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A Bottom-up Cost Analysis of a High Concentration PV Module

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Acknowledgments

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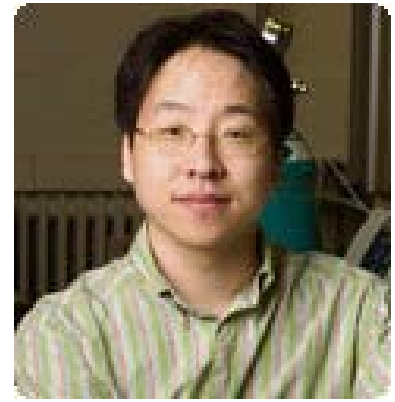
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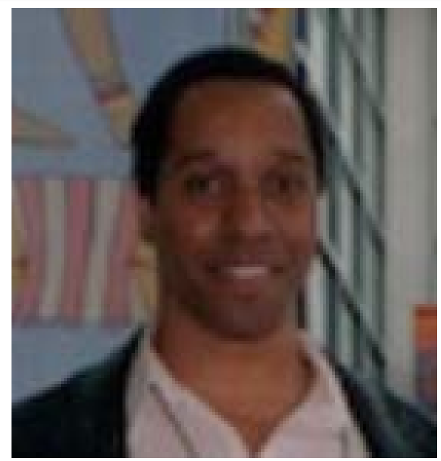
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All our collaborators in industry

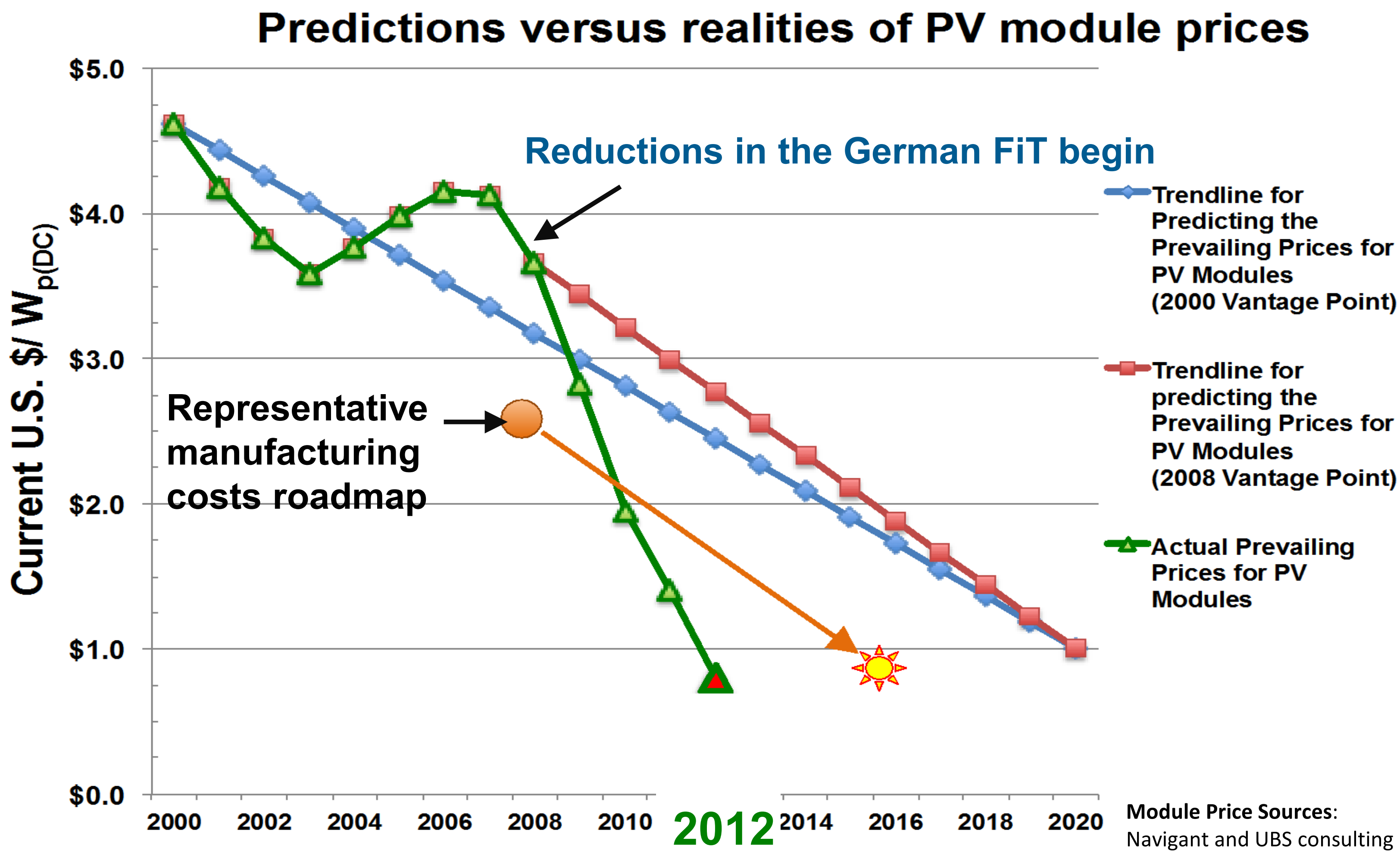
SEAC management team for helpful reviews of this work

Executive Summary

- We have created a bottom-up cost model for analyzing III-V multi-junction cells and HCPV modules
- There are several avenues to reduced cell manufacturing costs:
  - Largest drivers are scale, manufacturing yield, and substrate reuse
  - Metallization costs, III-V deposition rates, and precursor prices are also important contributors
- Many different components (cell, structure, receiver board, thermal management) contribute significantly to cost and represent opportunities for cost reduction, although performance trade-offs must always be considered.
- Increases in cell efficiency and reduction in cell costs represent significant opportunity for module cost reductions across many designs
- The ultimate competitiveness of HCPV must be determined with a complete systems and LCOE analysis, which we are currently undertaking

Motivation: Changing Flat-plate PV Prices

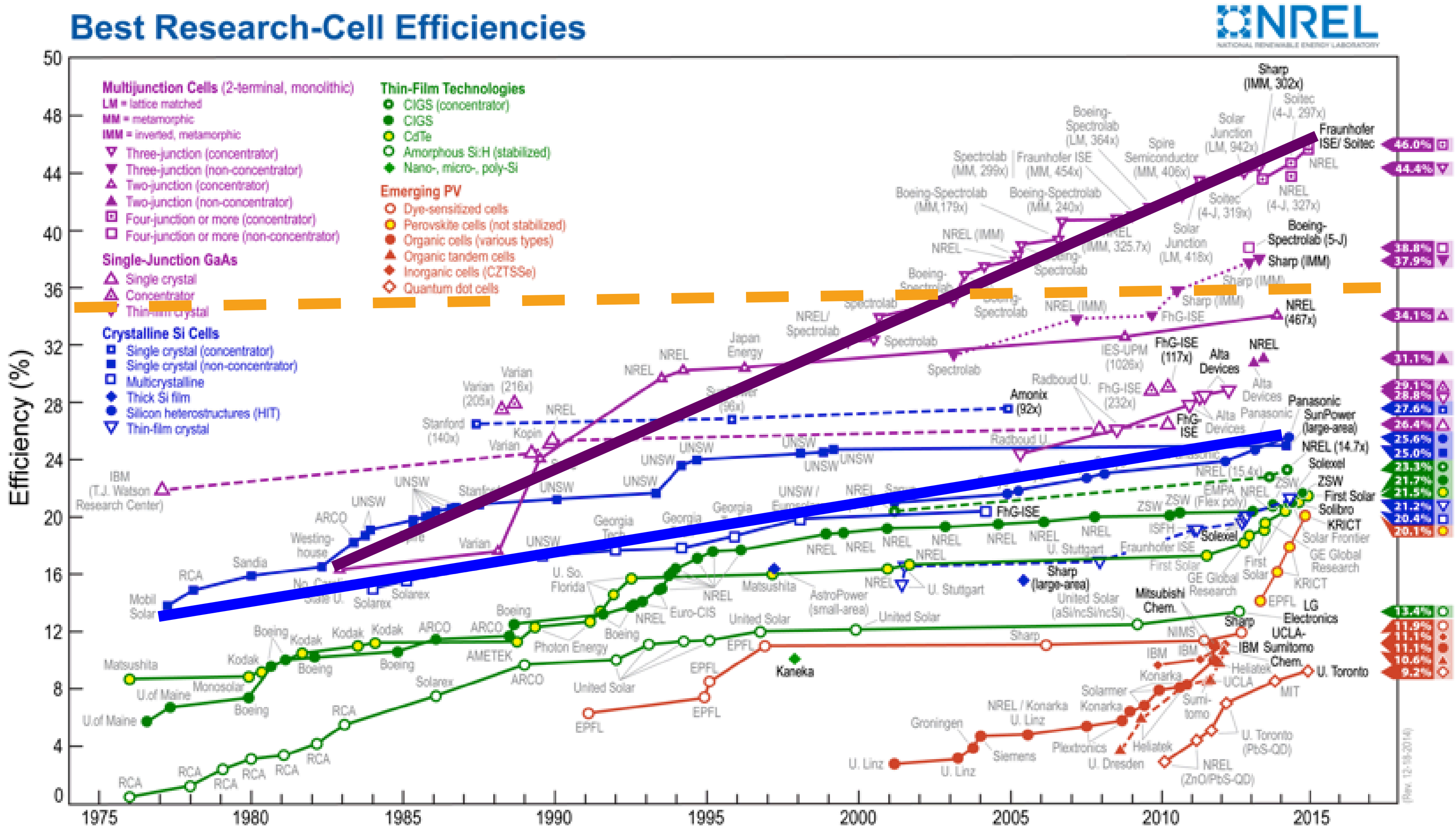
What is the value proposition of CPV today now that traditional, flat-plate PV prices have plummeted?



Module Price Sources: Navigant and UBS consulting services

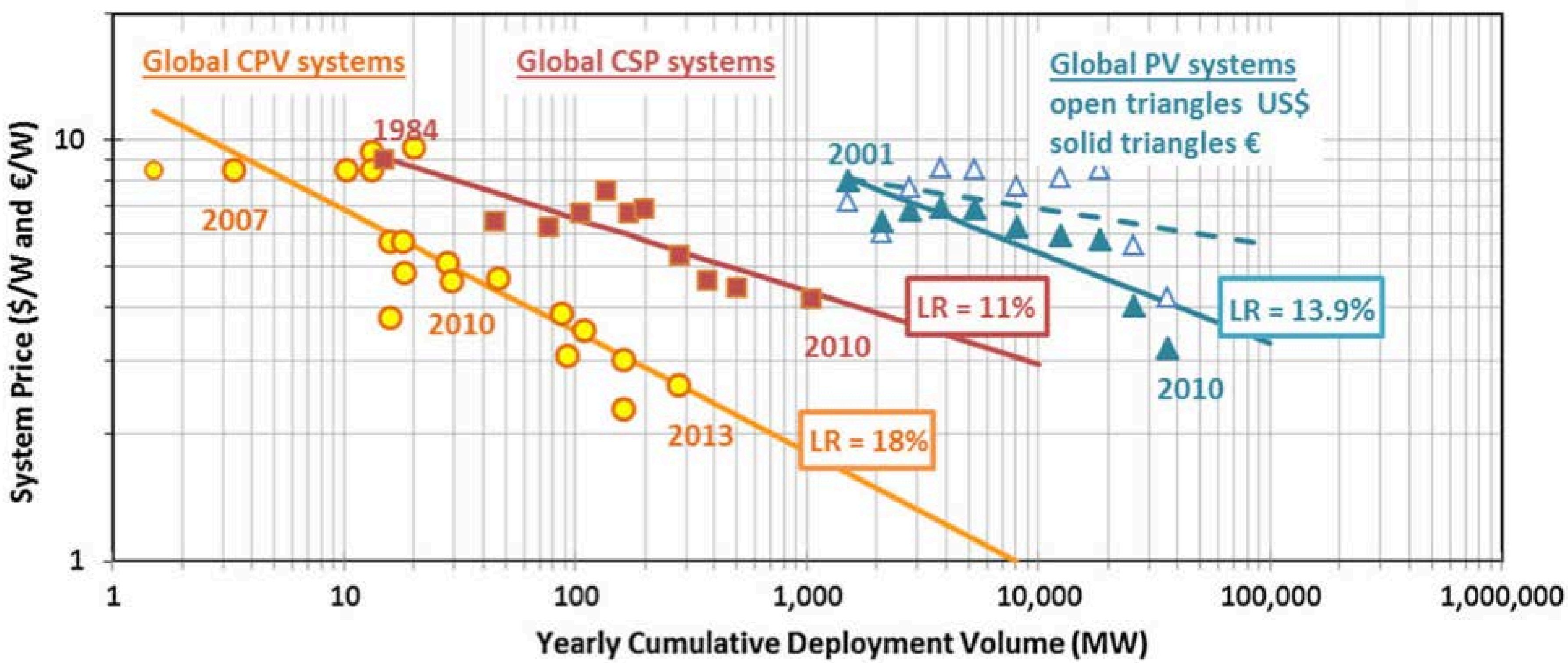
Motivation: Efficiency

- High efficiencies of III-V cells (purple) could allow for significant future module and system cost reductions for HCPV
- Efficiency is a lever for decreasing module costs, system costs, and LCOE



Motivation: Low Reported Costs

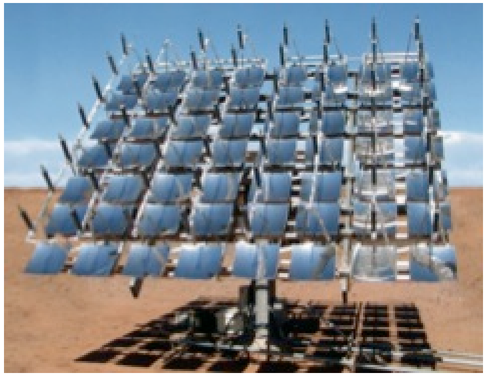
CPV has reported system costs within the range of traditional, flat-plate PV at much lower volumes.



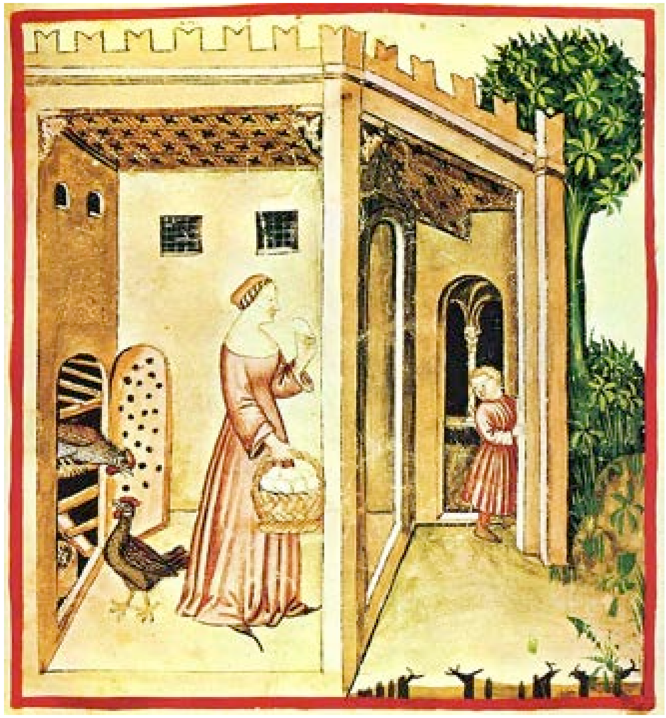
Haysom, J.E.; Jafarieh, O.; Anis, H.; Hinzer, K.; Wright, D. (2013). “Learning curve analysis of concentrated photovoltaic systems.” *Prog. Photovolt: Res. Appl.* 1556: 239.

Motivation: Bankability and Scale

The struggles of the CPV market, combined with the higher complexity of the technology, lack of standardization, and small number of installations, may present barriers for obtaining the funding necessary to scale and reduce costs



NREL image gallery 13735, 13740, 18303



From "Chicken or the egg." (2015). Accessed March 2015: http://en.wikipedia.org/wiki/Chicken_or_the_egg.

Analysis Objective

Calculate the $/W$_p$ costs of a model HCPV module and III-V multi-junction cells

- Provide an understanding of where HCPV costs are and could be with current technology if manufacturing was scaled up
- Illuminate the cost drivers for this technology, as well as potential pathways for future cost reductions
  - Understand potential challenges in achieving these cost reductions
- Set the stage for future levelized cost of energy (LCOE) calculations.

Manufacturing Cost Analysis Methodology

Methods

- Bottom-up calculation where we compute:
  - Materials
  - Utilities
  - Labor
  - Depreciation
  - Maintenance

  costs associated with each step in the manufacturing process
- Input data sourced from multiple material suppliers and equipment vendors
- Results reviewed by industry members and NREL experts who provide feedback to improve and validate the model.

Assumptions

- Manufacturing in low-cost region of the United States
- Annual production volumes:
  - For cells: 50 MW and 0.1 MW (at one sun)
  - For modules: 100 MW
- Depreciation schedules:
  - 5-year and 7-year straight-line for cell and module equipment, respectively
  - 15-year straight-line for buildings.

Minimum Sustainable Price (MSP)

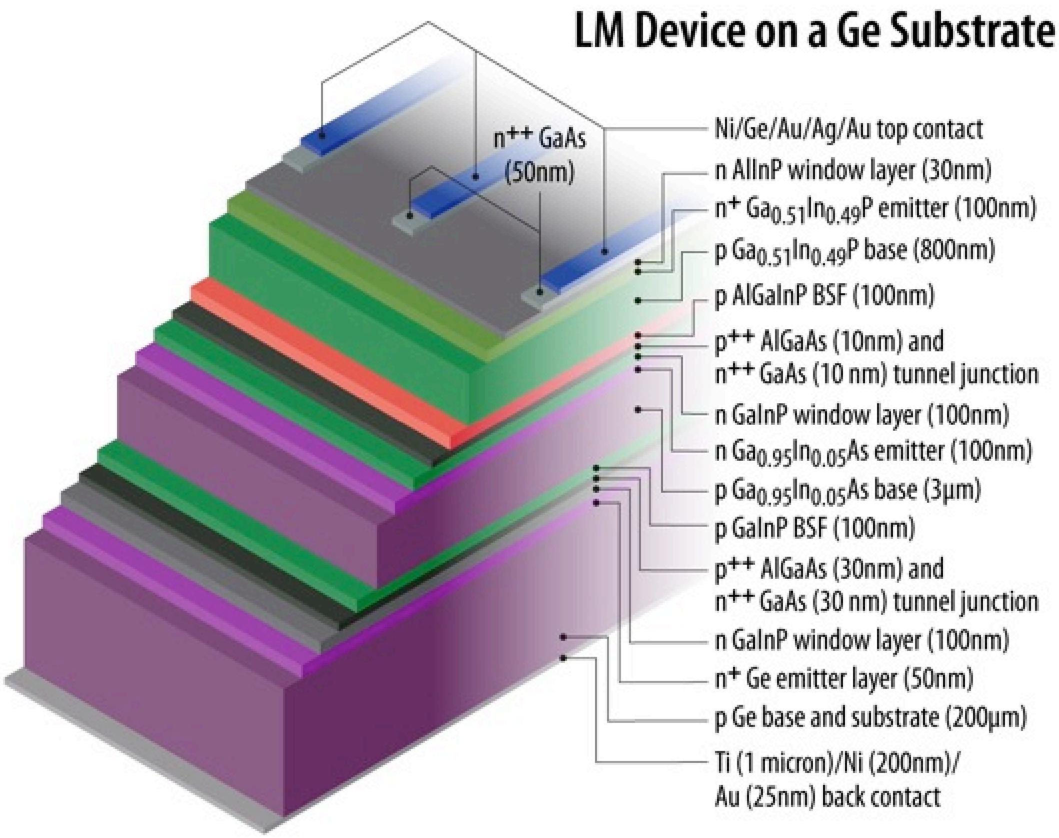
- MSP: The price at which the net present value (NPV) of a 20-year project is equal to zero
  - **Minimum price required to generate a required rate of return**
  - We set the required rate of return to be the weighted average cost of capital (WACC)

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

    - E = % equity, D = % debt, r_e = cost of equity, r_d = cost of debt, r_t = corporate tax rate
    - WACC = 15% calculated for the U.S. PV market in 2014
    - More information in: Fu, Ran et al. "Economic Measurements of Polysilicon for the Photovoltaic Industry: Market Competition and Manufacturing Competitiveness," IEEE JPV 5, pp. 515-524 (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

Model Triple Junction III-V Cell

- This type of cell is currently the most commonly used by the HCPV industry, but several different triple junction III-V cell designs are commercially available.



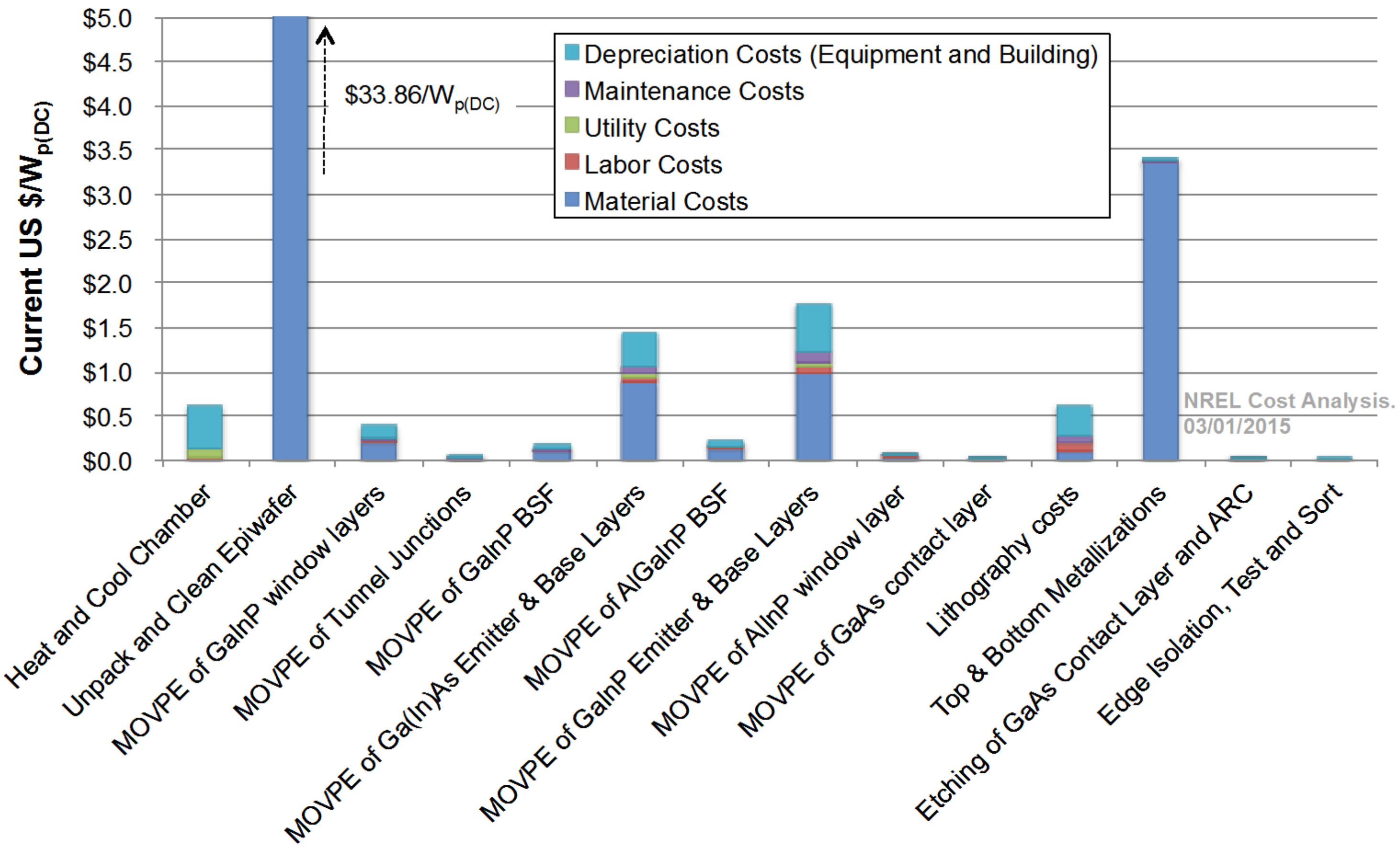
- Details on the manufacturing process for III-V cells can be found in:

Woodhouse, M.; Goodrich, A. (2014). "Manufacturing Cost Analysis Relevant to Single-and Dual-Junction Photovoltaic Cells Fabricated with III-Vs and III-Vs Grown on Czochralski Silicon." NREL/PR-6A20-60126. Golden, CO: NREL. http://www.nrel.gov/docs/fy14osti/60126.pdf

III-V Multi-junction Cell Cost Drivers

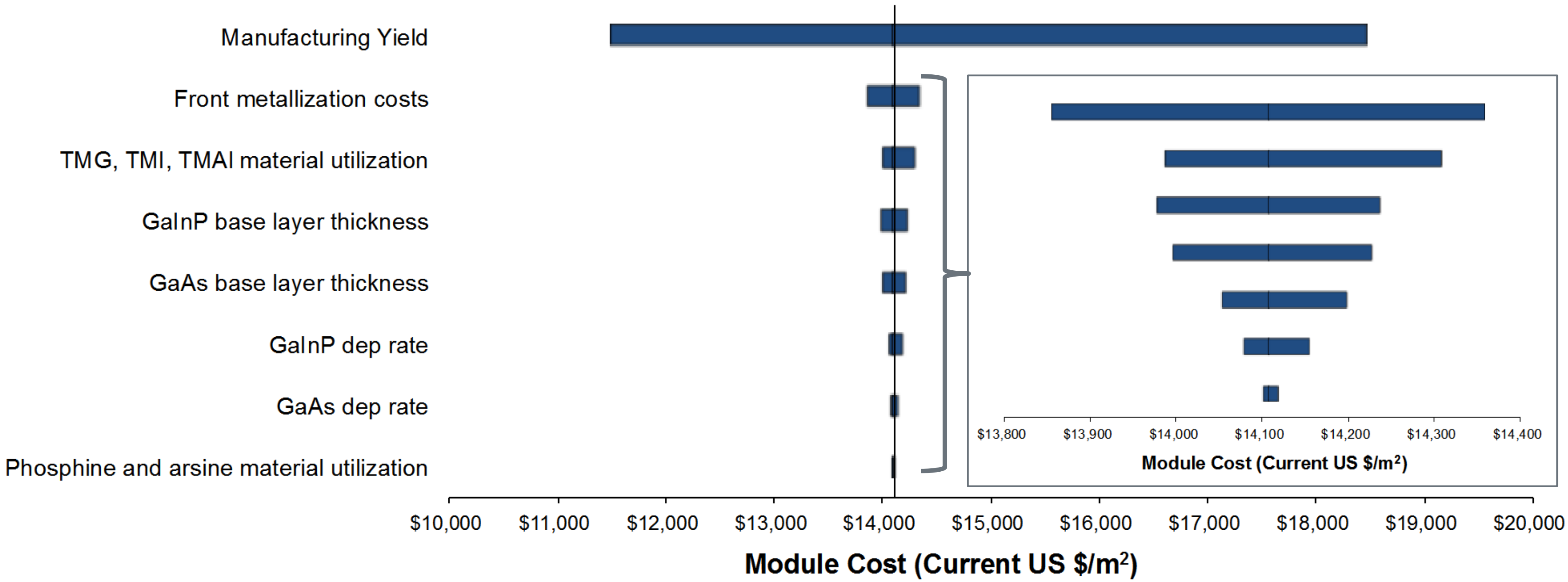
Biggest cost drivers:

- Ge substrate ($150/6’’ wafer)
- Low manufacturing yield (80% assumed here)
- Metallization (Au and Ag targets, low material utilization)
- Base layers (expensive precursors, slow deposition).



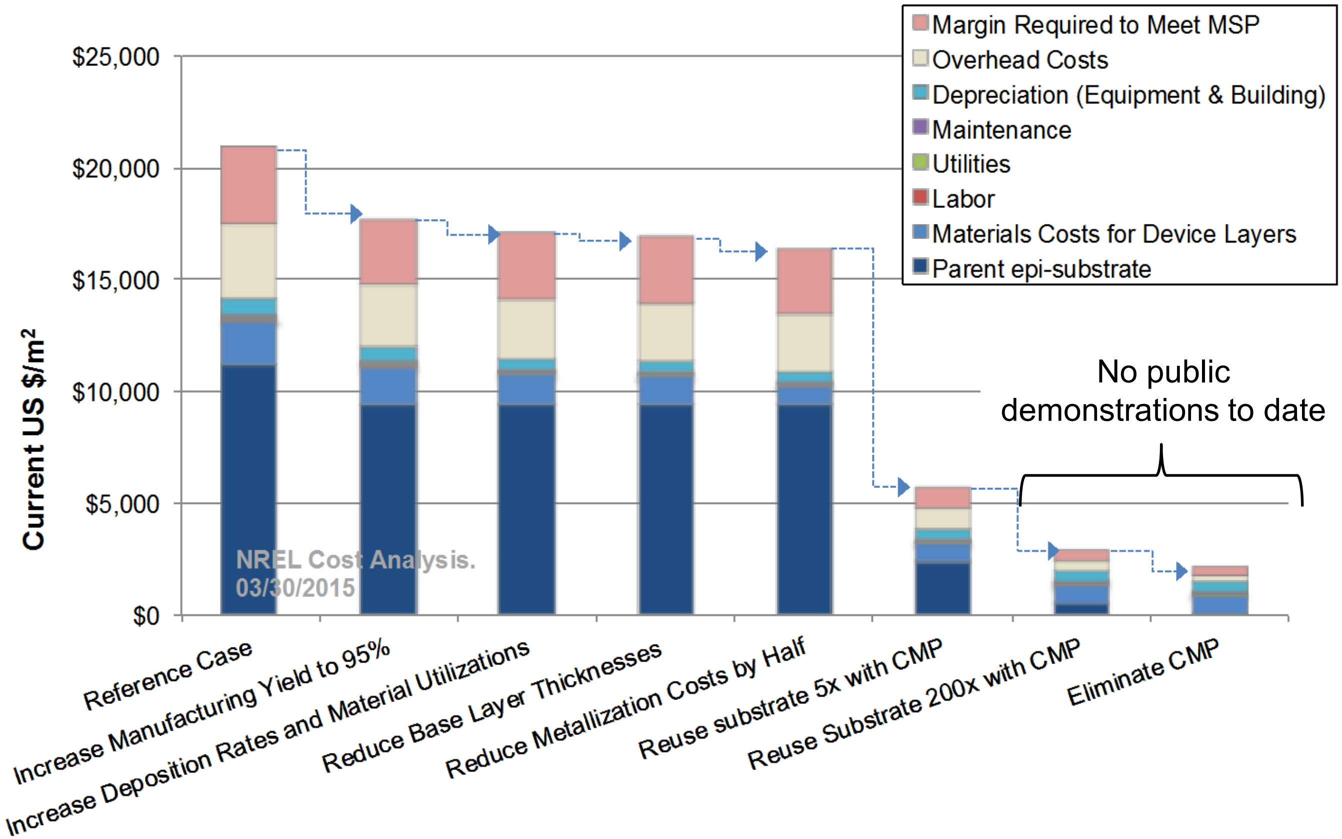
Cell Cost Sensitivity Analysis

Sensitivity of Cell Costs to a ± 25% Change in Input Parameter



- Current manufacturing yields for III-V multi-junctions: 75%-85%, 80% used for our reference case
- Note this sensitivity is itself sensitive to the initial design
- This also not reflective of the magnitude of changes that might be technically possible

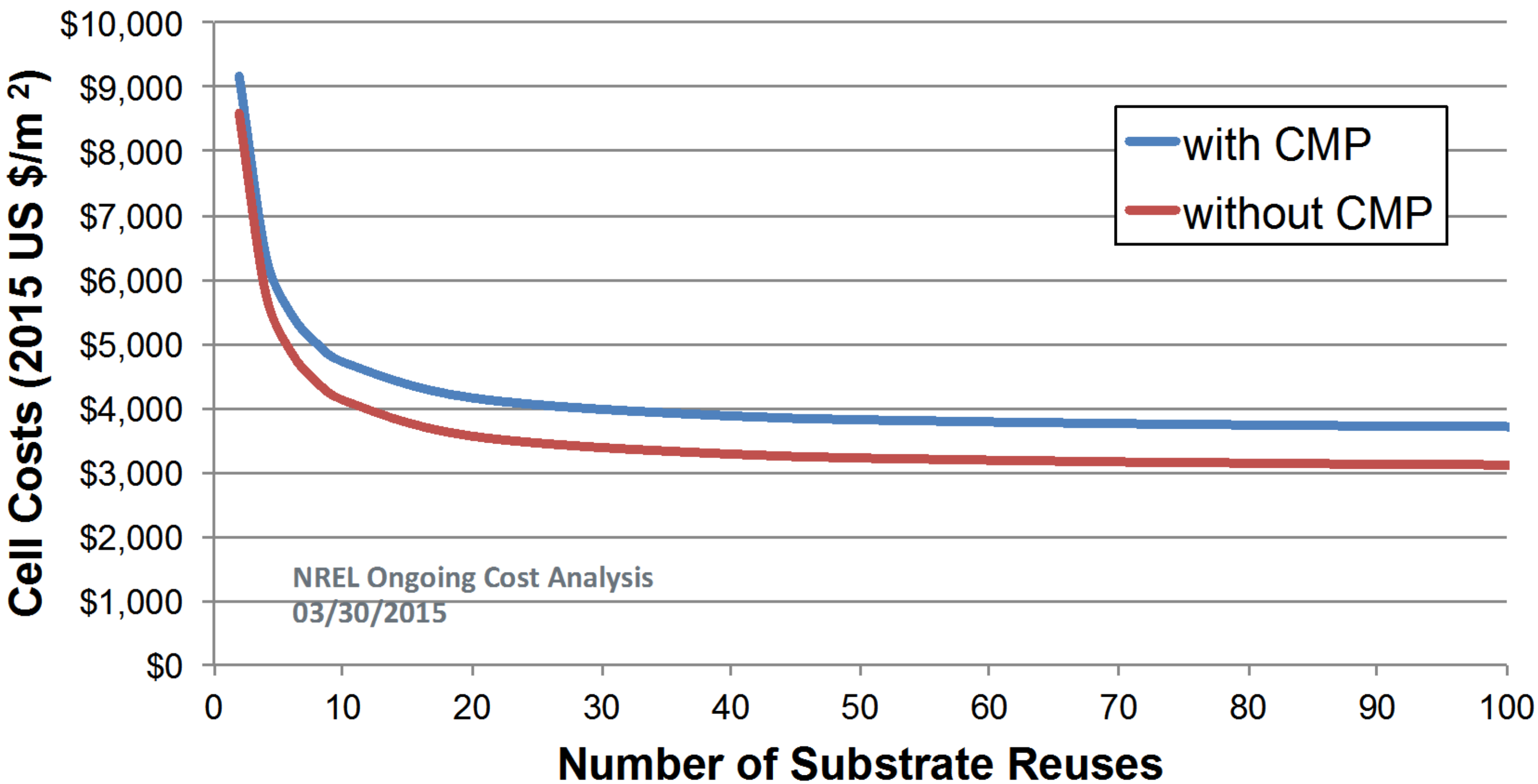
Cost Reduction Roadmap



No wafer reuse assumed in the reference case. For 50MW/year 1 sun equivalent production capacity

- Increased material utilization and deposition rates estimated for maintaining material quality
- Currently, only 5-10 substrate reuses have been publically demonstrated
- **No currently known methods for achieving a high number of reuses of the Ge substrate. It's not clear how this could be accomplished at scale, or what additional layers would need to be grown. Thus this may not even be feasible at scale or for large numbers of reuses, or could add costs beyond what is shown here. NREL has ongoing work to investigate these issues.**

Impact of Substrate Reuse



- For reference case parameters
- Diminishing returns after 50 substrate reuses
- Again, the additional processing steps or layer growth required to achieve a substrate reuse at scale is currently unknown, so the estimates of costs with many substrate reuses are likely low.

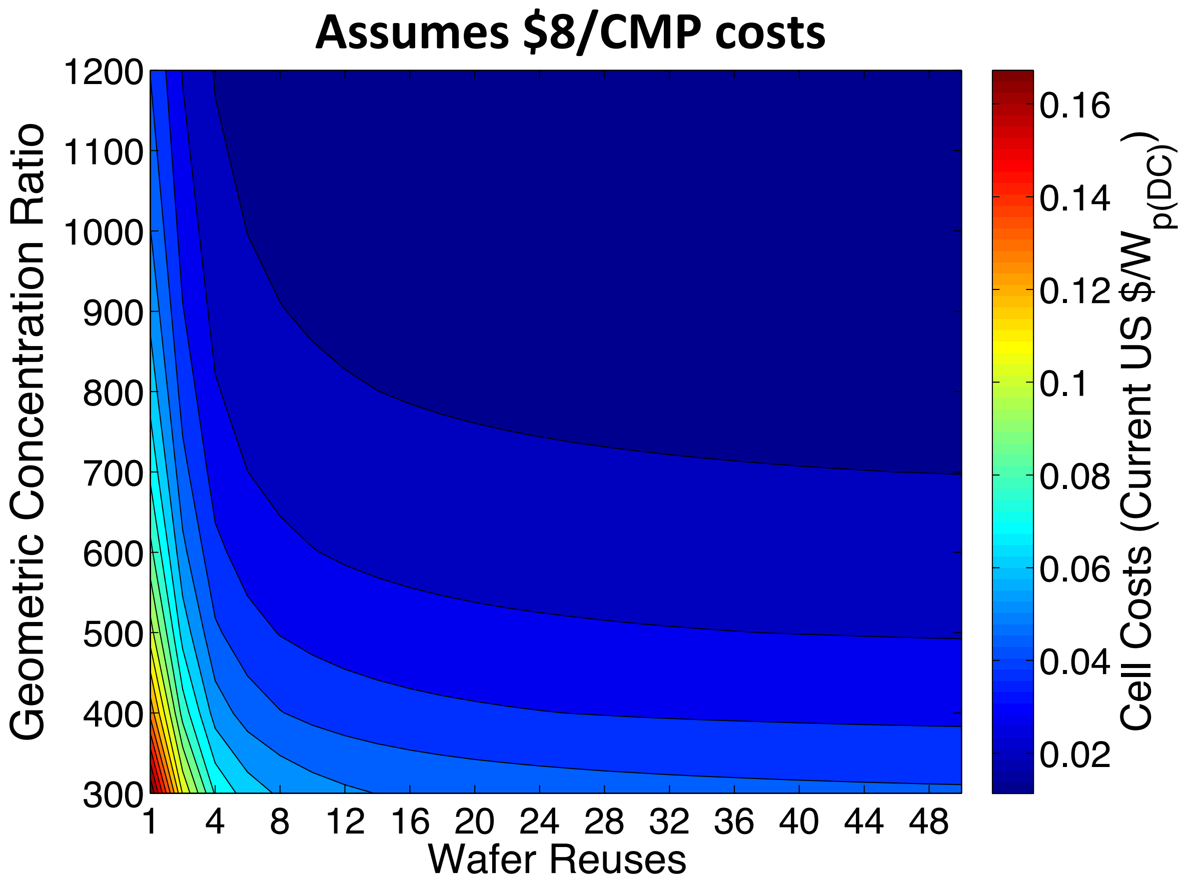
Costs at Concentration

$$\frac{\$}{W_{p(DC)}} = \frac{\text{cost/area}}{\text{Power output/area}} = \frac{1}{\eta_S P_x}\left[\frac{\phi_S}{C} + \frac{\phi_x}{\eta_x}\right]$$

- Φ_s = cell costs in $\$/m^2$
- Φ_x = primary optic costs in $\$/m^2$
- C = effective (or optical) concentration ratio
- η_x = throughput efficiency of the concentrator
- η_s =cell efficiency
- P_x = 1,000 W/m^2 and corresponds to the CSTC incident DNI solar resource.

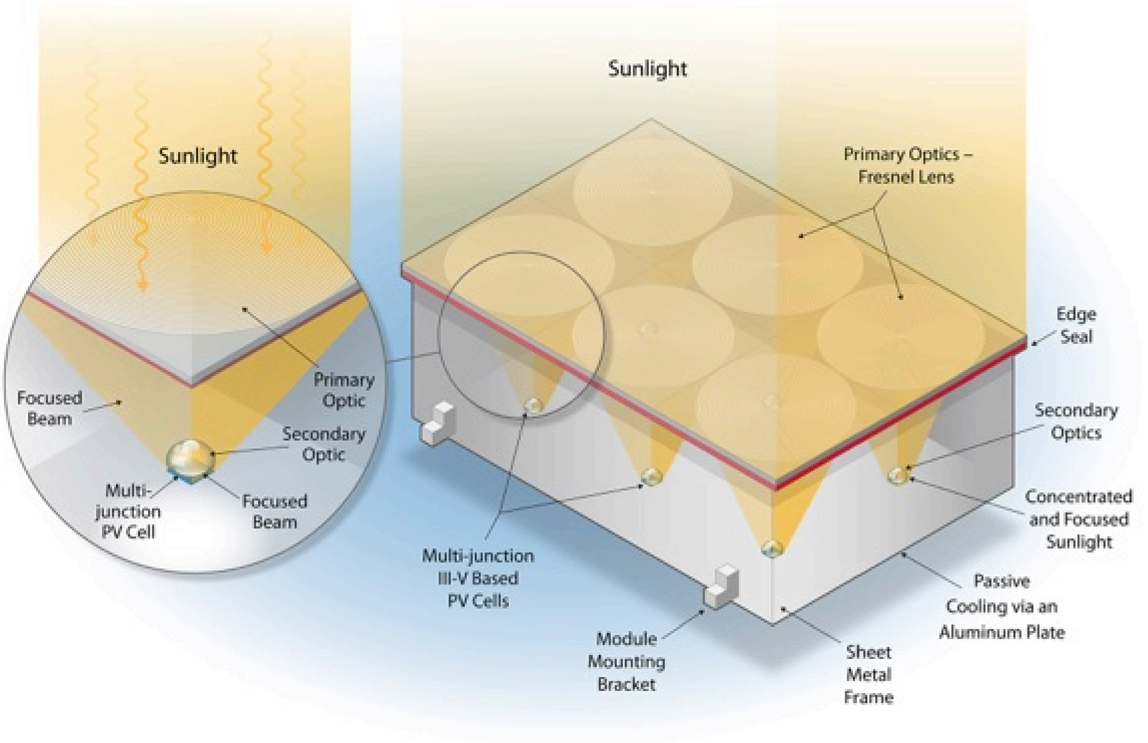
Fahrenbruch, A.L.; Bube, R.H. (1983). "Concentrators, Concentrator Systems, and Photoelectrochemical Cells." *Fundamentals of Solar Cells Photovoltaic Solar Energy Conversion.* Elsevier.

Impact of Concentration and Wafer Reuse



- At high concentrations, much lower cell costs could be achieved even with only 5-15 substrate reuses.
- Even without substrate reuse, cell costs can be manageable at high concentrations.

Model Module Design



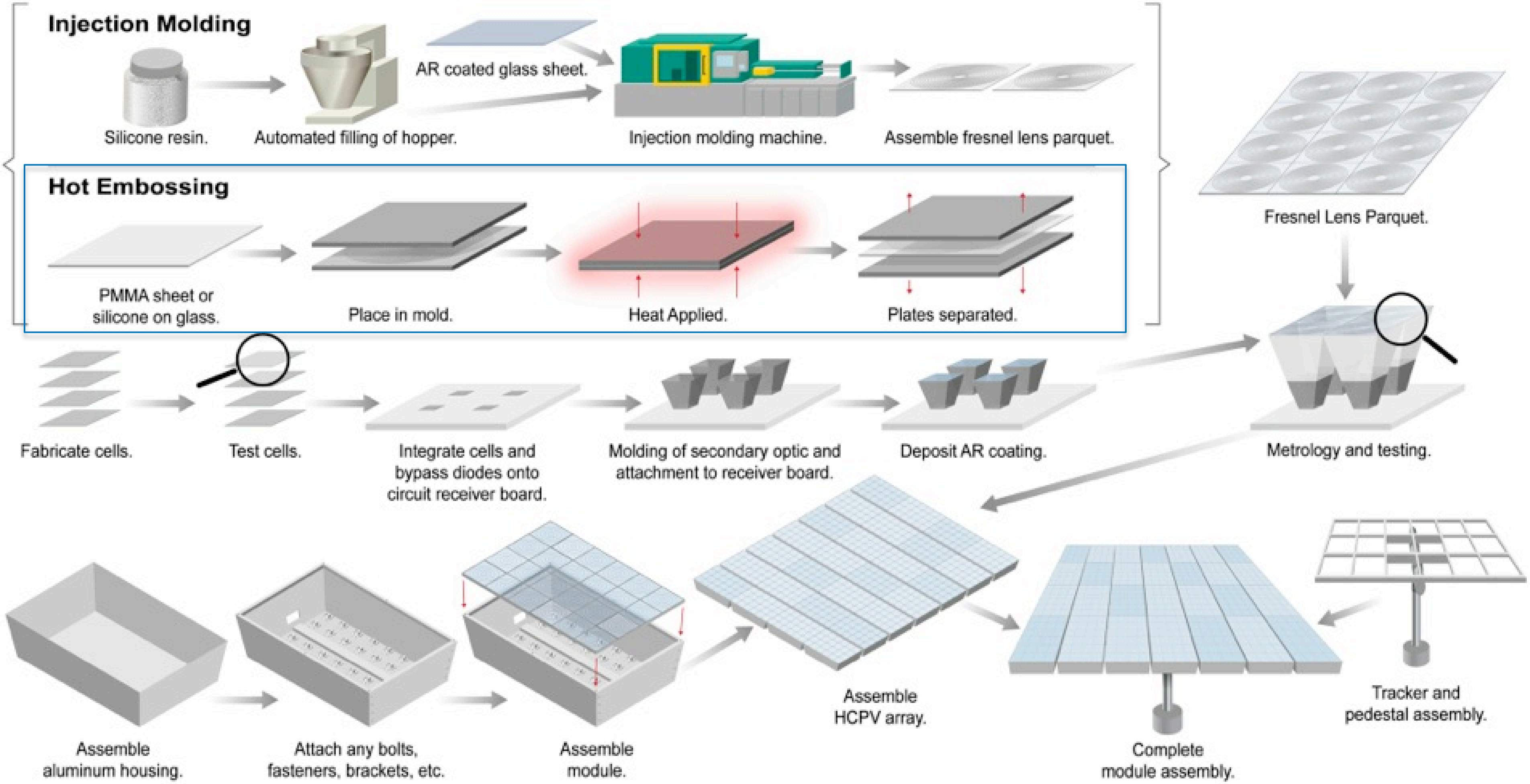
Reference Design

- 1,000x geometric concentration
- 30% module efficiency
- Silicone-on-glass (SOG) Fresnel lens primary
- Dome secondary lens
- 5mm x 5mm Ge/Ga(In)As/GaInP cells
- 50 cells/module
- Rectangular box housing
- Passive thermal management via an aluminum plate.

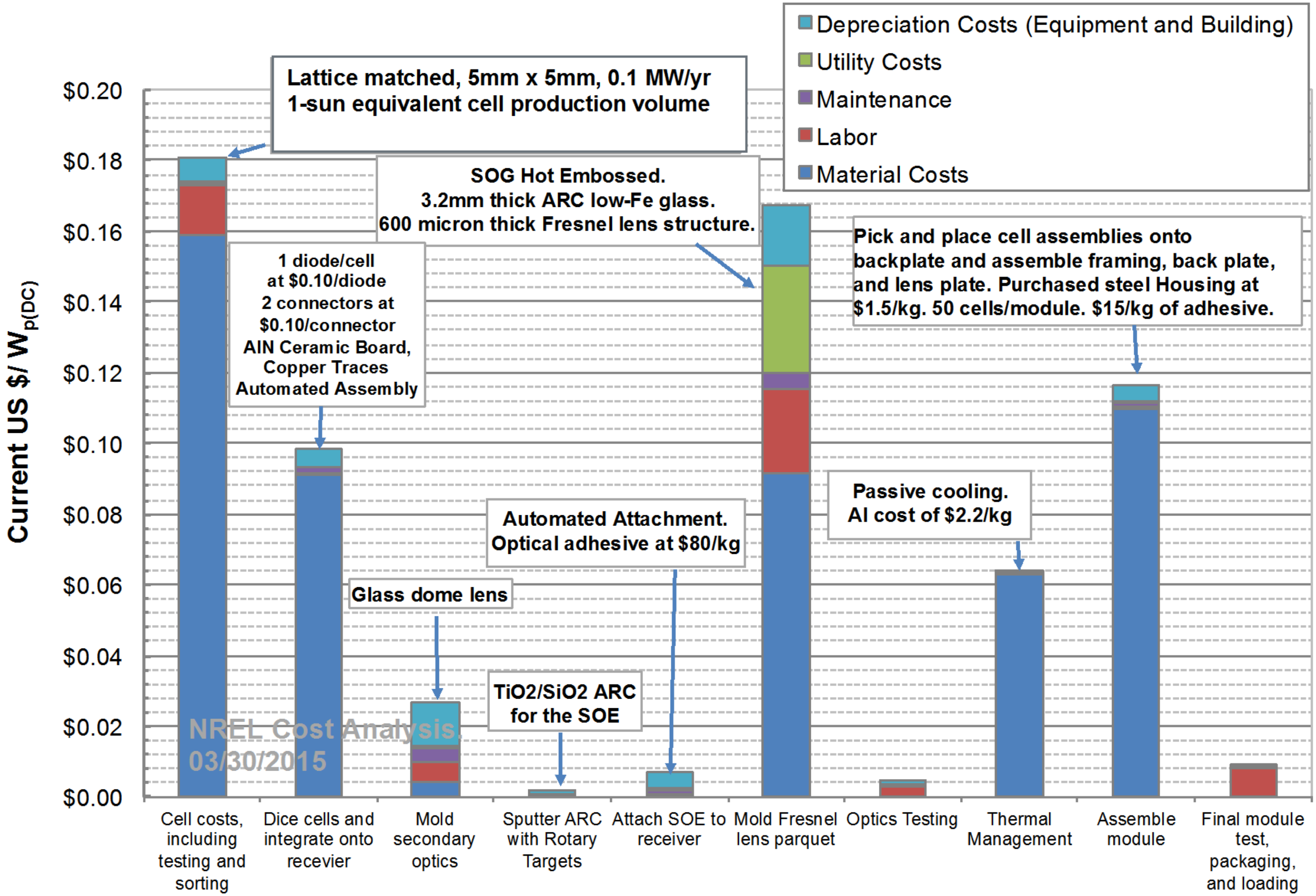
While this model is certainly not representative of the entire HCPV space, which includes a wide variety of designs, it contains the same fundamental elements as many commercial modules.

Manufacturing Process Flow

Injection molding is more typical for PMMA lenses.

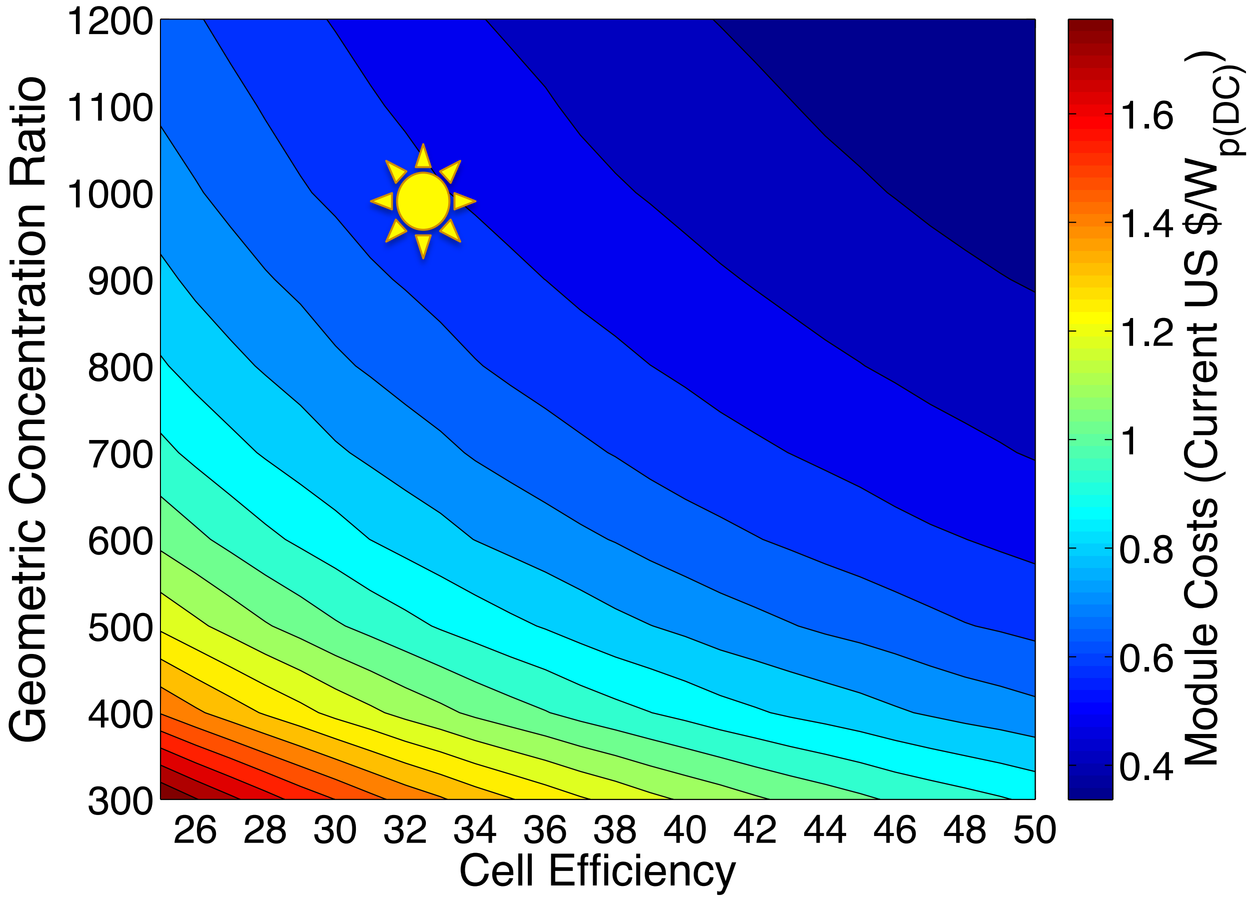


Step-by-step Module Manufacturing Costs



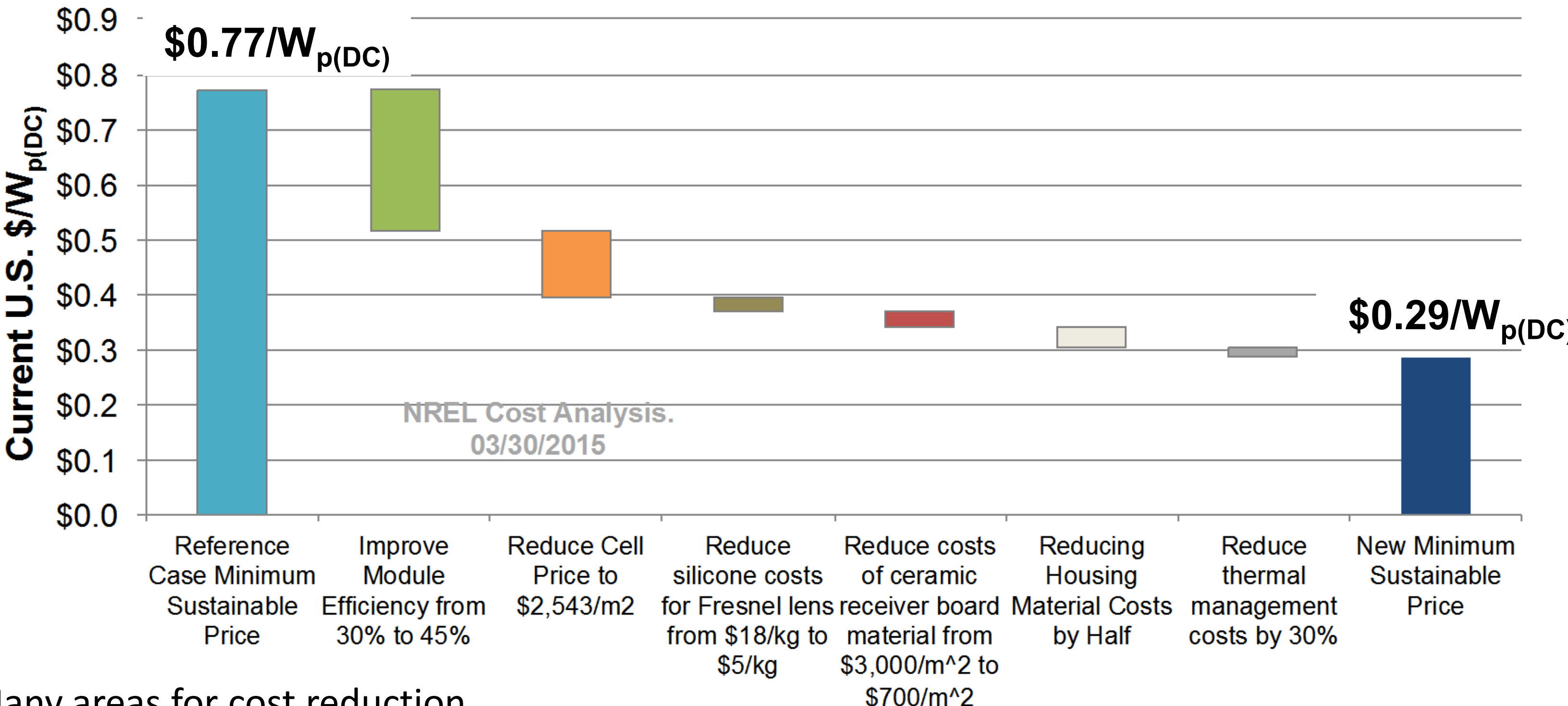
Many pieces contribute to cost (cells, optics, housing, receiver board, and thermal management)

Impact of Concentration and Efficiency



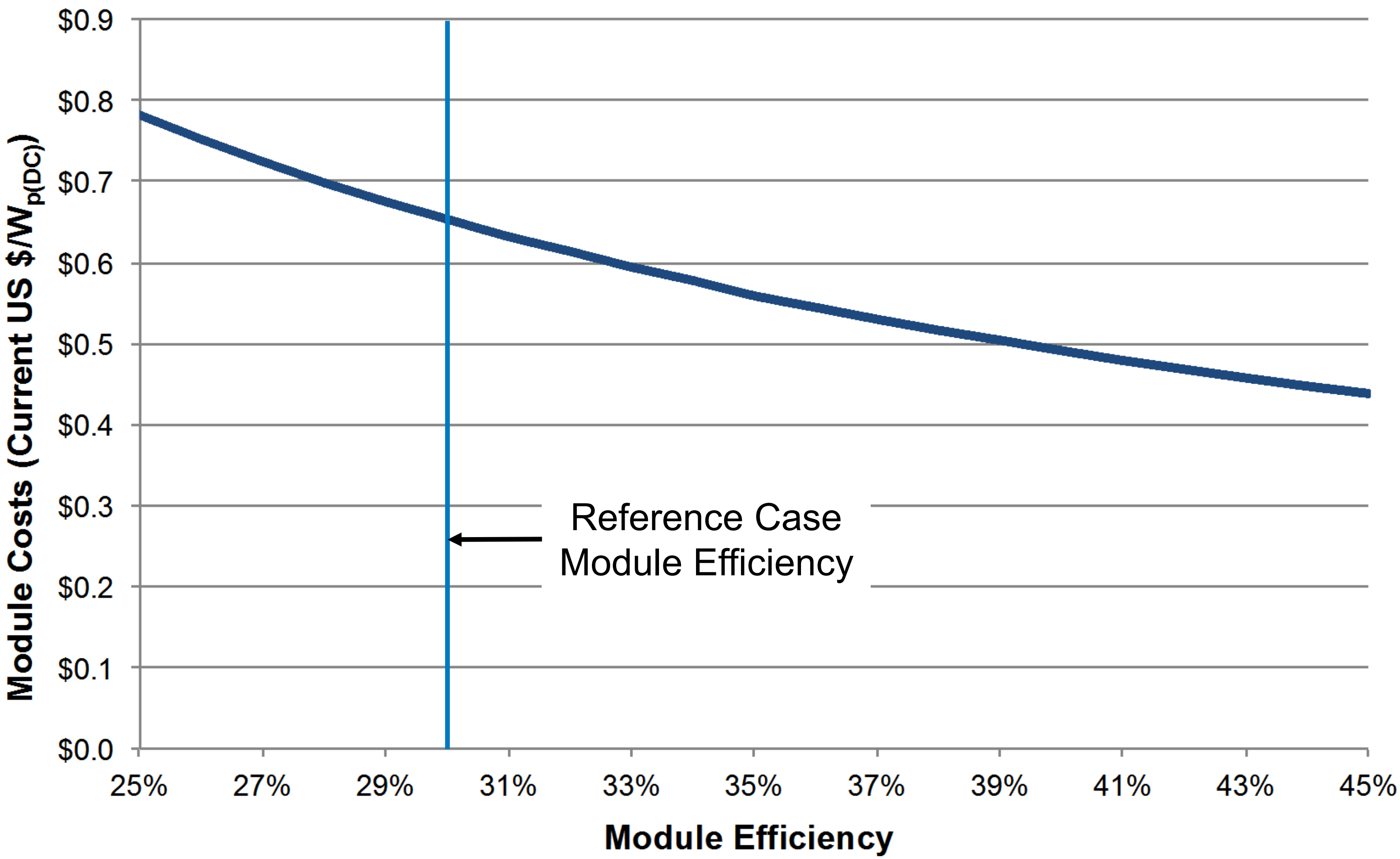
- Concentration ratio and cell efficiency are coupled
- At higher concentrations, additional thermal management will be required
- This curve is only relevant for this specific module design.

Potential Pathways to Reduced Cost



- Many areas for cost reduction
  - Will need reductions in many component costs in $/m^2, or increase in efficiency to achieve dramatic cost reductions
- **Performance-cost trade-offs and technical feasibility of these cost reductions must be explored in more detail.**
  - It may not be possible to achieve all of these improvements and maintain performance.
  - Improving cell efficiency will likely increase $/m^2 cell costs. But scale and manufacturing learning could help reduce cell $/m^2 costs while maintaining or improving efficiency.
  - Alternative designs may be able to achieve additional cost reductions, this just gives an example.

Impact of Efficiency on Module Costs



Module Efficiency = (Cell Efficiency)*(Throughput Efficiency)

Throughput efficiency considers optical efficiency and acceptance angle.

Summary and Conclusions

- We have examined the cost drivers and potential cost associated with a model HCPV module and cells
  - The HCPV design modeled here reaps the full benefits of scale with production volumes ≥ 100 MW/year, but may also be cost competitive at much lower production volumes
    - Learning is not included in this analysis and could play an additional role in reducing costs
  - There is significant room for cell cost reductions, particularly if manufacturing yields and substrate reuses can be improved in a scaled process
  - Module efficiency improvements and cell cost reductions represent significant opportunities for future HCPV module cost reductions
- Cell and module costs are an important starting point for analyzing HCPV, but no conclusive statements about the competitiveness of HCPV can be drawn based on these numbers alone
  - An extensive analysis of system costs, energy production, and LCOE in a given location is required in order to resolve this question.

Thank you!

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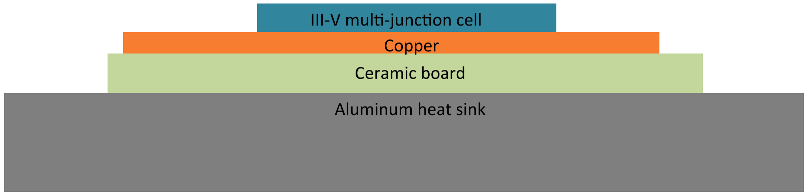
We are always interested in collaborating with industry, other national labs, or universities!

Back-up Slides

Thermal Management Modeling

Thermal Management: Methods

- Simulations of thermal management requirements were performed in conjunction with Dr. Hohyun Lee of Santa Clara University.
- The simulations incorporated the geometries shown here. The model was a simplification, with the following were not included:
  - Detailed assumptions about the geometry of the copper traces
  - The effect of the bypass diode
  - The effect of structural supports or module housing
  - *Thus, thermal management requirements may be slightly overestimated*
- We compared thermal management solutions with Al_2O_3, SiN_x, and AlN ceramic boards with assumed thermal conductivities of 25 W/mK, 90 W/mK, and 180 W/mK, respectively.
- **Aluminum volumes required to maintain temperatures below 353 K were computed via thermal modeling and then used to compute materials costs, assuming an aluminum price of $2.2/kg. Processing costs were determined by consultation with heat sink vendors.**

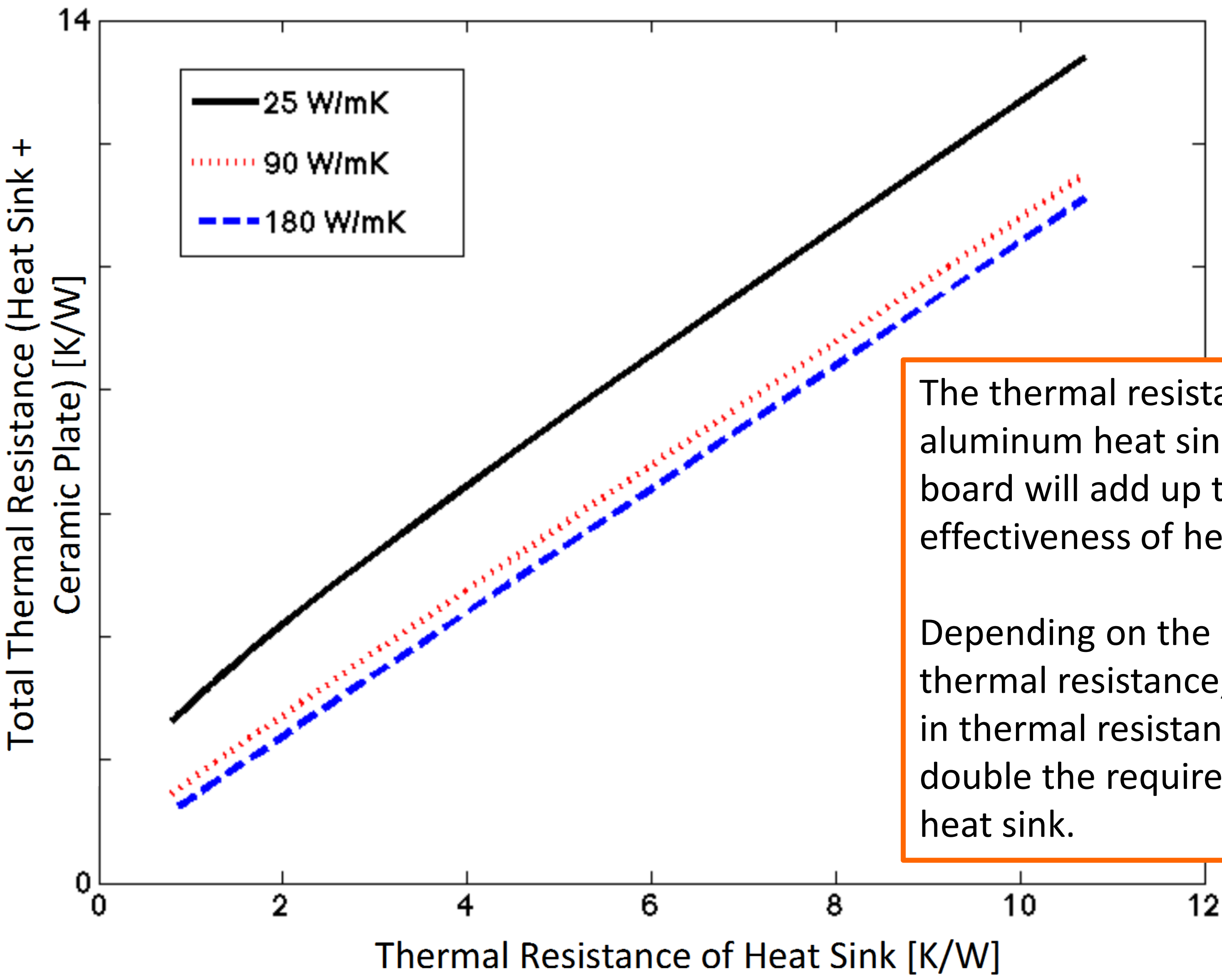


Side view of the simulated geometry without fins.

Input Assumptions to the Thermal Model

Layer	Thermal Conductivity (W/mK)	Thickness (mm)
III-V multi-junction cell	60	0.205
Copper	285	0.2
Ceramic board	varied	varied
Aluminum plate	205	3

Total Thermal Resistance

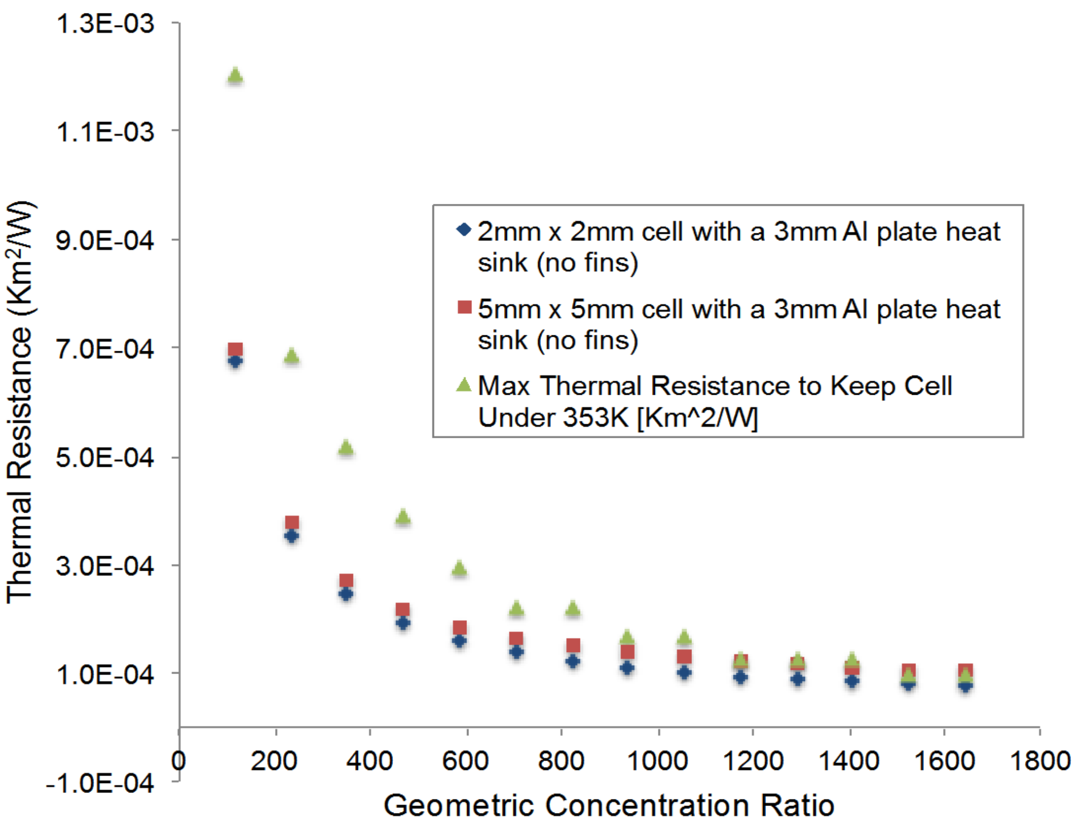


The thermal resistances of the aluminum heat sink and ceramic board will add up to determine the effectiveness of heat dissipation.

Depending on the range of thermal resistance, 30% reduction in thermal resistance can easily double the required volume of the heat sink.

Thermal Management Results

- The figure below assumes a ceramic plate of thermal conductivity 90 W/mK. Results are similar with a 180 W/mK ceramic plate.
- This analysis illustrates that a 3mm thick aluminum plate is sufficient to maintain cell temperatures below 353K for a wide range of concentrations in a point-focus system.
- At scale, a significant difference in the cost of AlN and SiN_x plates is not expected.



$$C_g = \frac{C_{eff}}{(1-\eta_{cell}) \cdot \eta_{optical} \cdot \frac{850}{1,000}}$$

C_{eff} is the effective concentration corresponding to the amount of thermal energy the thermal management system is required to dissipate.

For the plot shown at the left, we assume 41% cell efficiency and 85% optical efficiency → $C_g = C_{eff}/0.426$

Energy Production Issues

Energy Production

Limitations on energy production in CPV modules (true for both LCPV and HCPV)

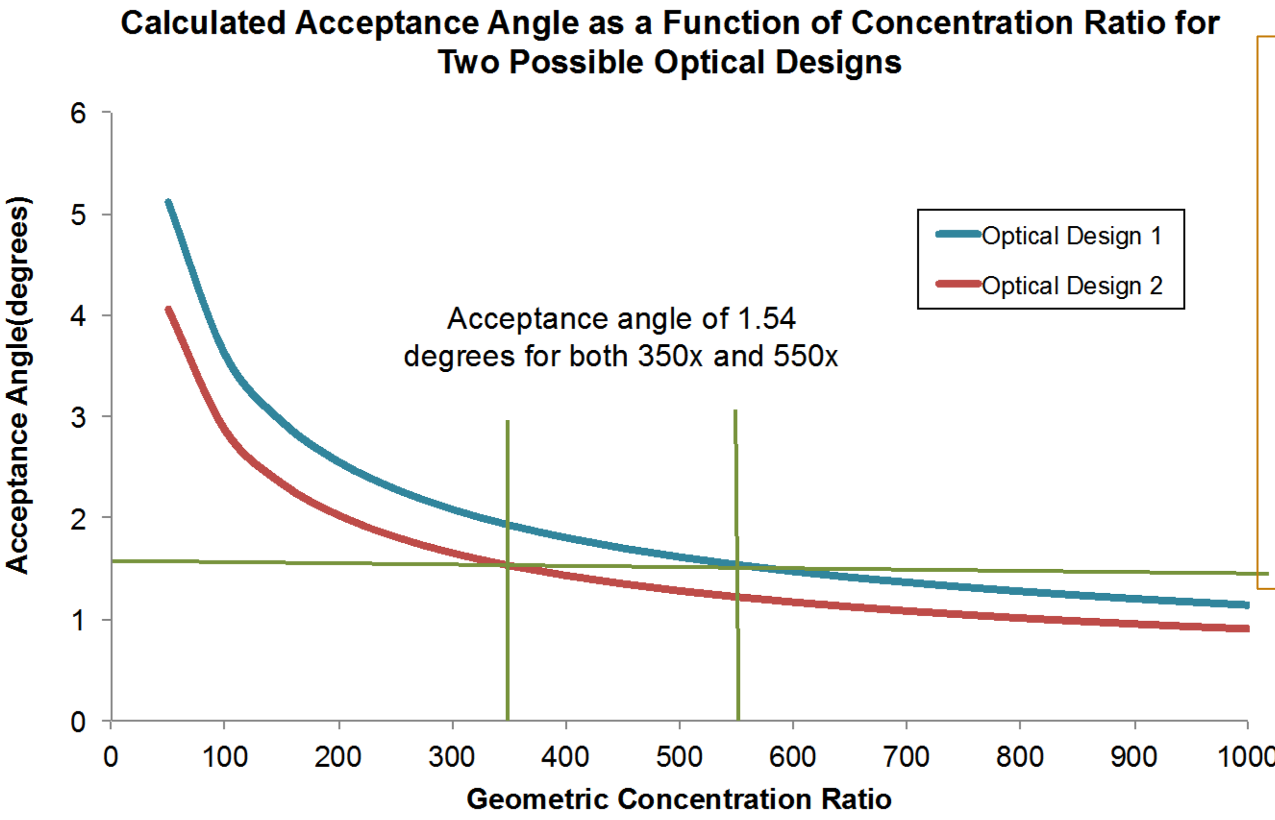
- **System Efficiency**
- **Solar Resource**, in terms of location, spectrum, season, time of day
- **Other Qualities of Solar Resource**, such as the angular spread of the sunlight and whether or not the resource is direct or diffuse
- **Angular Response of the Module**, determined by the optical design, module alignment, temperature, mechanical stress on the optics
- **Tracker Error/Accuracy**, determined by the tracker slew drive, controller, and module support structure.

Also a factor for flat-plate modules

Unique to CPV

Acceptance Angle

- Acceptance angle is always a function of concentration, with lower concentrations having a larger acceptance angle.
- However, acceptance angle is also a function of the optical design, and so there can be a higher concentration design with the same acceptance angle as a lower concentration design with different optics, as shown in the example below.

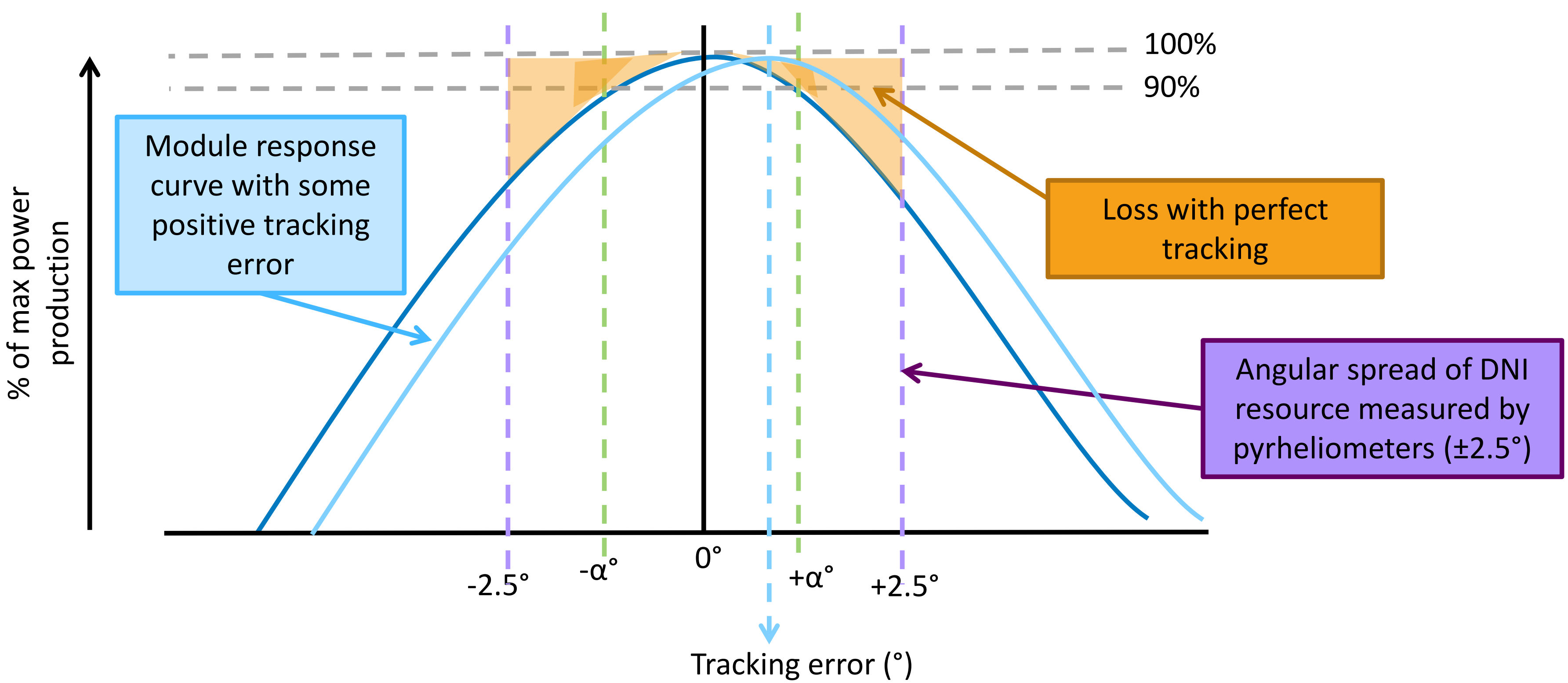


The acceptance angle *for ideal concentrator*, i.e., the *theoretical maximum acceptance angle*, is determined by the following relationship:

$C = n^2/\sin^2\theta$

C = concentration ratio < C_g
θ = acceptance angle
n = refractive index

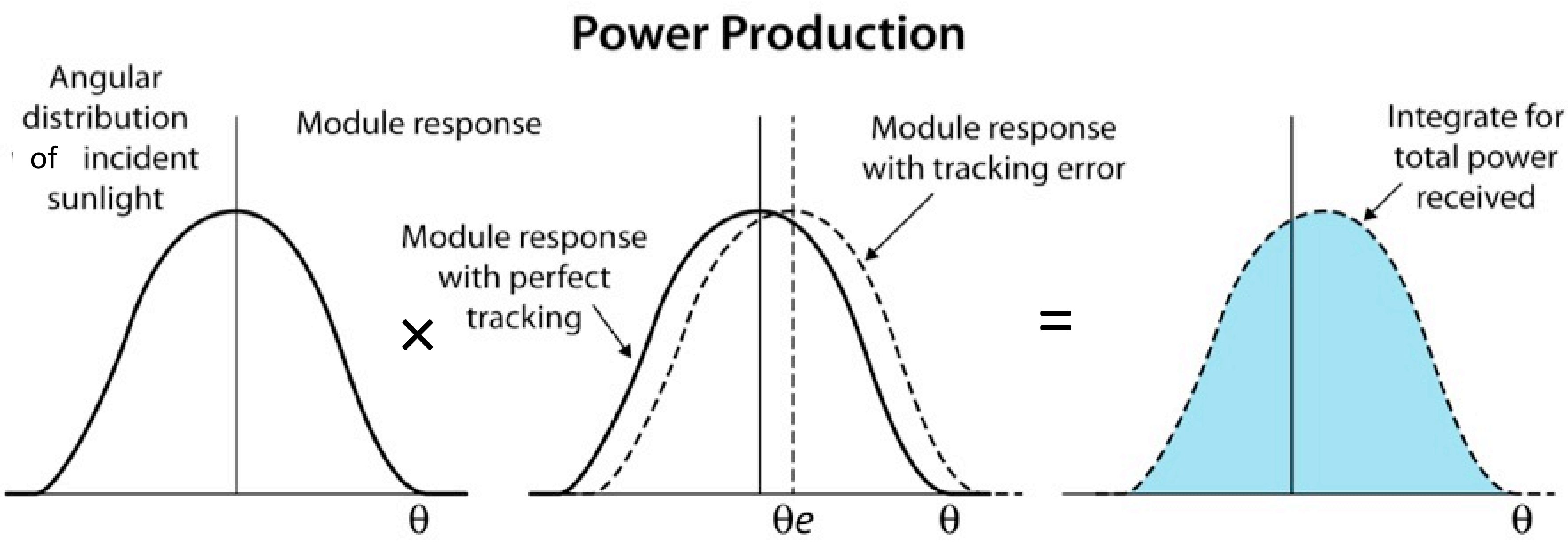
How Does this Translate to Efficiency?



- Efficiency lost due to acceptance angle limitations and tracker errors will depend on the specific module response curve
- There is currently no standard definition of acceptance angle. People use 90%, 95%, and 98% acceptance angles in the literature, with 90% being the most common
- Just stating an acceptance angle does not paint the full picture of expected energy production changes
  - Notably, if tracker or alignment errors are either large to begin with or larger than expected (due to high wind, optical misalignment developing as a result of refractive index change or mechanical flexing of the optics, etc.), the energy production could actually be much less.

A Method for Computing Power Production

Total power production will be the profile of incident sunlight as a function of angle and wavelength multiplied by the module response as a function of angle and wavelength, integrated.



Energy Production

- Because of the complexity in CPV, and the lack of complete understanding of the DNI resource, it is difficult to correctly model energy production.
- Thus, there is not a fully developed understanding of how much module energy production can vary with location, time of year, and module design.
  - This includes issues like impact of wind load on tracker error, effects of soiling for different module designs, etc.
  - This also includes uncertainty in the spectral response of different III-V multi-junction cells, which is the subject of current research efforts.
- This information also is essential to correctly determining the LCOE advantage (or disadvantage) of HCPV compared to flat-plate PV and tracked flat-plate PV in different locations for different modules.
- Some published studies on HCPV system energy production, measured and modeled, are listed in the note. This is an active area of study.

References on Energy Production

Kurtz, Sarah et al. ***Key parameters in determining energy generated by CPV modules.*** **Prog. Photovolt: Res. Appl. (2014)**

Gomez-Gil, Francisco, et al. *Analysis and Prediction of Energy Production in Concentrating Photovoltaic (CPV) Installations*. ***Energies*** (2012)***, 5*, 770-789**

Liu, Mingguo et al. ***Performance Analysis and Modeling of the World's Largest CPV Power Plant.*** **39th**
IEEE Photovoltaic Specialists Conference (PVSC), 1749 – 1754, 16-21 June 2013.

Kinsey, Geoggrey et al. ***Energy prediction of Amonix CPV solar power plans.*** **Prog. Photovolt: Res. Appl., 794-796 (2011)**

King, C. ***Site Data Analysis of CPV Plants.*** **35th IEEE PVSC, 3043-3047, 20-25 June 2010, Honolulu, HI.**

Energy Production

Recent work by Kurtz et al. (2014) has shed light on some issues related to energy production in several CPV modules.

- This data was taken in Golden, CO. For many regions where CPV may be deployed, the difference between winter and summer months is expected to be much smaller.
- While the trends are linear, there is not an exactly linear relationship between performance ratio and acceptance angle as there is also dependence on specific module design.

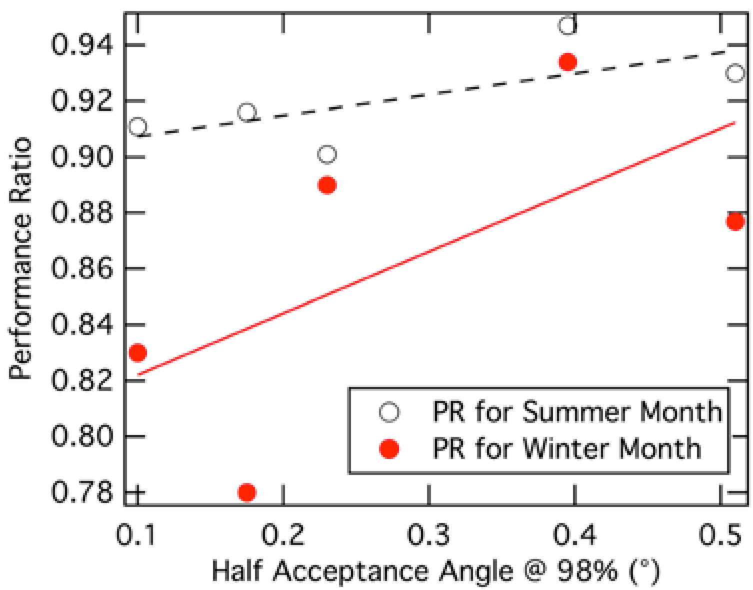


Figure 4. The performance ratio (PR) observed for a month of data as a function of acceptance angle for summer and winter months for five modules. The lines indicate least-square fits to each set of five data points.

Each dot represents a different module that was measured.

Integral of

Solar Input vs. angle

X

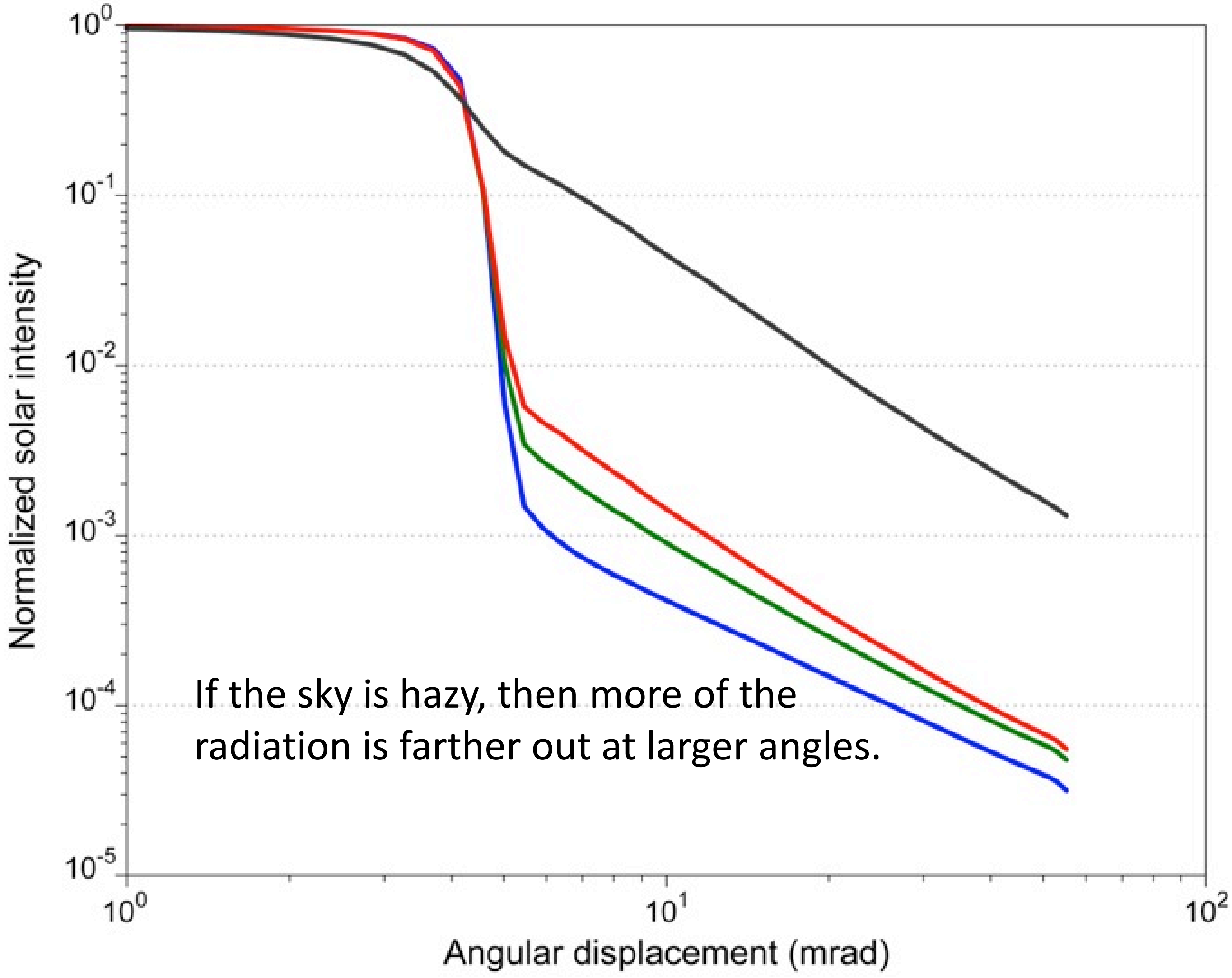
CPV Throughput vs. input angle

dθ

= actual DNI into concentrator system

$$\int I(\theta)T(\theta)\,d\theta = \text{effective DNI}$$

P_x vs. Angle


Normalized solar intensity
Angular displacement (mrad)
If the sky is hazy, then more of the radiation is farther out at larger angles.

Input Assumptions

Backup: Manufacturing Assumptions Made in Calculating Cell Costs

TABLE 1. Cell Manufacturing Assumptions for the Reference Case

Parameter	Value
GaAs deposition rate	15 μm/hour
$Ga_{0.63}In_{0.37}As$ deposition rate	3 μm/hour
GaInP deposition rate	2.5 μm/hour
AlInP deposition rate	4 μm/hour
AlGaAs deposition rate	3 μm/hour
AlGaInP deposition rate	2 μm/hour
Material utilization for TMG, TMI, and TMAl	25%
Material utilization for PH_3 and AsH_3	15%
MOCVD Tool Uptime	85%
Wafer (either grown on or ELO)	6’’ round

Backup: Input Parameters for the Reference Case HCPV Module

TABLE - Input Parameters for the Reference Case HCPV Module Design.

Parameter	Symbol	Value
Geometric concentration ratio	C_g	1,000
Module efficiency	η_{mod}	30%
Primary optic		Silicone-on-glass (SOG) Fresnel lens
Secondary optic		Glass dome refractive lens
Cell size		5mm x 5mm
Cell type		LM Ge/Ga(In)As/GaInP
Number of cells per module	N	50
Optical train F-number	f	1
Thermal management system		Passive
Module housing type		Rectangular box housing, steel

Converting Costs to $/W at Concentration

Concentration Ratio

$$C_g = C_{max} = A_{aperture}/A_{solar\ cell} = A_x/A_s$$

- Concentration is the process by which light from a larger area, A_x, is directed to a smaller area, A_s.
- **The throughput efficiency describes the losses in that process and it can be called the total optical efficiency.** $C_{effective}$ is the ratio of the optical power density at the solar cell to that at the concentrator entrance aperture.
- Power density (or irradiance) is measured in W/m^2.
- $C_g > C_{effective}$.
- $C_{effective} = C_g$ times throughput efficiency $= C_g\ \eta_x$.

Notes on the Equation for Computing $/W at Concentration

- $C = P_S/P_x$
- The module efficiency is the product of the cell and throughput efficiencies, so that $\eta_{mod} C_g = \eta_S C$
- C_g is the geometric concentration
- C is the effective (or optical) concentration ratio
- η_x is the throughput efficiency of the concentrator
- η_s is the cell efficiency
- P_x is 1,000 W/m^2 and corresponds to the CSTC incident DNI solar resource.

IEC. (2013). "IEC 62670-1 ed1.0. Photovoltaic concentrators (CPV) – Performance testing – Part 1: Standard Conditions."

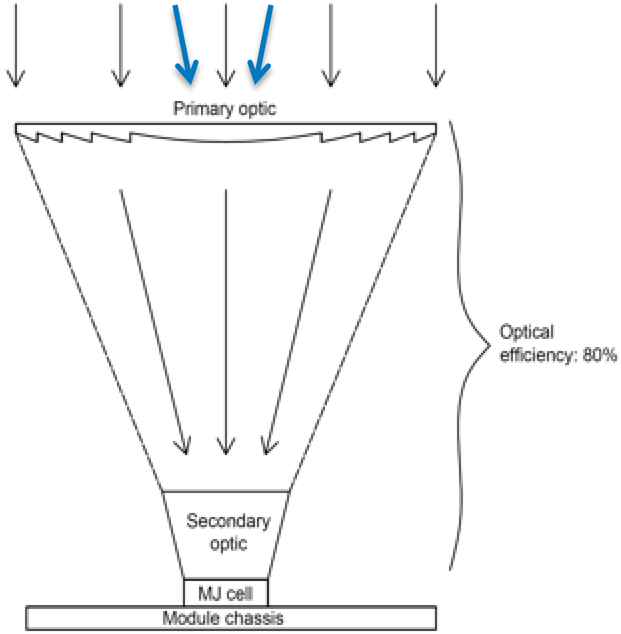
Cost Equations: Step 1

For this discussion, let's take $C_{effective} = C$

$C = P_s/P_x$ = **optical power density seen by the solar cell divided by the incident un-concentrated solar (optical) power density**

P_x = incident solar power density

$C = \eta_x A_x/A_s$



A is an Area

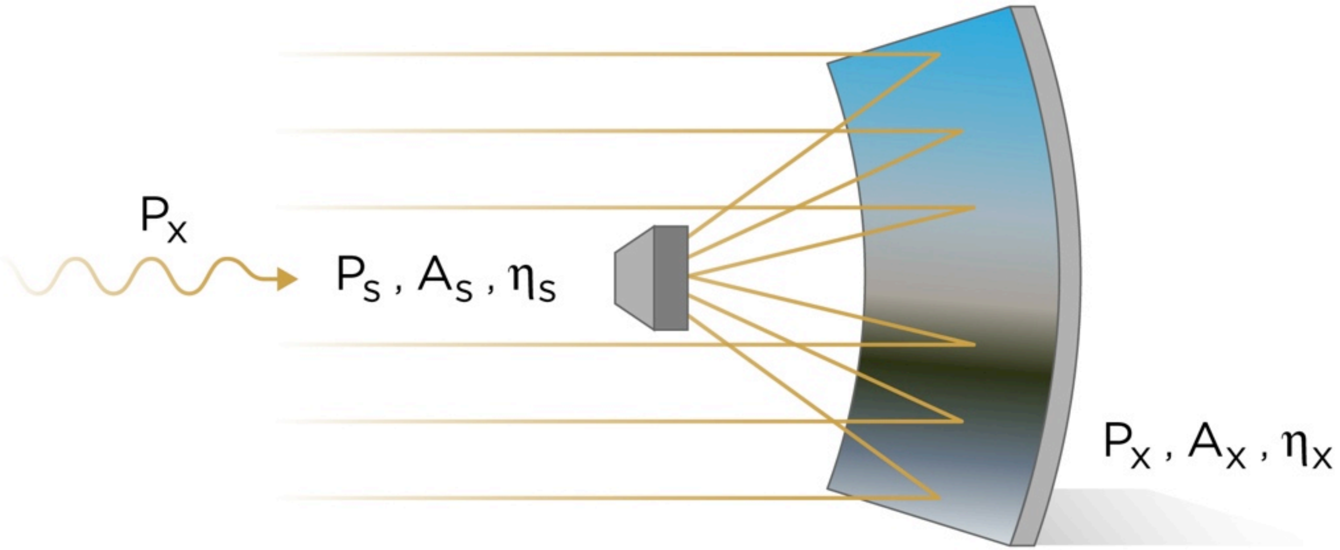
η_x is the concentrator throughput efficiency

Source: Fahrenbruch, A.L.; Bube, R.H. (1983). *Fundamentals of Solar Cells Photovoltaic Solar Energy Conversion.* Elsevier.

Cost Equations: Step 2

$$\text{Power Output} = \eta_s A_s P_s = \eta_s \eta_x A_x P_x$$

η_s = conversion efficiency of solar cells



All diagrams were drawn by Al Hicks, NREL.

Source: Fahrenbruch, A.L.; Bube, R.H. (1983). *Fundamentals of Solar Cells Photovoltaic Solar Energy Conversion.* Elsevier.

Realize that for the CPV solar cells,

- Electrical power output per unit area = $(\eta_s P_s)$
- But that's $(\eta_s \eta_x A_x P_x)/A_s$
- This is $C\eta_s P_x$
  - We use the actual (footprint) area, A_s, of the cell.
  - $\phi_s / C\eta_s P_x$ is the cost per unit area divided by the electrical output per unit area.

Caveat: Cell area may not equal receiver area.

Cost Equations: Step 3

Cost per unit area of the solar cell = ϕ_s

Cost per unit area of the concentrator = ϕ_x

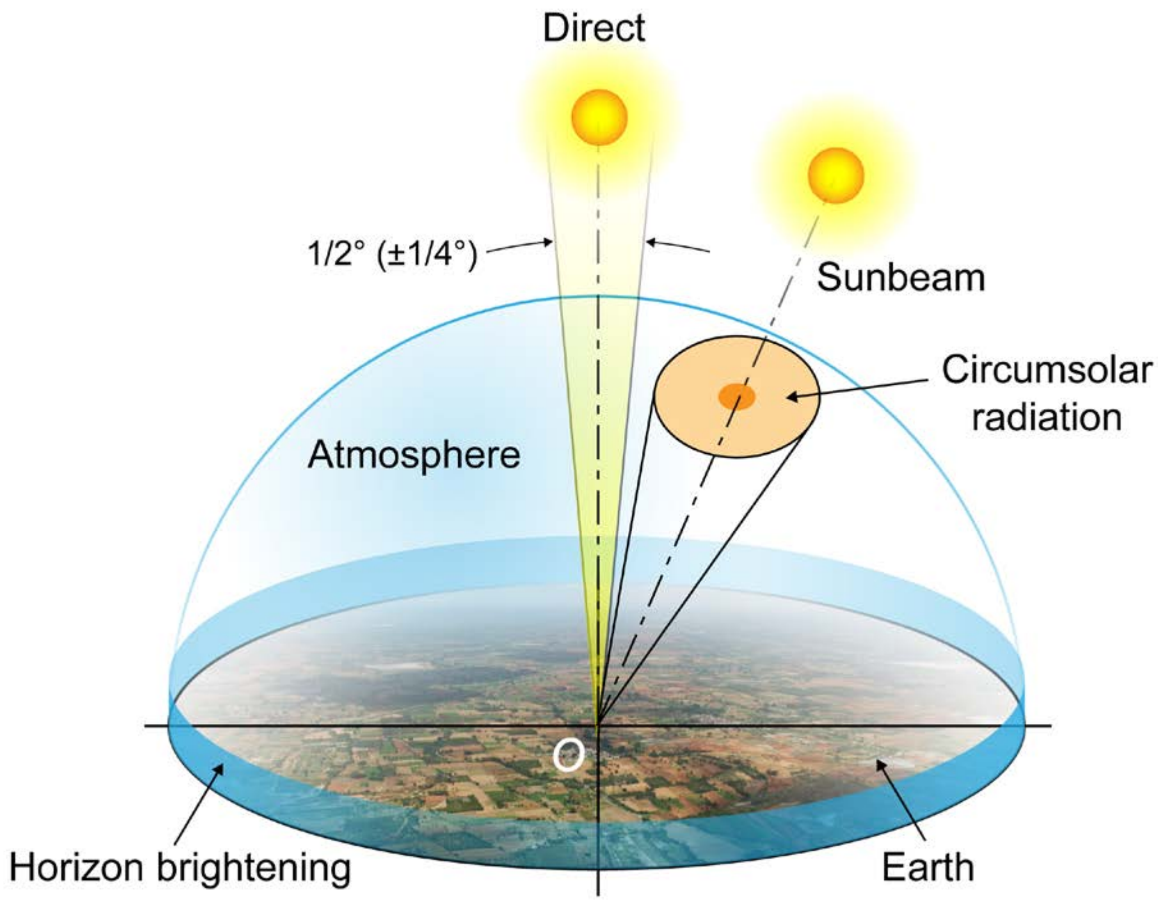
$$\$/W_p = \frac{\text{cost/area}}{\text{power output/area}} = \phi_s/C\eta_s P_x + \phi_x/\eta_s \eta_x P_x$$

$$\frac{1}{\eta_s P_x}\,[\phi_s/C + \phi_x/\eta_x]$$

Source: Fahrenbruch, A.L.; Bube, R.H. (1983). *Fundamentals of Solar Cells Photovoltaic Solar Energy Conversion.* Elsevier.

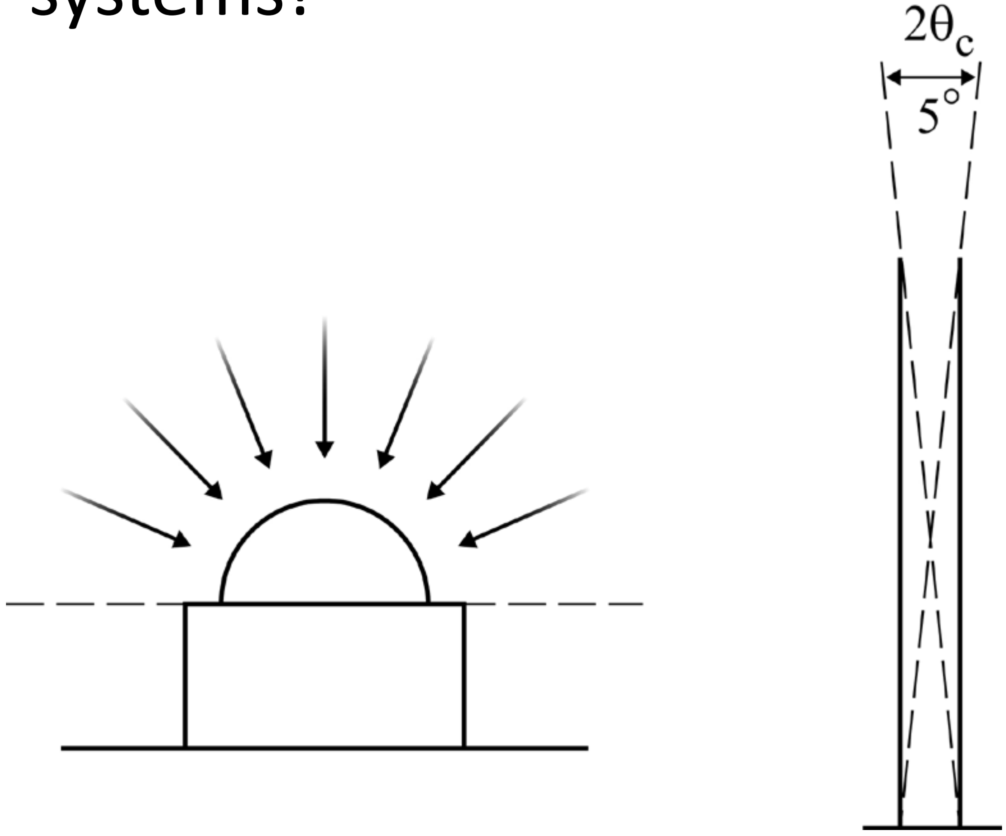
Energy Production Issues

We do not always have the same energy in the same solid angle.



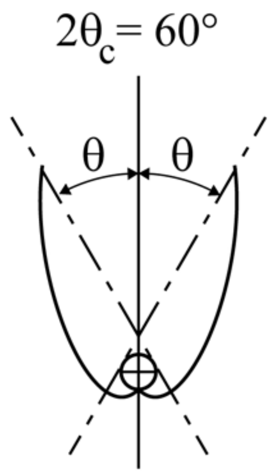
All diagrams were drawn by Al Hicks, NREL.

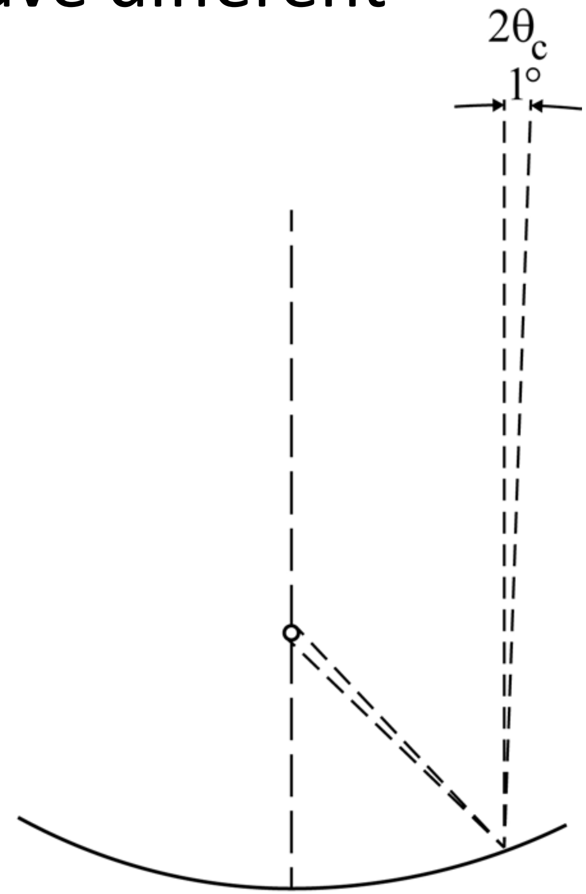
Our current measurement systems (for DNI solar resource) look at angles larger than the acceptance angle of most CPV systems!



All diagrams were drawn by Al Hicks, NREL.

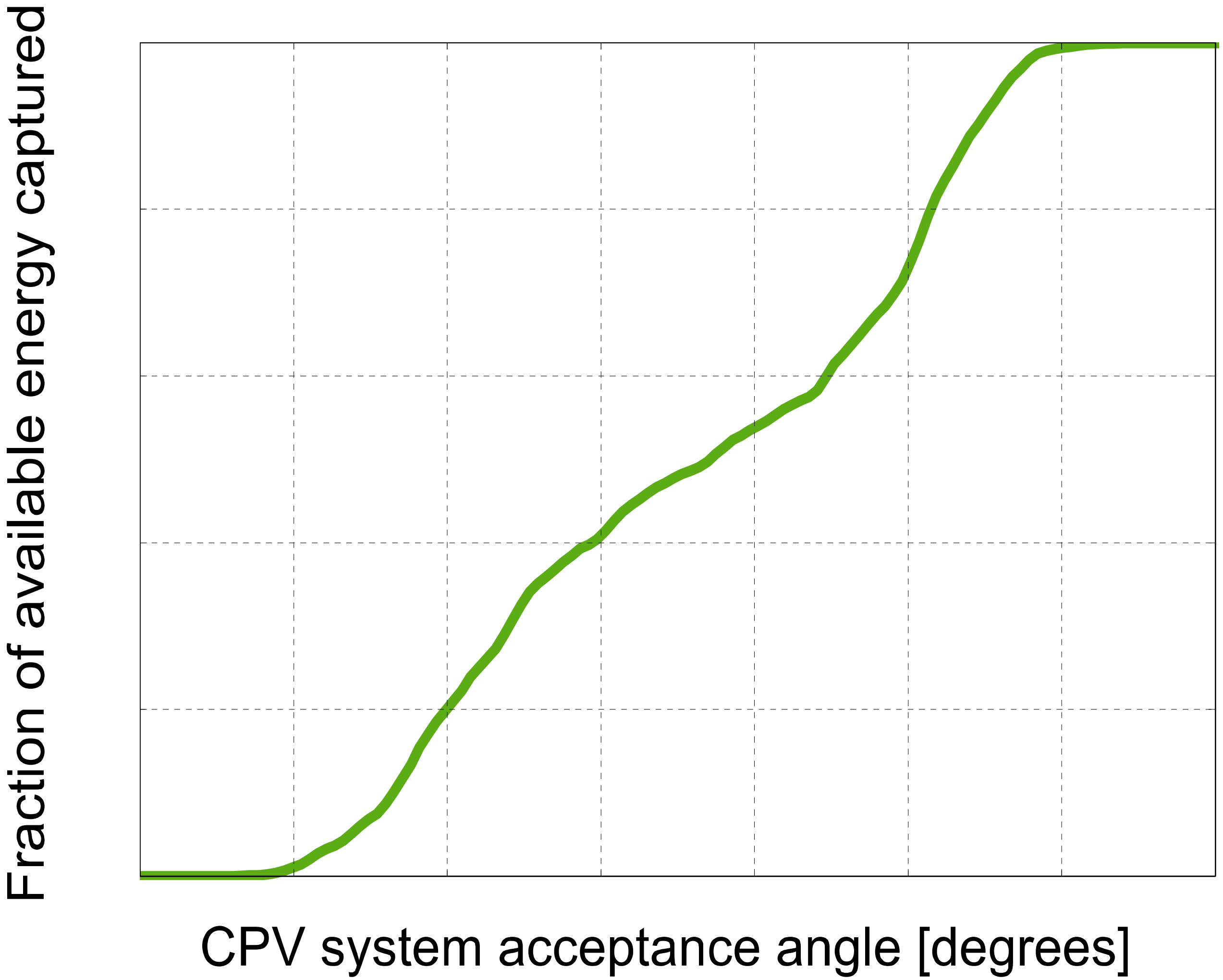
Different concentrators have different acceptance angles.





All diagrams were drawn by Al Hicks, NREL.

CPV Energy Capture

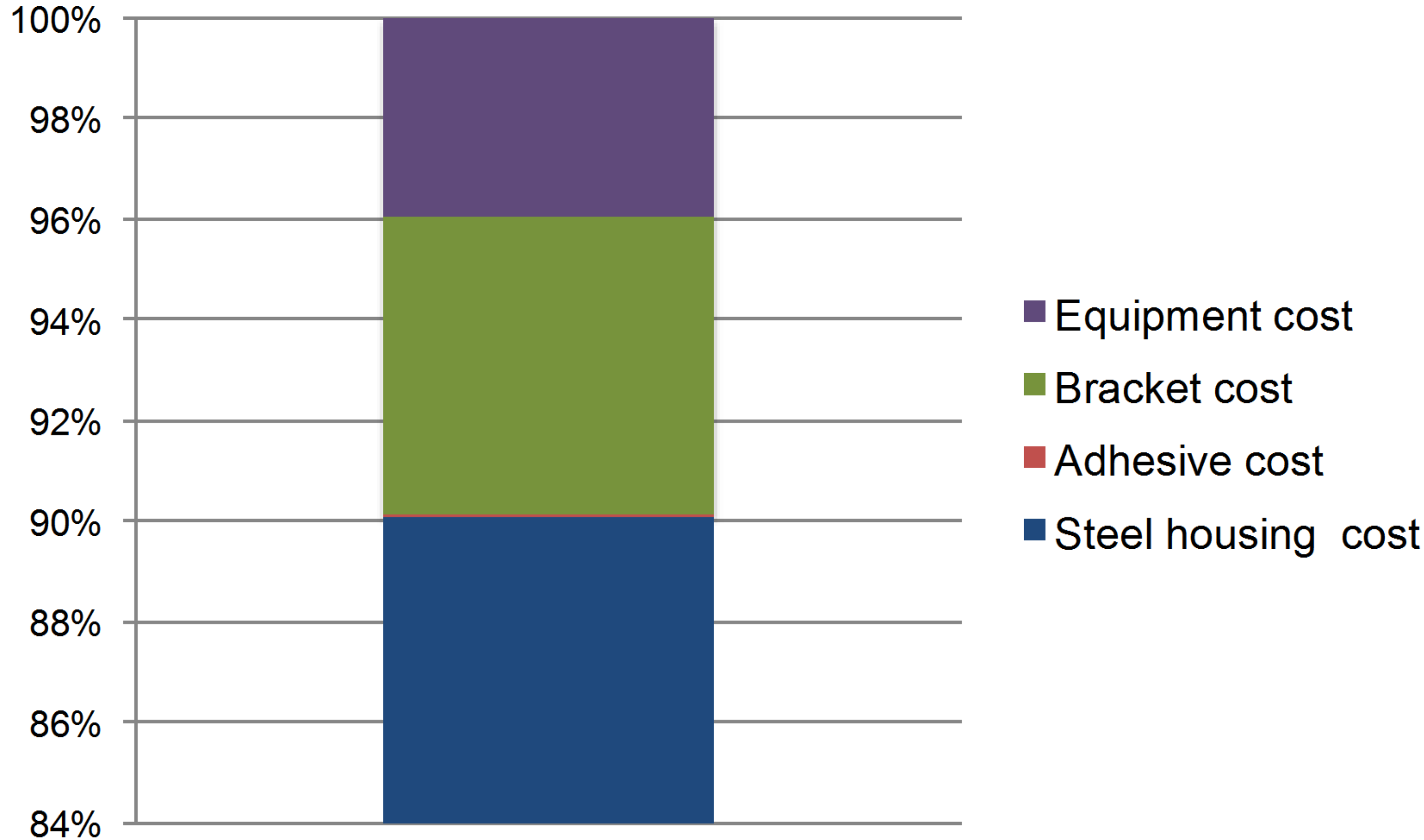


on of acceptance angle

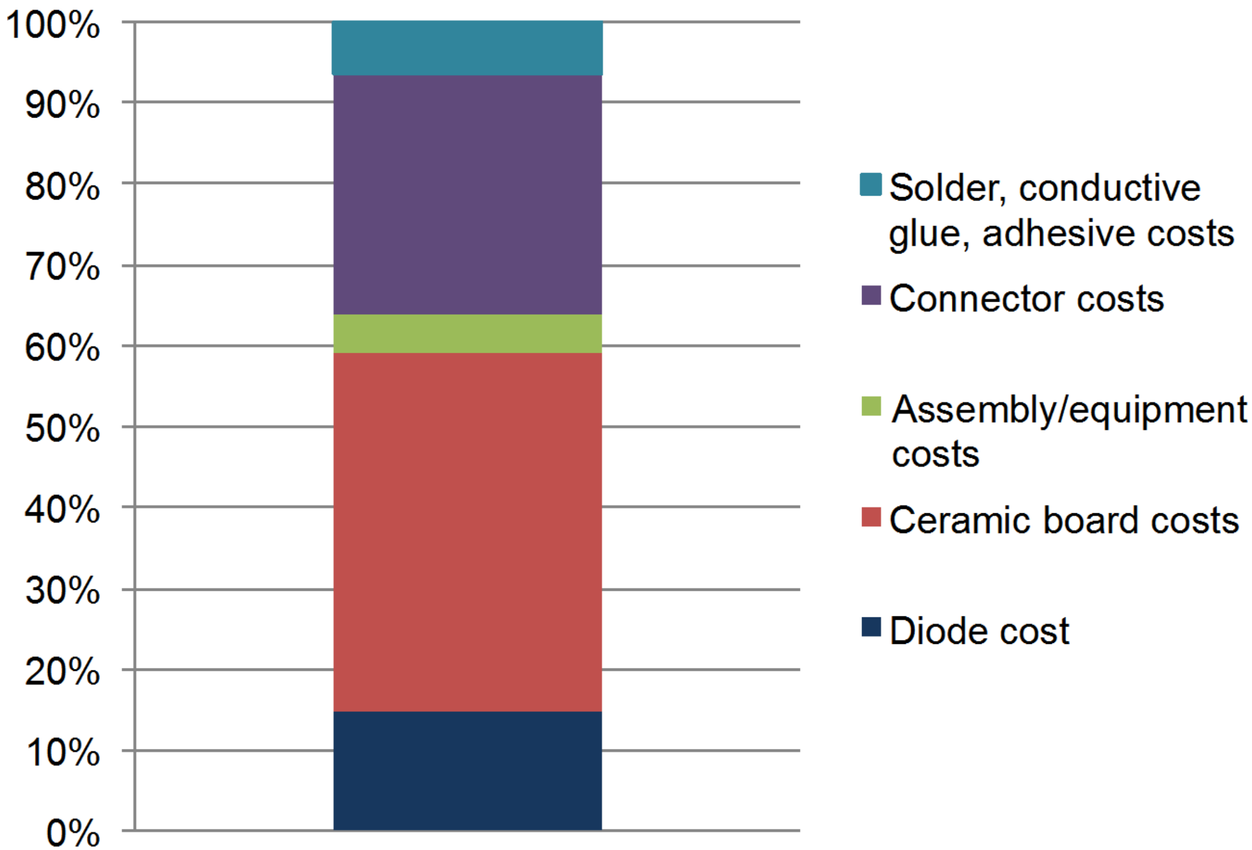
Deep-dive into cost breakdowns

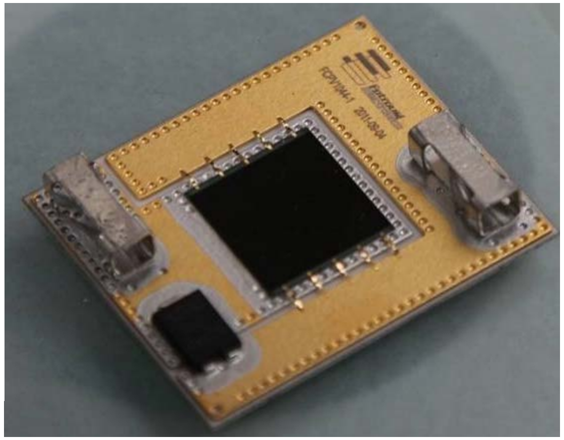
Breakdown of Module Housing Costs by Type

Assumes $3.2/kg steel costs (include materials costs and cost to manufacture housing pieces), $20/kg adhesive costs



Breakdown of Receiver Board Costs





Receiver board
From "Concentrated photovoltaics." (2015). Accessed March 2015: http://en.wikipedia.org/wiki/Concentrated_photovoltaics.