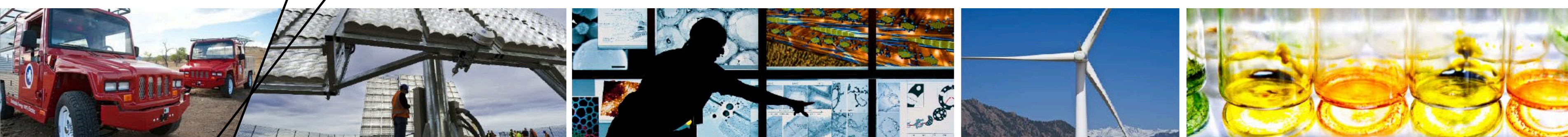
Cost and Potential of Monolithic CIGS Photovoltaic Modules



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NREL CIGS Team

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Overview of Presentation

- **$/W manufacturing costs and minimum sustainable price calculations for monolithic, glass-glass CIGS modules**
    - Sputtering plus sulfurization after selenization (SAS)
        - Batch
        - In-line rapid thermal process (RTP)
    - 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**

Photo by Shell Solar, NREL 10803

Motivation

CIGS technology has made great strides…

- Efficiency
  - 1970s: 4% efficient cells
  - 2015: 21.7% record lab efficiency and 13-15% average production module efficiencies
- Production capacity
  - Solar Frontier: GW-scale
  - Stion, TMSC Solar, and Avancis: 100-200MW/year
- Improved stability and degradation.

…but

- CIGS accounts for only ~2-4% of PV market shipments
  - 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 publically 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)

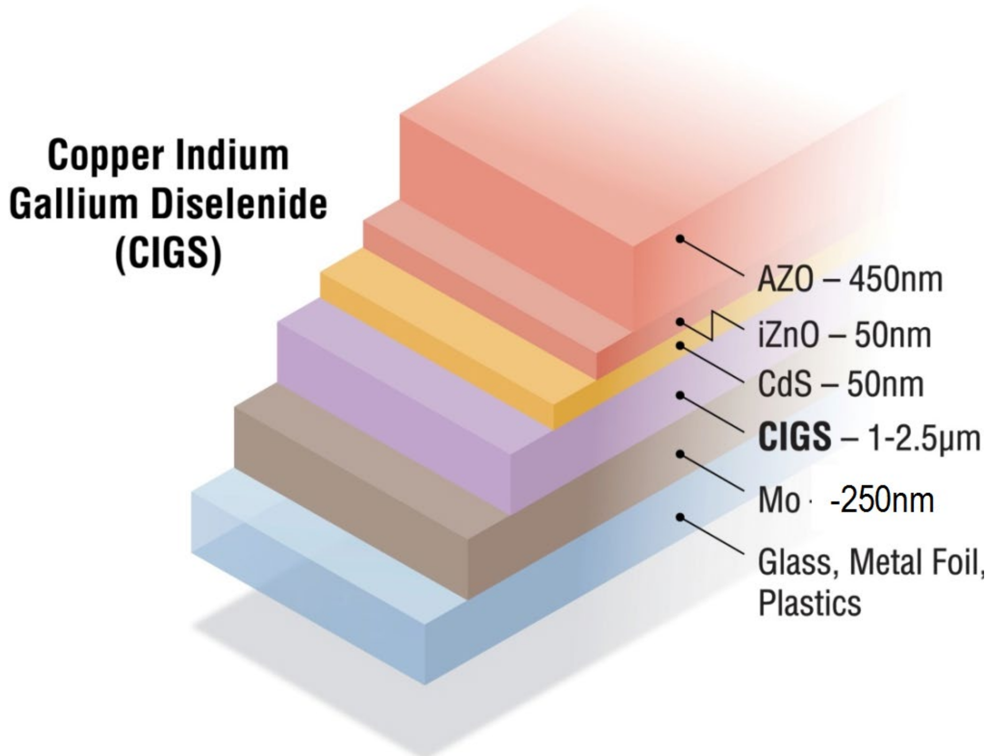
1.6m x 0.6m substrate size

1.5 µm thick CIGS layer
250 nm thick Mo layer

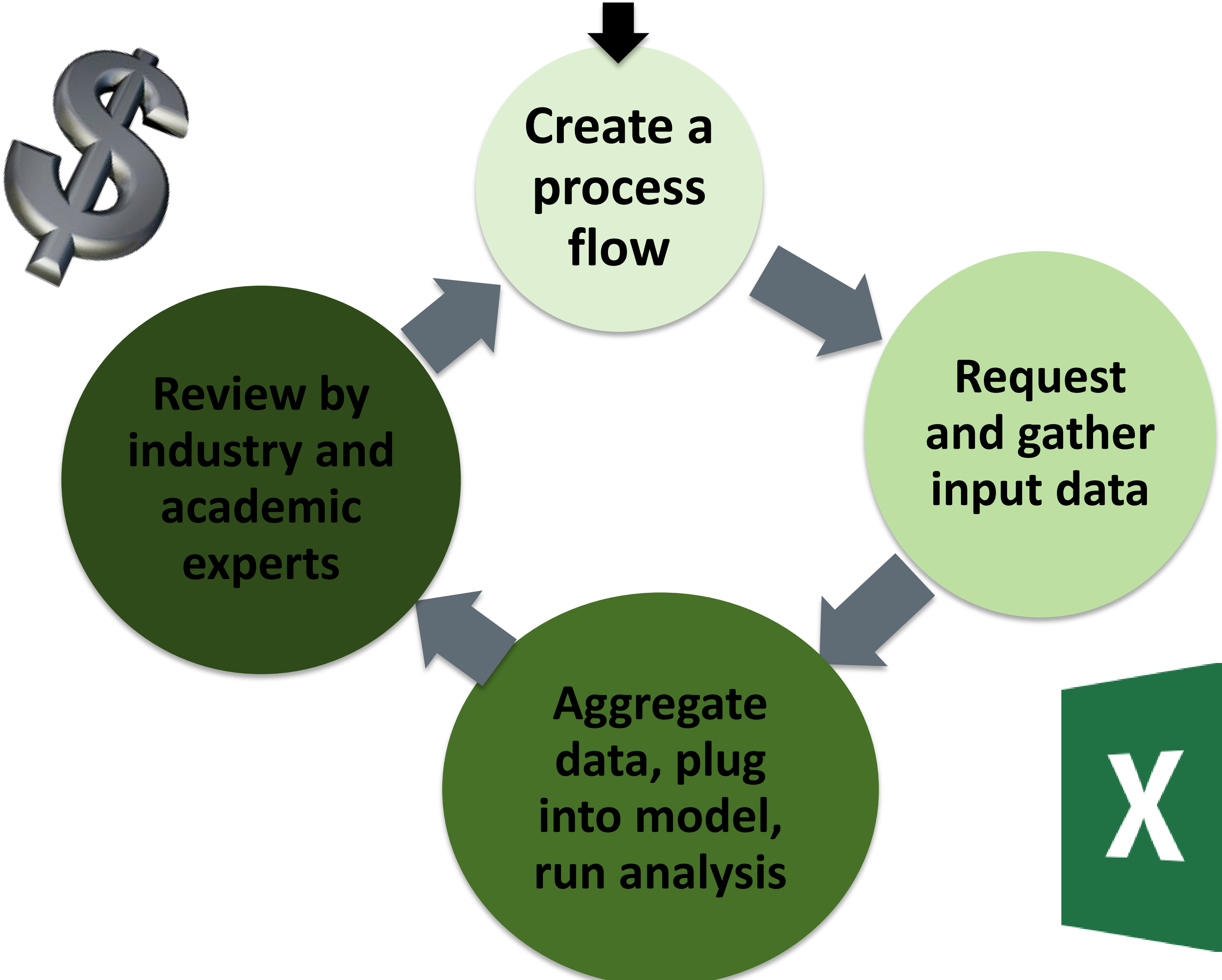
Ga/(In+Ga) = 0.31
Cu/(In+Ga) = 0.92

14% module efficiency

U.S. manufacturing
100MW/year production volume.



Method for Computing Manufacturing Cost



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.**

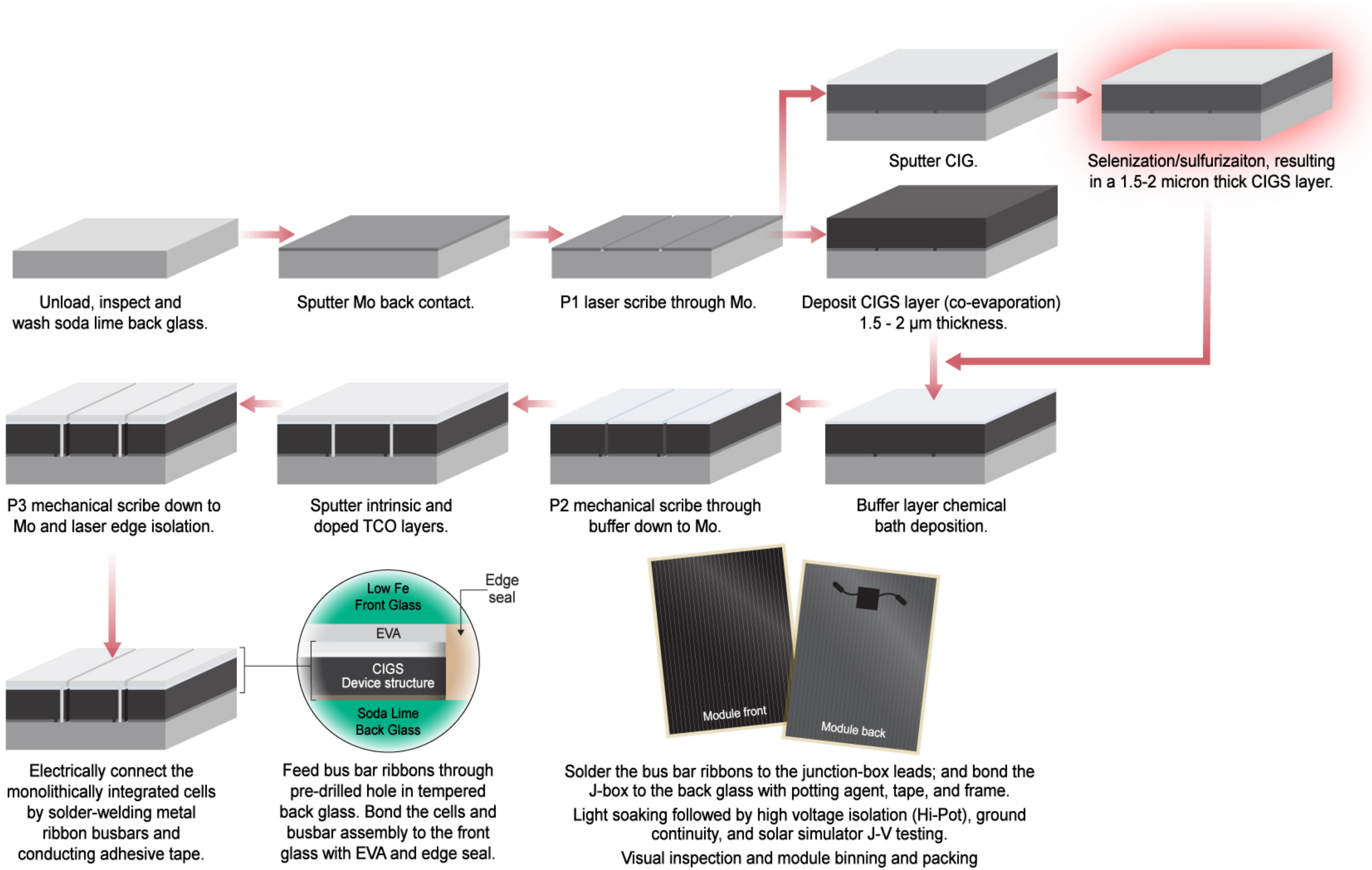
Minimum Sustainable Price (MSP)

- 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 = cost of equity, r_d = cost of debt, r_t = corporate tax rate
    - WACC = 14.5% calculated for the U.S. PV cell and module companies in 2015
    - More information in: Fu, R.; James, T.; Woodhouse, M. (2015). "Economic Measurements of Polysilicon for the Photovoltaic Industry: Market Competition and Manufacturing Competitiveness." *IEEE JPV* 5; pp. 515-524. Accessed May 2015: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7042229.
- 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.

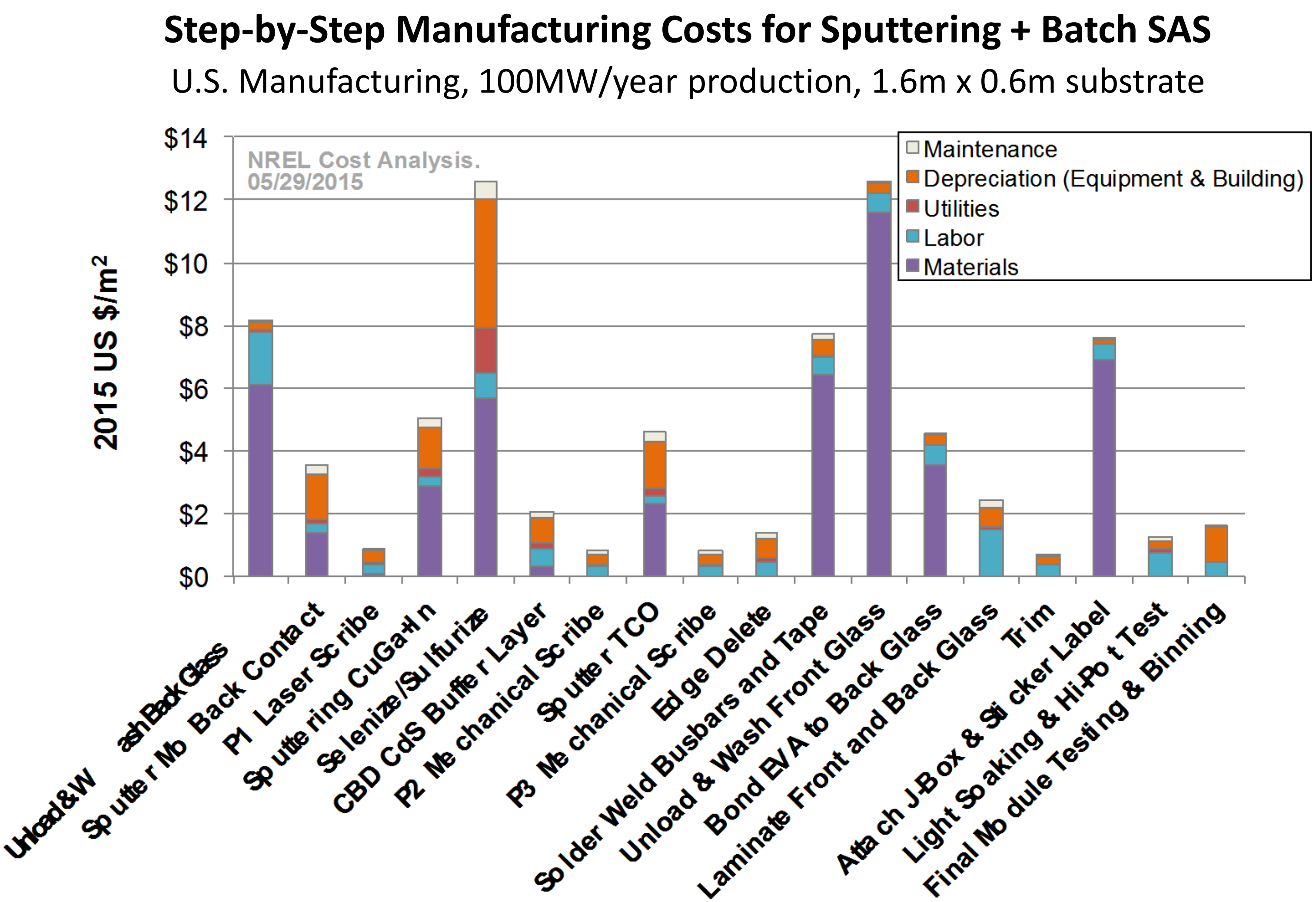
Manufacturing Process Flow



CIGS Absorber Deposition Processes

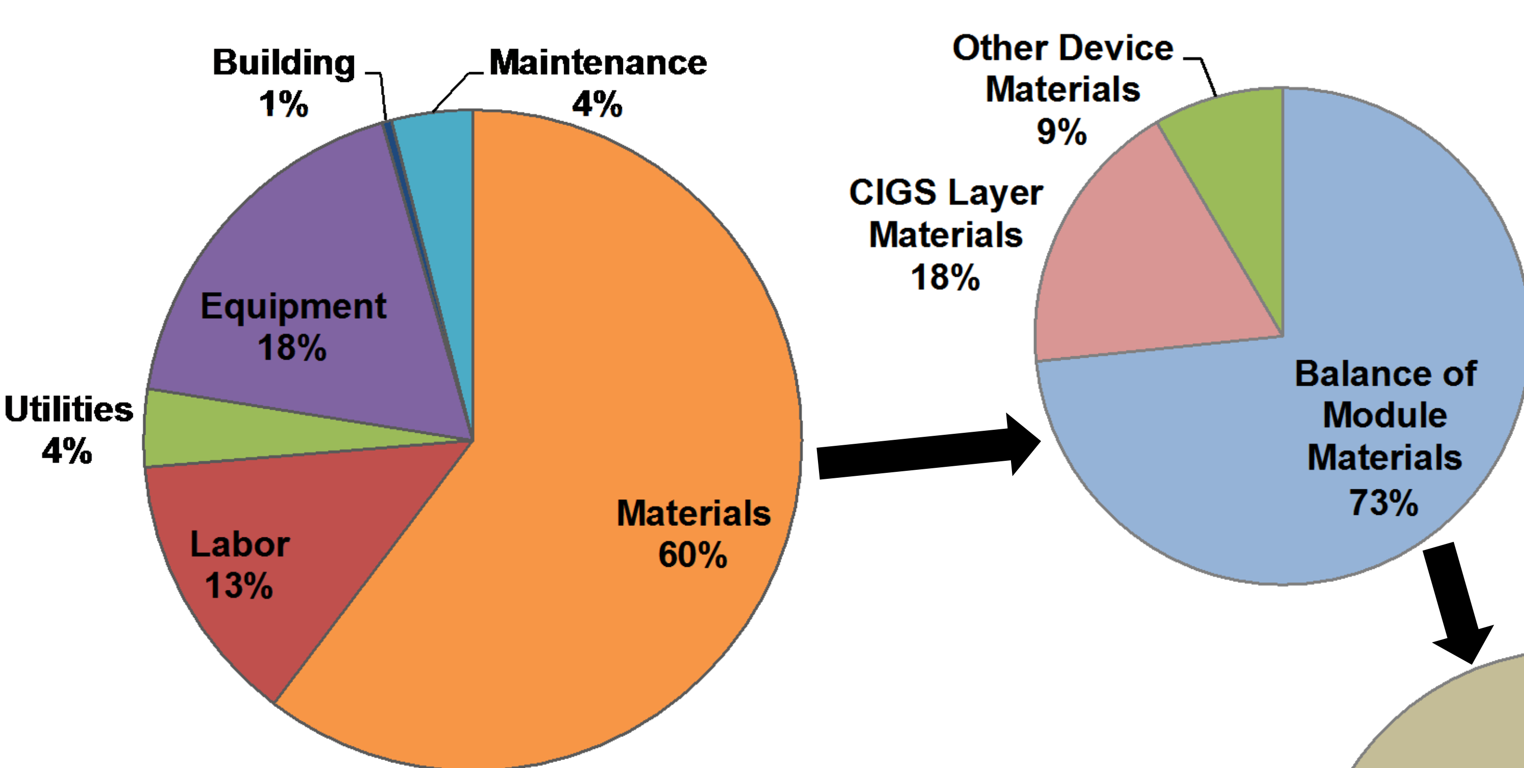
- **Sputtering plus sulfurization after selenization (SAS)**
  - Batch: More mature, deployed in large-scale production today, higher efficiency, high yield **Reference case**
  - In-line RTP: Higher throughput if high yields can be achieved at scale, elemental Se
- **Co-evaporation**
  - Not yet deployed in large-scale commercial production, earlier stage
  - 3-stage process: Record cell efficiencies, low throughput, high capital cost
  - 1-stage, in-line process: Higher throughput, lower efficiency than 3-stage.

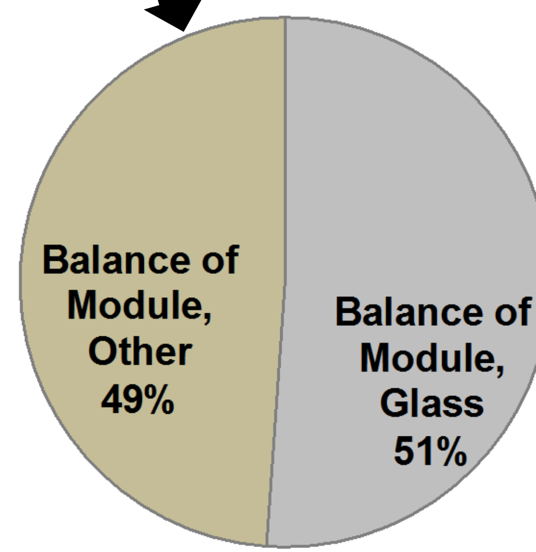
Step-by-Step Manufacturing Costs



- **Total module manufacturing cost: $78.22/m² ($0.59/W_{DC} at 14% efficiency)**
- **MSP: $0.72/$W_{DC}$.**

Manufacturing Cost Breakdown

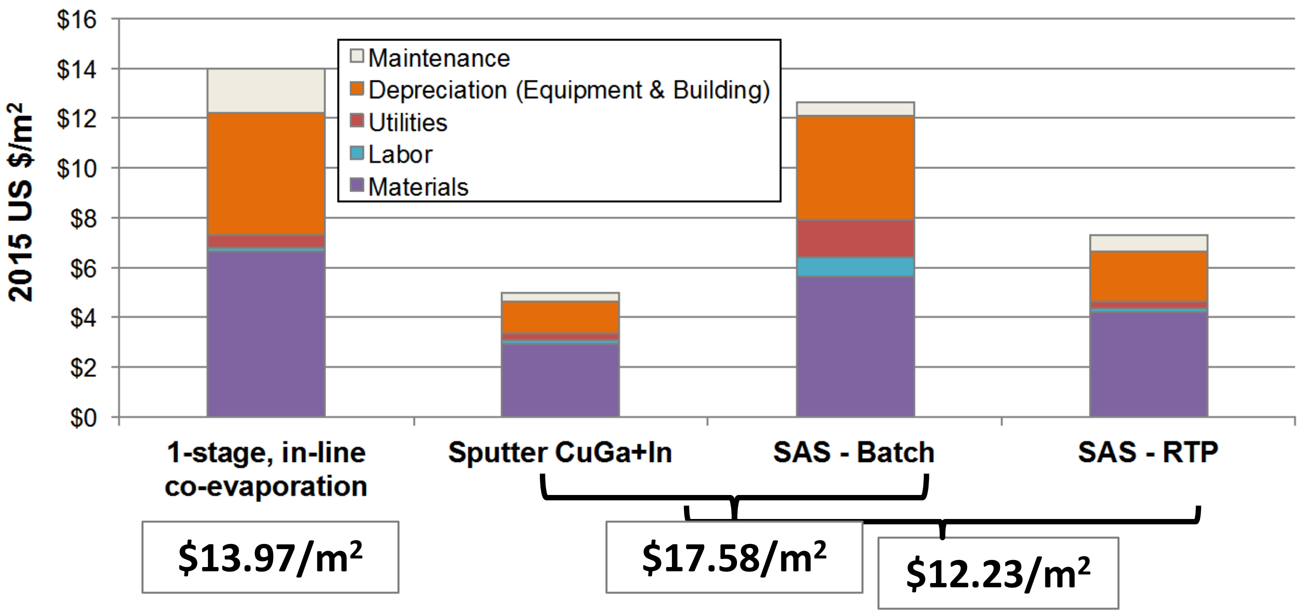




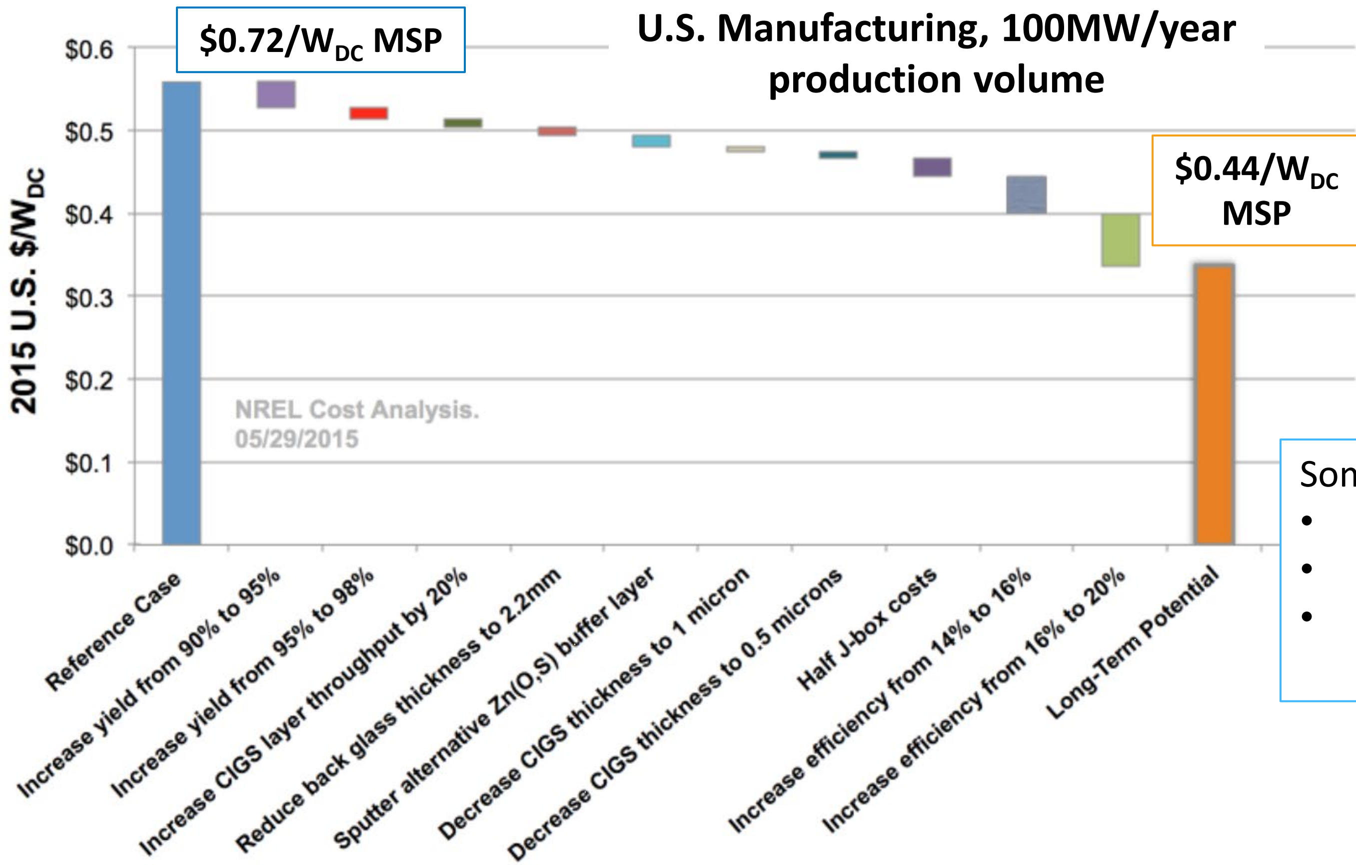
- **Material costs dominate**
  - Balance of module materials are a significant cost driver
- **The SAS step represents the largest device cost**
- **Exact breakdown will vary by region of manufacturing.**

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.



Manufacturing Cost Reduction Roadmap



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.

- 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.

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.

TABLE II

COMPUTED NOMINAL LCOES IN PHOENIX, AZ

Federal ITC Level

9.99

0%

- 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.

Summary and Future Work

- **We have built a bottom-up cost model for different CIGS manufacturing processes.**
  - 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.}$
  - 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%).**
  - 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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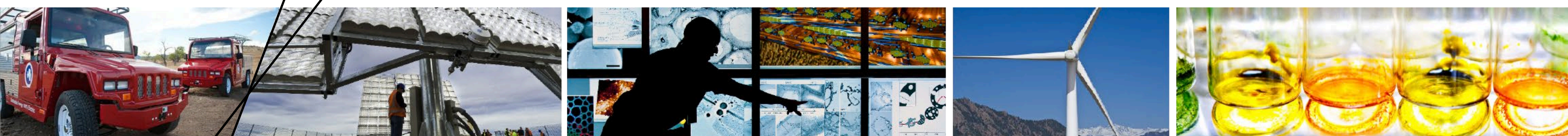

Complete LCOE Inputs

TABLE I
INPUT ASSUMPTIONS FOR LCOE CALCULATIONS

Input Parameter	
ss	6%