Cost and Potential of Monolithic CIGS Photovoltaic Modules

IEEE Photovoltaic Specialists Conference, New Orleans

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June 17, 2015
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Acknowledgments

Funding

Dr. Michael Woodhouse  
Co-Author

Ran Fu  
Team Member, Systems Costs

NREL CIGS Team

All our collaborators in industry
Overview of Presentation

• $/W manufacturing costs and minimum sustainable price calculations for monolithic, glass-glass CIGS modules
  o Sputtering plus sulfurization after selenization (SAS)
    – Batch
    – In-line rapid thermal process (RTP)
  o Co-evaporation
    – In-line, 1-stage process
    – 3-stage process

• Cost reduction roadmap
• Levelized cost of energy (LCOE) for CIGS and standard c-Si technology
Motivation

CIGS technology has made great strides...

• Efficiency
  o 1970s: 4% efficient cells
  o 2015: 21.7% record lab efficiency and 13-15% average production module efficiencies

• Production capacity
  o Solar Frontier: GW-scale
  o Stion, TMSC Solar, and Avancis: 100-200MW/year

• Improved stability and degradation.

...but

• CIGS accounts for only ~2-4% of PV market shipments
  o Vast majority of modules sold to the Japanese market

• Several CIGS start-ups have been acquired by Hanergy or have closed

• A lack of public CIGS companies means there is little publicly available information on costs and prices.
Reference Case Assumptions

Glass-glass monolithic module
- Low-iron tempered front glass (3.2mm thick)
- Soda lime back glass (3.2mm thick)

1.6m x 0.6m substrate size

1.5 μm thick CIGS layer
250 nm thick Mo layer

Ga/(In+Ga) = 0.31
Cu/(In+Ga) = 0.92

14% module efficiency

U.S. manufacturing
100MW/year production volume.
Method for Computing Manufacturing Cost

1. Request and gather input data
2. Aggregate data, plug into model, run analysis
3. Create a process flow
4. Review by industry and academic experts
Method for Computing Manufacturing Cost

- Total cost of ownership for each step in the manufacturing process
  - Materials
  - Utilities
  - Labor
  - Depreciation (equipment and facilities/building)
  - Maintenance
- Assume a largely automated manufacturing process
- 7-year and 15-year straight-line depreciation schedules for equipment and building, respectively.
Minimum Sustainable Price (MSP)

• MSP: The price at which the net present value (NPV) of a 20-year project is equal to zero
  - **Minimum price necessary to generate a required rate of return**
  - We set the required rate of return to be the weighted average cost of capital (WACC)

\[
WACC = E \cdot r_e + D \cdot r_d \cdot (1 - r_t)
\]

- \(E = \%\) equity, \(D = \%\) debt, \(r_e = \text{cost of equity}\), \(r_d = \text{cost of debt}\), \(r_t = \text{corporate tax rate}\)
- WACC = 14.5% calculated for the U.S. PV cell and module companies in 2015

• Included in the NPV calculation:
  - Manufacturing costs
  - Overhead costs
    - Research and development (R&D) costs, assumed to be 8% of revenue
    - Sales, general, and administrative (SG&A) costs, assumed to be 4% of revenue
    - Other costs (warranty, legal), assumed to be 2% of revenue
  - Taxes, 28% effective federal corporate tax rate assumed
  - Zero salvage value.
Manufacturing Process Flow

Unload, inspect and wash soda lime back glass.

Sputter Mo back contact.

P1 laser scribe through Mo.

Deposit CIGS layer (co-evaporation) 1.5 - 2 μm thickness.

Sputter CIG.

Selenization/sulfurization, resulting in a 1.5-2 micron thick CIGS layer.

P3 mechanical scribe down to Mo and laser edge isolation.

Sputter intrinsic and doped TCO layers.

P2 mechanical scribe through buffer down to Mo.

Buffer layer chemical bath deposition.

Electrically connect the monolithically integrated cells by solder-welding metal ribbon busbars and conducting adhesive tape.

Feed bus bar ribbons through pre-drilled hole in tempered back glass. Bond the cells and busbar assembly to the front glass with EVA and edge seal.

Solder the bus bar ribbons to the junction-box leads; and bond the J-box to the back glass with potting agent, tape, and frame.

Light soaking followed by high voltage isolation (Hi-Pot), ground continuity, and solar simulator J-V testing.

Visual inspection and module binning and packing.
CIGS Absorber Deposition Processes

• Sputtering plus sulfurization after selenization (SAS)
  o **Batch**: More mature, deployed in large-scale production today, higher efficiency, high yield
  o **In-line RTP**: Higher throughput if high yields can be achieved at scale, elemental Se

• Co-evaporation
  o Not yet deployed in large-scale commercial production, earlier stage
  o **3-stage process**: Record cell efficiencies, low throughput, high capital cost
  o **1-stage, in-line process**: Higher throughput, lower efficiency than 3-stage.

Reference case
Step-by-Step Manufacturing Costs

Step-by-Step Manufacturing Costs for Sputtering + Batch SAS

U.S. Manufacturing, 100MW/year production, 1.6m x 0.6m substrate

- Total module manufacturing cost: $78.22/m² ($0.59/W_{DC} at 14% efficiency)
- MSP: $0.72/W_{DC}
Material costs dominate
  - Balance of module materials are a significant cost driver
• The SAS step represents the largest device cost
• Exact breakdown will vary by region of manufacturing.
Comparison of Process Costs

- This comparison assumes equal manufacturing scale and yields could be achieved. Additional efforts into the in-line RTP and co-evaporation processes are required to meet these goals.
- We find the 3-stage co-evaporation process to be more expensive than 1-stage co-evaporation or sputtering + batch SAS today.
- 16% efficiency for leading modules on commercial lines has been demonstrated both from sputtering + batch SAS and 1-stage, in-line co-evaporation. Which process will have a long-term efficiency advantage is unknown.

![Graph showing process costs](image)

- 1-stage, in-line co-evaporation: $13.97/m²
- Sputter CuGa+In: $17.58/m²
- SAS - Batch: $12.23/m²
- SAS - RTP: $13.97/m²
Manufacturing Cost Reduction Roadmap

- Decreasing the thicknesses to below 1.5 microns may require engineering to maintain process repeatability, as well as light-trapping structures or electron reflectors. This is an open question.
- Additional reductions could be achieved if throughput for the CIGS absorber process could be achieved without sacrificing efficiency.
- Efficiency improvements are key to future module and system $/W reductions.

Module efficiency (average production):
- 16% near-term
- 18% mid-term
- 20% long-term (requires significant development).

Some companies may already:
- Be achieving ≥ 95-96% yields
- Be using ~2mm back glass
- Be using Zn(O,S) buffer layer.
Scale and Manufacturing Location

• Preliminary estimates indicate that scaling from 100MW/year to 1GW/year could reduce total module costs by $0.03-$0.04/W_{DC}.

• Manufacturing in a low-cost labor location could save an additional $0.05/W_{DC} at the assumed level of automation in our model.

• Costs will always depend on the manufacturing location, supply chain, and specific company.
LCOE of CIGS and Standard c-Si

- Single-owner utility model
- 7.5% nominal discount rate, 30-year analysis period
- No state or local incentives included
- Use $0.72/W_{DC}$ computed CIGS MSP for these assumptions as the module price
- $0.65/W_{DC}$ used as the global c-Si module price.

For a given system price in this climate, CIGS can achieve a lower LCOE because of the low temperature co-efficient and good low-light performance

- Increasing module efficiency would drive down system costs, a major contributor to LCOE
- Reducing degradation rate from -0.96%/yr assumed here to -0.5%/year could decrease CIGS LCOE by ~0.5 ¢/kWh, depending on the module
- SAM may underestimate CIGS energy production according to industry interviews.

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<thead>
<tr>
<th>Federal ITC Level</th>
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<th>9.99</th>
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TABLE II
Computed Nominal LCOEs in Phoenix, AZ

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Summary and Future Work

• We have built a bottom-up cost model for different CIGS manufacturing processes.
  o For U.S. manufacturing and 100MW/year production with sputtering + batch SAS, we calculate a total module manufacturing cost of $0.59/W_{DC} ($0.72/W_{DC} MSP) with potential to reduce below $0.40/W_{DC}.
  o Materials, balance of module, and the SAS process represent major module cost drivers.

• Using our modeled module cost numbers, we estimate the LCOE of CIGS to be close to that of standard c-Si. The difference is primarily driven by the higher system price due to the lower module efficiency (14% vs. 16%).
  o Deeper study of observed energy production in CIGS systems and energy production modeled with SAM is warranted.

• Better resolution on global material costs, supply chains, and competitiveness would provide further insight into current CIGS costs and market dynamics.
Thank you!
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# Complete LCOE Inputs

## TABLE I

**Input Assumptions for LCOE Calculations**

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