Sustainability of Solar Energy & Energy Storage

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U.S. Senator Fulbright

- Graduate of University of Arkansas
- Rhodes Scholar at Oxford 1924–28
- U.S. House of Representative 1942–44
- U.S. Senate 1945–75
- Chair of Senate Foreign Relations Committee 1959–74
- Fulbright Resolution

J. William Fulbright
1905–1995
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Public Law 87-256, 1961
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- One of the oldest and largest international exchange programs: 70 years
- Bi-nationalism: “two-way exchange”
- Promotion of mutual understanding
- Public diplomacy: “giving something back”
- Over 160 participating countries

For Swedish graduate students and scholars:

www.fulbright.se
Arizona Landscape

Four Peaks from my home
Outline

- Current & future global energy demands
  - Scales required for PV & storage
- Showstoppers & bottlenecks to terawatt PV & storage
  - Availability of raw materials
  - Energy input for Si wafers & modules
  - Recyclability of end-of-life PV modules
  - Terawatt-scale storage of solar electricity
    - Recycling of batteries
  - Manufacturing and installation costs
- Strategic R&D directions for PV & storage
Acknowledgments

This talk is based primarily on:


Individuals to acknowledge:

- D. Holladay (SEMATECH)
- E. Stechel (ASU)
Background

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

- A 5-year joint effort initiated by SEMATECH (D. Holladay) & myself (2006–2011)
- Forced me to look into sustainability & scalability of PV & other renewable energy technologies in general
How Much Energy Do We Need?

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

Conclusion #1

PV & storage technologies have to be deployed at tens of terawatts, or they will have little impact on our energy mix or carbon emission.

- By 2100, global energy demand is projected to reach 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 under steady state.

We need ~100 TW_{p} of solar PV installed & ~3.7 TW_{p}/yr annual production!
**Implications for PV & Storage**

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

- There are huge amounts of wastes and end-of-life devices from any PV or storage technology
  - Limited capabilities to handle/recycle them would prevent PV from reaching a terawatt scale
Industry Status as of 12/31/16

- ~0.3 TW\textsubscript{p} global installed capacity
  - Annual revenues ~$300B
  - ~77 GW\textsubscript{p}/yr production
  - ~45% annual growth since 2005
  - ~0.8% global electricity capacity

- If 100 TW\textsubscript{p} by 2100, the industry has to expand ~327\times in 84 yrs

The potential for PV is enormous!

Growth of PV Industry*
Rapid growth expected to continue

* SolarPower Europe 2017
PV Industry Breakdown 2016

Four commercial technologies

- Wafer-Si (~190 µm): 94%
  - Multi-Si ~70% & mono-Si ~24%
- Thin-film (<5 µm): ~6%
  - CdTe ~3.8%
  - Thin-film Si: ~0.6%
  - CuIn_xGa_{1-x}Se_2 (CIGS, x=\sim0.7): ~1.6%

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 shares
Current PV Technologies

Best Research-Cell Efficiencies

Multijunction Cells (2-terminal, monolithic)
- LM = lattice matched
- MM = metamorphic
- 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)

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

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

Thin-Film Technologies
- CIGS (concentrator)
- CIGS
- CdTe
- Amorphous Si:H (stabilized)

Emerging PV
- Dye-sensitized cells
- Perovskite cells (not stabilized)
- Organic cells (various types)
- Organic tandem cells
- Inorganic cells (CZTSSe)
- Quantum dot cells

NREL 2016

Efficiency (%)
Cost: A Well-Known Bottleneck

Cost is a major bottleneck: \( \sim 2 \times \) today

But

- PV cost coming down quickly
- Fossil fuel prices trending up

Would the PV industry take off when fossil fuel prices exceed PV cost?

The answer is likely a NO!

2022 Cost of Electricity*

- Solar electricity \( \sim 2 \times \) more expensive than other forms of electricity today
- By 2022 it is likely to be lower than coal and nuclear

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost (¢/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>5.2–15</td>
</tr>
<tr>
<td>PV</td>
<td>6.7</td>
</tr>
<tr>
<td>CSP</td>
<td>18.4</td>
</tr>
<tr>
<td>Geothermal</td>
<td>4.3</td>
</tr>
<tr>
<td>Hydropower</td>
<td>6.6</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>5.7–11</td>
</tr>
<tr>
<td>Coal</td>
<td>12.3–14</td>
</tr>
<tr>
<td>Nuclear</td>
<td>9.9</td>
</tr>
</tbody>
</table>

* DOE EIA, Annual Energy Outlook 2017
A Bottleneck for Wafer Silicon

- The process to make w-Si modules is costly, energy-intensive and polluting: ~4.2 kWh/Wp for monocrystalline Si modules
- Annual production of 3 TWp of mono-Si modules would require ~65% of the 2012 global electricity consumption,* w/o considering transmission losses

C.S. Tao et al, SEMSC 95 (2011) 3176  
* DOE EIA, International Energy Statistics 2014
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 a better purification process is still needed to reduce the energy input
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 Cells</strong></td>
<td>~4.2 kWh/W_p</td>
<td>~3.3 kWh/W_p</td>
</tr>
<tr>
<td><strong>Multi-Si Cells</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 kWh/kg (Siemens)
- In U.S., industrial electricity ~7¢/kWh
- Electricity cost for poly-Si is ~$15/kg: How can the industry profit when the poly-Si price drops below $15/kg?
  - Cheap hydropower, but its capacity is limited*
  - Self-generation ~5¢/kWh, but from fossil fuels
  - Low energy input = low cost + short energy payback time

Electricity consumption for Si PV is 2.5–4.2 kWh/W_p
- Electricity cost for 1 W_p is 17–29¢/W_p
- Si modules sold for 32–37¢/W_p today: Little room for profit

* N.S. Lewis, MRS-B 32 (2007) 808
Requirements for TW 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 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 of these requirements!

CdTe Solar Cells

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

Abundance of Elements

Our energy/environmental crisis will not be solved by CdTe

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

* USGS, Mineral Commodity Summary 2013
Best-Scenario Estimation

Estimation based on material consumption in PV modules and material reserve

- If there is 10 g of a material on the planet and each module takes 1 g of that material, at best we can make 10 modules
- It assumes 100% material utilization
  - All the reserve can be extracted: Some too expensive to extract
  - All the reserve exclusively for PV: Other industries often compete for the material
  - No material loss during fabrication
- It also assumes infinite module lifetime
  - Current modules are typically rated for 25 years
- None of these assumptions can be true – best scenarios
Other Scarce Materials

Indium in CIGS
- Known reserve 11,000 tons*
- Best scenario 1.1 TW<sub>p</sub> from CuIn<sub>0.7</sub>Ga<sub>0.3</sub>Se<sub>2</sub>
- ~0.36% of the 2100 energy demand
- Competitions for In
  - FPD, LED, lasers, nitride power devices
  - Hard for the PV industry to compete

Silver in wafer-Si
- Used as front electrode
- Known reserve 530,000 tons*
- Best scenario 20.5 TW<sub>p</sub>
  - 0.11 g/cell
  - 4.26 W<sub>p</sub>/cell assumed
- ~6.7% of the 2100 energy demand
- 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 ~7% 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>17.5%</td>
<td>Silver</td>
<td>530,000</td>
<td>20.5 TW_p</td>
<td>3.08</td>
<td>6.7%</td>
</tr>
<tr>
<td>CdTe</td>
<td>12.8%</td>
<td>Tellurium</td>
<td>24,000</td>
<td>492 GW_p</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_p</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 PV is the only technology capable of terawatt-scale deployment today, but it has lower efficiency, higher cost & is losing market share (0.6%)

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

- It limits deployment rate of PV
  - Need $\sim 3.7 \text{ TW}_p/\text{yr}$
- CdTe
  - Annual production of Te $\sim 550$ tons*
    - Te to be depleted in 44 yrs
  - Best scenario $11 \text{ GW}_p/\text{yr}$
  - Current production $\sim 2.9 \text{ GW}_p/\text{yr}$ by First Solar
    - Room for growth limited: It has to lose market share
- Wafer-Si
  - Production of Ag 26,100 tons/yr**
    - Ag to be depleted in 20 yrs
  - Best scenario 1.01 TW$_p$/yr
- CIGS
  - Production of In 820 tons/yr**
    - In to be depleted in 14 yrs
  - Best scenario 83 GW$_p$/yr

* USGS, Minerals Yearbook 2012
** USGS, Mineral Commodity Summary 2015
**Conclusion #3**

Without technical breakthroughs, current commercial PV technologies excluding thin-film Si would plateau at ~1.1 TW_p/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_p/yr)</th>
<th>Years to Depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer-Si</td>
<td>17.5%</td>
<td>Silver</td>
<td>26,100</td>
<td>1,010</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>Cl GS</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>
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<td>–</td>
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* Thin-film Si PV is the only technology capable of terawatt-scale deployment today, but it has lower efficiency, higher cost & is losing market share

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

First showstopper: $\sim 3 \text{ TW}_p$ PV w/o storage
- The grid can serve as a buffer, to some extent, w/o storage
  - But unlikely to take $>10\%$ from PV & wind w/o storage
- Current global electricity capacity $5.5 \text{ TW}^*$
  - Limits PV & wind capacity to $\sim 550 \text{ GW}$ or $\sim 3.7 \text{ TW}_p$

Second showstopper: $\sim 36 \text{ TW}_p$ PV w/o conversion
- In US, $32\%$ of energy we use is non-renewable electricity**
  - Another $5\%$ is electricity from hydropower
- Current global energy consumption $\sim 18 \text{ TW}$
  - If $30\%$ of energy is non-renewable electricity, i.e. $5.4 \text{ TW}$
  - Limits PV to $\sim 36 \text{ TW}_p$ unless solar electricity is converted to a fuel

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

- **GW capable**
  - Pumped hydropower
  - Compressed air
  - Limited by geology
- **kW to MW**
  - Various batteries
    - Flywheel
    - Supercapacitor
    - Hear storage
    - Superconducting magnet

Storage Performance*

TW scale storage requires GW scale capacity for hours to months

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% in Sweden
- Typical laptop batteries are 50 Wh each
  - 473 laptop batteries/person for the 7 billion people on Earth

Sustainability of battery technology
- Amounts of natural resources needed to make these batteries
- Amounts of wastes and end-of-life batteries to handle

Materials for batteries must be Earth-abundant!
Earth-Abundant Elements?

Reduced Periodic Table of Earth-Abundant Elements*

- Cutoff 100 million tonnes known reserve
- Only 27 elements in the table
- No Li, V, Br, or Cd
- Can we find an efficient, low-cost storage medium in the table?

* M. Tao, Terawatt Solar Photovoltaics: Roadblocks and Opportunities (Springer, 2014)
Recycling of PV Modules

- Stead-state 100 TWₚ total installation & 25-yr module lifetime
  - 4 TWₚ/yr modules through their lifetime
  - If 17% efficiency, there are $2.4 \times 10^4$ km²/yr waste modules
    - The size of New Jersey has to be recycled each year
  - IREA predicts 78 million tons of waste modules by 2050*
    - Equal to over 4.2 billion waste modules by 2050

- CdTe is recycled by First Solar
  - Cd is toxic & Te is rare

- PV CYCLE recovers only Al frame & glass from Si modules

Recycling of Si Modules

- With >90% of the market, Si modules are rarely recycled & technology not ready yet
  - Ag would be depleted in 20 years
  - Pb is toxic

- There are financial incentives to recycle Si modules
  - ~6 g/module of Ag worth $2.70–9.30/module
    - 98% recovery and $13–45/oz of Ag price
  - ~650 g/module of solar-grade Si worth ~$8/module
    - 85% recovery and $15/kg of poly-Si
    - Savings in energy to purify Si
  - ~$15/module to recover

Si module recycling can be a profitable business w/o government support
Cost Breakdown

- Installation
  - 75% of the system cost
    - Balance of system, design, permitting, financing, labor, hardware...

- Energy
  - Poly-Si, wafering, Al frame

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

- Processing
  - Diffusion, AR coating, metallization, interconnect...
  - Non-vacuum continuous processing

* A. Goodrich et al, SEMSC 114 (2013) 110
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 or Al)
  - Recyclability of end-of-life modules
  - Module standardization for lower system cost
  - Non-vacuum inline continuous fabrication
  - Low-kerf wafering of ingot

- Thin-film Si: lower cost & higher efficiency

- Future PV: Earth-abundant, energy-efficient materials

- Cross-cutting: Terawatt-scale storage of solar electricity
  - Storage medium must be Earth-abundant
  - Recyclability of storage batteries
My Research Portfolio

- A scalable & sustainable Si PV industry
  - Electrorefining of metallurgical-grade Si
  - Substitution of Ag electrode with Al
  - Profitable recycling of Si cells & modules
  - Spray deposition of Earth-abundant metal oxides for PV
  - Module standardization through efficiency uniformization
  - Grain boundary passivation by sulfur

- A scalable & sustainable thin-film PV industry
  - Metal oxysulfide absorber with $\sim$1.4 eV direct bandgap

- A sustainable solar energy infrastructure
  - A $\text{Zn} \leftrightarrow \text{ZnO}$ loop for off-grid storage of solar electricity
  - Load-managing PV systems for 25% lower LCOE
Si Module Recycling

- PV CYCLE recovers only Al & glass
- Our 3-step process
  - Module recycling
  - Cell recycling
  - Waste handling

A Recycling Process for Si Modules

- Who is going to pay for it? It pays for itself!
- ~99% module by weight recovered
- Recovered Si is solar-grade Si & recovered metals >99% pure
- ~$12/module in revenue from Ag & solar-grade Si
Recovery of Multiple Metals

Voltammetry of Solution Deposits by EDX

**Voltammetry of Solution**
- $\text{HNO}_3$ to dissolve 4 metals from cells: Ag, Pb, Cu & Sn
- Sn precipitates as SnO$_2$ in leach solution
- Sequential electrowinning to recover Ag, Cu & Pb from leach solution

**Deposits by EDX**
- Recovered metals >99% pure
- Our target >98% metal recovery
- Recovered Ag ~5.7 g/module worth ~$3.50 @ $17/oz of Ag

W.-H. Huang et al, 43rd PVSC (2016)
Recovery of Solar-Grade Si

How to maximize Si recovered?

- Only the base is solar-grade Si
  - NaOH to etch emitter & BSF in Si

- Sheet resistance monitoring
  - ~30 min to reach the base

Sheet Resistance vs. Time

- 85% recovery of solar-grade Si
- Recovered Si ~0.55 kg/module worth $9.35 at $17/kg of Si

Evolution of the Cell