PSE Challenges in Solar Research
CAPD Review Sunday March 11, 2012
B. Erik Ydstie

Solar grade silicon (J. Du)
Float Process for Silicon Wafers (G. Oliveros)
Dye Sensitized Solar cells (R. Panella)
Solar and wind on the Grid (J. Liu)
Supply Chain for Silicon Solar Cells

50% of system cost = Solar cell module + Balance of system (BOS)

30% of module cost

- Crystalline silicon production
- Wafer production
- Cell fabrication

Solar-grade silicon

Aim: $20/kg

IC supply chain

- Metallurgical grade silicon
- SiCl₃H distillation
- Decomposition
- Crystallization
- Wafer
- Integrated circuit

REC Silicon, Moses Lake, WA

Fluidized Bed Si Production:
- 2005–2007: Demonstration scale
- 2008: Commercial scale

$3-5/kg

$40-60/kg

$40-60/kg
Supply Chain for Silicon Solar Cells

- **PV System**
  - **50% of system cost**
  - **Solar cell module**
  - **+ Balance of system (BOS)**

- **30% of module cost**
  - **Crystalline silicon**
  - **Wafer production**
  - **Cell fabrication**

- **Solar-grade silicon**

- **IC supply chain**
  - **Metallurgical grade silicon**
  - **SiCl₃H distillation**
  - **Decomposition**
  - **Crystallization**
  - **Wafer**
  - **Integrated circuit**

**REC Silicon, Moses Lake, WA**

**Fluidized Bed Si Production:**
- 2002–2005  Pilot plant
- 2005–2007  Demonstration scale
- 2008       Commercial scale

**Aim:** $20/kg

**IC supply chain**
- **$3-5/kg**

**$40-60/kg**
The proposed solution: Design and Control of Solar Silicon FBR process from Silane to Solar Silicon.

Siemens Reactor
Batch Process
1100°C (TCS)
650 °C (Silane)

Fluid Bed Reactor
Continuous Process
Large surface area
650 °C

Goal: develop scale-up and control models to optimize granular yield and control particle size.

\[ SiH_4(g) \rightarrow Si(s) + 2H_2(g) \]

increase throughput
Reduce energy cost

Ron Reis REC Silicon, Paul Ege Reactech
2 PhD students
Multi-scale Modeling Approach

Particles are well-mixed
Integrate over time for particle size distribution

Gas and powder are plug flow
Integrate over height for granular yield

Operation challenges
- Fast dynamics – fluidization, reaction
- Slow dynamics – particle size distribution
- Distributed parameters
  - Particle size distribution
  - Chemical reaction, yield loss
  - Bed fluidization

Computational fluid dynamics
Simulate to obtain model input
Model Verification using Pilot Plant Data

Time constant for particle size distribution about 50 hours.

Weak control of distribution function

Difficult to control yield loss (sensitive system)
Scale-up models: from pilot to demonstration plant

**Granular Product and Seed Mean Diameter Correlation**

\[
\ln \left( \frac{D_{ap}}{D_{as}} \right) = \frac{1}{3} \left[ \ln \left( 1 + \frac{Y}{S} \right) - \ln \left( \frac{n_p}{n_s} \right) \right]
\]

- **Y-Yield**
- **S-silane feedrate**
- **D- average diameter** (p - product, s-feed)
- **n- particle feedrate** (p - product, s-feed)

Full Scale Production on Moses Lake in 2009
- Multi-scale modeling
  - Captures physics of system (CFD, Chemistry, Population balance)
  - Useful for scale-up and design
  - Predicts process dynamics
- “Natural Discretization” of population balance
- New closure relation
- Stability and control (Juan Du)
- **REC Silicon's $970 million expansion project** in Moses Lake houses 24 fluid bed reactors to produce 6,500 metric tons of polysilicon per year
- Christy’s Thesis has been “sold” from the library

- NSF Graduate Research Fellowship Program
- REC Silicon
- Reactech Process Development Inc.
Silicon Wafers using Float Process

Current methods are carried out in batch
Continuous processes yield inferior product

Single crystalline 18-20%
Multi-crystalline 14-16%
EGF etc 10-14%
**Float Process for Silicon Wafers**

2009-2013 NSF and PA Nano grants to study crystallization, fluid flow and heat flow, process scale-up and detailed design, process control, commercialization.

- Si Wafer
  - nano texturing
  - doping
  - contacts
  - anti-reflective coating
Dye Sensitized Solar Cell – Simple Construction

Glass

TCO (Transparent Conducting Oxide)

TiO2 nanoparticles

Dark organic dye

Photoanode

TiO2 application, sintering, and dye soaking

Reflective Pt Cathode

Cell sealing and liquid electrolyte injection

Cell sealing and liquid electrolyte injection
Dye Solar Cell Issues – TCO Recombination

- Undesirable electrolyte interactions with TCO surface

\[ 2\text{TCO}^* + \text{I}_3^- \rightarrow 2\text{TCO} + 3\text{I}^- \]

- Stop recombination by applying smaller titania nanoparticles under aqueous conditions

\[ \text{pH and electrolyte control} \]

Fast, low temperature deposition

Panella – Dec 2011
Application of Deposited Particles to Operating Cells

Small, 10 nm particles are able to strongly adsorb to the FTO surface

10 Ω/□ FTO under 150k magnification SEM
Crystalline nature encourages light scattering

10 Ω/□ FTO which has been exposed to TiO$_2$
nanoparticles under adsorbing conditions

Panella – Dec 2011
The pre-coated anode has been treated with an impinging jet with 10 nm TiO$_2$ nanoparticles.

On top of this, a ~30 µm layer of 25 TiO$_2$ particles has been applied by doctor-blading and drying a concentrated slurry. The normal anode only has the doctor-bladed layer, not the 10 nm layer.

<table>
<thead>
<tr>
<th></th>
<th>$I$ (short circuit) mA/cm$^2$</th>
<th>$V$ (open circuit)</th>
<th>Fill Factor</th>
<th>IPCE</th>
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<tbody>
<tr>
<td>&quot;Pre&quot; Coated Cell</td>
<td>2.55</td>
<td>0.46</td>
<td>0.441</td>
<td>0.52%</td>
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<tr>
<td>Standard Cell</td>
<td>1.41</td>
<td>0.33</td>
<td>0.417</td>
<td>0.19%</td>
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</table>
Frequency Control in Systems with Wind Power

Project with PITA
Juhua Liu (PhD), Bruce Krogh (ECE)

• Wind fluctuations → deviation from 60Hz.
• Conventional generation compensates (slow)
• Need for decentralized approaches for stability analysis and design
• Our Approach: Use thermodynamic stability analysis (entropy as “Lyapunov function”)
IEEE WECC 9-Bus Test Case

- Wind farm about 25% of system capacity
- Wind power fluctuation ±5% of average power
- Redesign Gen-3’s governor for frequency control
- The system is passive

\[
Z = \frac{1}{2} \omega^2
\]

Kinetic energy

\[
S = -\frac{2}{3} \sqrt{\frac{2}{J}} Z^\frac{3}{2}
\]

Entropy

\[
\frac{\partial S}{\partial Z} = \pm \omega
\]

Angular velocity
Generator Model: Swing Equations (per unit)

\[
\begin{align*}
\dot{\theta}_i &= \omega_i - \omega_0 \\
\frac{2H_i}{\omega_0} \ddot{\omega}_i &= T_{mi} - T_{ei} - K_{Di} (\omega_i - \omega_0) \\
\omega_0 &= 2\pi 60 \text{ rad/s} \\
P_{mi} &= \frac{T_{mi} \omega_i}{\omega_0} \\
P_{ei} &= T_{ei} \omega_i/\omega_0 \\
P_{ei} &= \sum_{j=1, j \neq i}^{n} f_{ij}
\end{align*}
\]

Network Model: DC Power Flow

\[f_{ij} = E_i E_j B_{ij} \sin (\theta_i - \theta_j)\]

\[f_{ij} \approx E_i E_j B_{ij} (\theta_i - \theta_j)\]

\[f_{ij} = -f_{ji}\]

\(B_{ij}\): susceptance
Performance Evaluation

- Gen-3 on robust $H_{\infty}$ control, others on droop control (PI)

$$G_{C3} = \frac{8460s^2 + 5579s + 2.411E5}{s^3 + 6349s^2 + 1.444E5s + 2.284E5}$$

**Frequency deviation**

**Closed-loop gain from $P_W$ to $\omega_3$**

<table>
<thead>
<tr>
<th>Time (Sec)</th>
<th>Frequency deviation (mHz)</th>
<th>Frequency (rad/sec)</th>
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<tbody>
<tr>
<td>0</td>
<td>-60</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>50</td>
<td>60</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>100</td>
<td>40</td>
<td>$10^0$</td>
</tr>
<tr>
<td>150</td>
<td>20</td>
<td>$10^1$</td>
</tr>
<tr>
<td>200</td>
<td>0</td>
<td>$10^2$</td>
</tr>
</tbody>
</table>

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