Showstoppers & Bottlenecks to Terawatt Solar Photovoltaics

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Outline

- Principle of solar cells
- Current & future global energy demands
  - Scales required for solar PV
- Requirements for a terawatt-capable PV technology
- Showstoppers & bottlenecks to terawatt PV
  - Availability of raw materials
  - Energy input for Si wafers & modules
  - Recycling of end-of-life PV modules
  - Terawatt-scale storage of solar electricity
  - Manufacturing and installation costs
- Suggested strategic R&D directions for PV
This talk is based primarily on:

This analysis started with the establishment of the U.S. Photovoltaic Manufacturing Consortium (Albany, NY, 2011)

- A 5-year joint effort initiated by SEMATECH (D. Holladay) & myself (2006–2011)
- Forced me to look into longer-term, bigger-picture, national & global issues for PV technologies
- First presentations at Electrochemical Society fall meeting (Vienna, 2009) & U.S. PV Consortium Workshop (Washington DC, 2010)
Arizona Landscape

Sunrise over Four Peaks from my home
**Principle of Solar Cells**

- **Light-induced voltage**
  - Employed for solar-to-electric conversion

- **Two key processes**
  - Light absorption
  - Charge separation

- **Two requirements**
  - Light absorber: molecule or semiconductor
  - Potential difference: p-n, Schottky, or hetero

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**Si Solar Cell Operation**

- Si wafer: 200 μm low $10^{16}$ B doping
- Emitter: 0.5 μm $10^{19}$ P doping
- BSF: 10 μm low $10^{19}$ Al doping
- SiN$_x$: 75 nm
How Much Energy Do We Need?

Current global consumption 18 TW ($18 \times 10^{12}$ W)
Projected demand in 2100 46 TW

Conclusion #1

Any solar PV technology has to be deployed at a TW scale, or it will make little impact on our energy mix.

- By 2100, global energy demand will be 46 TW.
- If 30% from PV, that is 13.8 TW from PV.
- Time-averaged output ~15% of peak output, so ~92 TW\(_p\) PV installation needed.
- If the average lifetime of PV modules is 25 years, the annual production needs to reach ~3.7 TW\(_p/yr\).

We need ~100 TW\(_p\) of solar PV installed & ~4 TW\(_p/yr\) annual production!
Implications of Terawatt PV

- Terawatt-scale deployment of any PV technology requires massive amounts of natural resources
  - Raw materials, chemicals, electricity, water, transportation...
  - Limited supplies of natural resources could prevent PV from reaching a terawatt scale

- There are huge amounts of wastes and end-of-life modules from any PV technology
  - Limited capabilities to handle/recycle them would prevent PV from reaching a terawatt scale
Status of PV Industry as 12/31/14

- ~180 GW<sub>p</sub> global installed capacity
  - Annual revenues ~$250B
  - ~50 GW<sub>p</sub>/yr production
  - ~45% annual growth since 2005
  - ~0.5% global electricity capacity
- If 30% by 2100, the industry has to expand >500-fold in 85 years

The potential for PV is enormous!

Growth of PV Industry

Huge ups & downs as an industry in its infancy

European Photovoltaic Industry Association 2015
PV Industry Breakdown 2014

Four commercial technologies

- Wafer-Si (~200 μm): ~91%
  - Multi-Si >55%
  - Mono-Si ~35%

- Thin-film (<5 μm): ~9%
  - CdTe: ~4%
  - Si (amorphous or microcrystalline): ~2%
  - CuIn_{x}Ga_{1-x}Se_{2} (CIGS, x~0.7): ~3%

CdTe Market Share

- CdTe peaked in 2009 (13%) & has been losing market share since
- CdTe will continue to lose, & wafer-Si will continue to gain, market share
Current PV Technologies
Best Research-Cell Efficiencies

Multijunction Cells (2-terminal, monolithic)
- LM = tandem matched
- IMM = inverted, metamorphic
- Three-junction (concentrator)
- Three-junction (non-concentrator)
- Two-junction (concentrator)
- Two-junction (non-concentrator)
- Four-junction or more (concentrator)
- Four-junction or more (non-concentrator)

Thin-Film Technologies
- CIGS (concentrator)
- CdTe
- Amorphous Si:H (stabilized)
- Nano-, micro-, poly-Si
- Emerging PV
  - Dye-sensitized cells
  - Perovskite cells (not stabilized)
  - Organic cells (various types)
  - Organic tandem cells
  - Inorganic cells (CZTSSe)
  - Quantum dot cells

Single-Junction GaAs
- Single crystal
- Concentrator
- Thin-film crystal

Crystalline Si Cells
- Single crystal (concentrator)
- Single crystal (non-concentrator)
- Multicrystalline
- Thick Si film
- Silicon heterostructures (HIT)
- Thin-film crystal

Energy Policy

NREL 2014

Efficiency (%)
Cost: A Well-Known Bottleneck

- Cost is a major bottleneck: $3\times$ today
- But
  - But solar cost is coming down quickly
  - Fossil fuel prices going up quickly
- Would the PV industry take off when fossil fuel prices exceed PV cost?

The answer is likely a NO!

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost (¢/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>~7</td>
</tr>
<tr>
<td>PV</td>
<td>~13</td>
</tr>
<tr>
<td>CSP</td>
<td>~24</td>
</tr>
<tr>
<td>Geothermal</td>
<td>~5</td>
</tr>
<tr>
<td>Hydropower</td>
<td>~8</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>7–11</td>
</tr>
<tr>
<td>Coal</td>
<td>9–12</td>
</tr>
<tr>
<td>Nuclear</td>
<td>~10</td>
</tr>
</tbody>
</table>

2020 Cost of Electricity*

- Solar electricity $3\times$ more expensive than other forms of electricity today
- By 2020 it is likely $<1.5\times$ more expansive according to DOE

* DOE EIA, Annual Energy Outlook 2015
Cost Trend

Historical Module Price

Module price down 4-fold since 2005
System cost down 1.7-fold since 2005

System Costs

Residential & commercial
Utility-scale system $3.45/W_p in 2012

G. Barbose et al, Tracking the Sun VI (2013)
A Bottleneck for Wafer Silicon

- The process to make w-Si modules is costly, energy-intensive and polluting:
  ~4.2 kWh/W_p for monocrystalline Si modules
- Annual production of 3.7 TW_p of mono-Si modules would require ~79% of the 2012 global electricity consumption,* w/o considering transmission losses

* DOE EIA, International Energy Statistics 2014

C.S. Tao et al, SEMSC 95 (2011) 3176
An Alternative Process

- Directional solidification replaces Czochralski growth: 100 kWh/kg down to 15 kWh/kg & less material loss during wafering, but multi-Si ingot

  The industry trades performance for cost!

- Fluidized-bed process may replace Siemens process, but powder formation
Energy Payback Time

1 W_p PV produces
~1.35 kWh/yr in AZ
- ~15% time-averaged output

Energy payback time in Arizona
- Location dependent
- ~3 yrs for mono-Si
- ~2 yrs for multi-Si cells
- After that, installed PV produces net energy

Energy input for various scenarios*

<table>
<thead>
<tr>
<th></th>
<th>Siemens Process</th>
<th>Fluidized-Bed Process</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mono-Si Module</strong></td>
<td>~4.2 kWh/W_p</td>
<td>~3.3 kWh/W_p</td>
</tr>
<tr>
<td><strong>Multi-Si Module</strong></td>
<td>~3.4 kWh/W_p</td>
<td>~2.5 kWh/W_p</td>
</tr>
</tbody>
</table>

* M. Tao, Terawatt Solar Photovoltaics: Roadblocks and Opportunities (Springer, 2014)
Energy Means Cost

Electricity input for poly-Si is \(~220 \text{ kWh/kg (Siemens)}\)
- In U.S., industrial electricity \(~7\text{¢/kWh}\)
- Electricity cost for poly-Si is \(~$15/\text{kg}: \text{How can the industry profit when the poly-Si price drops below $20/\text{kg?}}\)
  - Use of cheap hydropower, but its capacity limited*
  - Self-generation \(~5\text{¢/kWh}\)
  - Low energy input = low cost + short energy payback time

Electricity consumption for mono-Si PV is \(~4.2 \text{ kWh/W}_p\)
- Electricity cost for 1 \(W_p\) is 29\text{¢/W}_p
- DOE target 50\text{¢/W}_p for modules: HOW?

* N.S. Lewis, MRS-B 32 (2007) 808
Requirements for Terawatt PV

Material requirements
- Abundant material
- Low-cost material
- Energy-efficient synthesis
- Low-cost synthesis
- Low-carbon synthesis
- Minimum health & environmental impact
- Stability & reliability in air & under UV
- Recyclability of end-of-life modules

Device requirements
- High minority carrier lifetime
- High absorption coefficient
  - Direct bandgap
- Broad absorption spectrum
- Suitable bandgap
  - ~1.4 eV
- Both conduction types
- Suitable resistivity

None of the current PV technologies meets all the requirements!

M. Tao, Interface 17(4) (2008) 30
Phenomenal growth
- First to reach $1/W_p$
- Grew 25-fold in 4 years
- But having been losing market share since

What will limit CdTe?
- Known reserve of Te 24,000 tons*
- Best scenario 492 GW_p
- ~0.16% of the 2100 energy demand

CdTe

Abundance of Elements

USGS, Rare Earth Elements – Critical Resources for High Technology 2002

* USGS, Mineral Commodity Summary 2015
What Is Best Scenario?

- Estimation based on material consumption in PV modules and material reserve
  - If there is 10 g of material on the planet and the consumption is 1 g/W_p, only 10 W_p modules can be made
  - The assumption is 100% material utilization
    - All the reserve can be extracted: Some may be too expensive to extract
    - All the reserve exclusively for PV: Other industries may compete for the material
    - No material loss during module fabrication
  - The assumption also include indefinite module lifetime
    - Current modules are typically rated 25 years
  - None of these assumptions can be true – best scenarios
Other Scarce Materials: In

- Multiple issues with CIGS
  - Poor manufacturability: Poor uniformity of three cations
  - Limited availability of In

- Estimation of maximum power from CIGS
  - Known reserve of In 11,000 tons*
  - Composition CuIn$_{0.7}$Ga$_{0.3}$Se$_2$
  - Best scenario 1.1 TW$_p$
  - $\sim$0.36% of the 2100 energy demand

- Competitions for In
  - FPD, LED, lasers, power devices, etc.
  - Hard for the PV industry to compete

* USGS, Mineral Commodity Summary 2008
Other Scarce Materials: Ag

- Silver used in wafer-Si cells as front electrode
  - Known reserve 530,000 tons*
  - Best scenario 10.1 TW\(_p\)
    - 12 μm Ag assumed
    - 7% surface coverage
  - ~3.3% of the 2100 energy demand
    - Realistically maybe 2%

- Competitions for Ag
  - Solders, brazing alloys, batteries, catalyst, jewelry, silverware...

* USGS, Mineral Commodity Summary 2015

C.S. Tao et al, SEMSC 95 (2011) 3176
Conclusion #2

Without technical breakthroughs, current commercial PV technologies excluding thin-film Si would provide <4% of the 2100 energy demand under best scenarios

<table>
<thead>
<tr>
<th>Cell Technology</th>
<th>Efficiency Used</th>
<th>Limiting Material</th>
<th>Reserve Base (ton)</th>
<th>Maximum Wattage</th>
<th>Averaged Output (TW)</th>
<th>% of 2100 Energy Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer-Si</td>
<td>16.8%</td>
<td>Silver</td>
<td>530,000</td>
<td>10.1 TW&lt;sub&gt;p&lt;/sub&gt;</td>
<td>1.52</td>
<td>3.3%</td>
</tr>
<tr>
<td>CdTe</td>
<td>12.8%</td>
<td>Tellurium</td>
<td>24,000</td>
<td>492 GW&lt;sub&gt;p&lt;/sub&gt;</td>
<td>0.074</td>
<td>0.16%</td>
</tr>
<tr>
<td>CIGS</td>
<td>14.3%</td>
<td>Indium</td>
<td>11,000</td>
<td>1.1 TW&lt;sub&gt;p&lt;/sub&gt;</td>
<td>0.165</td>
<td>0.36%</td>
</tr>
<tr>
<td>Thin-film Si*</td>
<td>9.8%</td>
<td>TW capable</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

* Thin-film Si is the only technology capable of terawatt-scale deployment today, but it has lower efficiency and higher cost and is losing market share

C.S. Tao et al, SEMSC 95 (2011) 3176
Annual Production of Materials

- Material production rate limits deployment rate of PV
  
- Required annual production $\sim$3 TW$_p$/yr
  
  - With 92 TW$_p$ total installation & 25-year module lifetime, $\sim$3.7 TW$_p$ modules will die each year
  
  - Annual production of 3.7 TW$_p$ will maintain a steady-state 92 TW$_p$ total installation
Annual Production of CdTe

- Annual production of Te ~550 tons*
  - Te to be depleted in 44 yrs
    - Reserve 24,000 tons
  - Best scenario 11 GW_p/yr
    - Realistically maybe 6 GW_p/yr
  - Current production ~2 GW_p/yr by First Solar
    - If First Solar has access to half of the Te produced, i.e. ~3 GW_p/yr
    - Room for growth limited for First Solar: It has to lose market share
    - First Solar has a good business model

But our energy/environmental crisis will not be solved by CdTe

* USGS, Minerals Yearbook 2012
** E. Fortunato et al, MRS-B 32 (2007) 242
Annual Production of Ag & In

- **Wafer-Si** employs Ag front electrode
  - Production of Ag 26,100 tons/yr*
    - Ag to be depleted in 20 yrs
  - Best scenario 498 GWp/yr
    - Realistically maybe 300 GWp/yr, currently ~50 GWp/yr

- **CIGS** *(CuIn$_{0.7}$Ga$_{0.3}$Se$_2$)*
  - Production of In 820 tons/yr & that of Ga 440 tons/yr*
    - In to be depleted in 14 yrs
  - Best scenario 83 GWp/yr
    - Limited by In
**Conclusion #3**

Without technical breakthroughs, current commercial PV technologies excluding thin-film Si would plateau at <600 GW<sub>p</sub>/yr under best scenarios

<table>
<thead>
<tr>
<th>Cell Technology</th>
<th>Efficiency Used</th>
<th>Limiting Material</th>
<th>Annual Production (ton)</th>
<th>Annual Production (GW&lt;sub&gt;p&lt;/sub&gt;/yr)</th>
<th>Years to Depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer-Si</td>
<td>16.8%</td>
<td>Silver</td>
<td>26,100</td>
<td>498</td>
<td>20</td>
</tr>
<tr>
<td>CdTe</td>
<td>12.8%</td>
<td>Tellurium</td>
<td>550</td>
<td>11</td>
<td>44</td>
</tr>
<tr>
<td>CIGS</td>
<td>14.3%</td>
<td>Indium</td>
<td>820</td>
<td>83</td>
<td>14</td>
</tr>
<tr>
<td>Thin-film Si*</td>
<td>9.8%</td>
<td>TW capable</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

*C S. Tao et al, SEMSC 95 (2011) 3176*
Storage of Solar Electricity

- First showstopper: $\sim3.7$ TW$_p$ PV w/o storage
  - The grid can serve as a buffer, to some extent, w/o storage
    - But unlikely to take $>10\%$ from PV w/o storage
  - Current global electricity capacity 5.5 TW*
    - Limits PV capacity to $\sim550$ GW or $\sim3.7$ TW$_p$

- Second showstopper: $\sim30$ TW$_p$ PV w/o conversion
  - In US, 32\% of energy we use is non-renewable electricity**
    - Another 5\% of energy is electricity from hydropower
  - Current global energy consumption $\sim18$ TW
    - If 25\% of energy is non-renewable electricity, i.e. 4.5 TW
    - Limits PV to $\sim30$ TW$_p$ unless solar electricity is converted to a fuel

* DOE EIA, International Energy Statistics 2014
** DOE EIA, Annual Energy Review 2011
Storage Options

- **GW capable**
  - Limited by geology
    - Pumped hydropower
    - Compressed air

- **kW to MW**
  - Various batteries
  - Flywheel
  - Supercapacitor
  - Hear storage
  - Superconducting magnet

Storage Performance

TW scale storage requires GW scale capacity for hours or even days

*IRENA, Electricity Storage 2012*  
B. Dunn et al, Science 334 (2011) 928
Case Study for Batteries

- If 30% from PV by 2100, i.e. 13.8 TW
  - If 50% of solar electricity requires storage, i.e. a minimum of \( \sim 1.7 \times 10^{11} \) kWh to be stored on a daily basis
    - Actually more than 50% due to weather
  - Typical laptop batteries are 50 Wh each
    - At least 473 laptop batteries/person for the 7 billion people on Earth
    - Amounts of natural resources needed to make these batteries?
    - Amounts of wastes and dead batteries to handle?
Recycling of PV Modules

- Stead-state 92 TW_p total installation & 25-year module lifetime
  - 3.7 TW_p/yr modules through their lifetime
  - If these are wafer-Si modules with 16.8% efficiency, there are 2.2x10^4 km^2/yr dead modules
    - The size of New Jersey has to be recycled each year

- CdTe is recycled by First Solar
  - Cd is toxic & Te is rare
  - But many companies are overlooking recycling
Recycling of Si Modules

- With >90% of the market, Si modules are not routinely recycled & technology not ready yet
  - Ag would be depleted in 20 years
  - Pb is toxic
- There are financial incentives to recycle Si modules
  - ~20 g/module of Ag worth $10–30/module
    - 95% recovery and $15–45/oz of Ag
  - ~650 g/module of solar-grade Si worth ~$10/module
    - 90% recovery and $18/kg of poly-Si
    - Savings in energy to purify Si
Cost Contributors

- **Installation**
  - >3/4 of the system cost, especially soft costs
    - Design, permitting, financing, labor, hardware...

- **Energy**
  - Poly-Si and Al frame

- **Raw materials**
  - Ag, Si, glass, Al frame, EVA, backsheet...

- **Processing**
  - Wafering, diffusion, AR coating, metallization, interconnect...
  - Non-vacuum continuous processing

* A. Goodrich et al, SEMSC 114 (2013) 110
Lower Cost by Standardization

One factor: Each PV system is individually designed
- Modules have different power & efficiency
  - Have to accommodate different modules with minimum mismatch
  - Require customized hardware
  - Replacing a bad module in a system is a headache

The reason: Cell efficiency dispersion
- Efficiency ranges 12–18% from “same” process, same ingot
  - Every cell/module has to be tested and sorted (binned)
  - Only cells with similar efficiencies are packaged into a module
  - Only modules with similar efficiencies are connected in an array

- Commercial modules have 2% efficiency dispersion
  - Disqualified cells lead to a higher cost

How to narrow the efficiency spread down to, say, ±0.5%?
Summary

Most PV technologies incapable of making an impact

Strategic R&D directions for a sustainable PV industry

- Wafer-Si based
  - Energy-efficient purification for solar-grade Si
  - Substitution of Ag with an Earth-abundant metal (Cu & Al)
  - Module standardization by cell efficiency uniformization
  - Non-vacuum continuous processing
  - Low-kerf wafering of ingot
  - Recycling of end-of-life cells/modules

- Thin-film Si: lower cost & higher efficiency

- Next-generation PV: Earth-abundant materials

- Terawatt-scale storage of solar electricity

Innovation! Innovation!! Innovation!!!