fabs

• PV industry needs to intelligently copy from the semiconductor and display industries

• A big issue is differentiation if common tools and processes become prevalent

• Differentiation cannot be based on design, process and equipment but needs to be based on scale manufacturing, lower cost of manufacture (higher yields, efficiencies), applications and market development
Enable new 5.7m² glass substrate standard (2.2m x 2.6m)
Where is silicon going?

- Significant opportunity for thin film silicon – α-Si and tandem structures
  - Low efficiency offset by low cost
  - Large integrated modules – 5.7 meters square
  - Application in large power systems, BIPV – not constrained by area

- Two directions to date with c-Si based on traditional thinking
  - Low cost multicrystalline silicon wafers derived from directionally solidified silicon ingots – lower efficiency
  - Higher cost, higher efficiency single crystal silicon

- Future directions
  - Efficiency enhancements with thin film silicon – multiband gap structures, light trapping etc.
  - Continuing cost reductions with multicrystalline ingots/wafers
    - Larger ingots – up to 1 Ton (1000Kg), thinner wafers
    - Efficiency advancements thru material and process innovation
  - Cost reduction and efficiency enhancements with single crystal silicon
    - n-type silicon, thinner wafers
    - Advanced device structures
    - Convergence between thin films and c-Si (heterojunctions; multi band gap devices --)
PV trajectory of the future?

Silicon today

- α-Si integrated factories at 6 to 10% efficiency emerging
- Multicrystalline silicon dominates, Single crystal for high efficiency - Efficiency range for conventional homojunction devices – 15 to 17%

Silicon tomorrow

- Efficiency and price pressures from thin film technologies – CdTe, α-Si
- Increasing drive towards high efficiency devices with crystalline silicon

![Diagram showing PV trajectory](image)

- Rear junction /interdigitated device
- Hetrojunction device

![Graph showing efficiency](image)

- Inter-digitated contacts to inter-digitated junctions
- n-type, high lifetime, single crystal silicon
Extending Core Nanomanufacturing™ Competencies into Solar

Experience from Semiconductor Manufacturing

Experience from LCD Manufacturing

German Advisory Council on Global Change (WBGU), 2004
Cell efficiency % | 15 | 17 | 20
Wafer thickness - μm | 450 | 250 | 150

Hess et. al. 22nd European Photovoltaic Solar Energy Conference, Sept 2007, Milan, Italy