MEPV System Cost Modeling

SAND2013-1674P

Reduce module cost with microscale PV cells, miniaturized concentrating optics, and microelectronic assembly tools and techniques

Reduce BoS costs by using up to 370,000 cells/m^2 to produce high voltage output, eliminating DC-to-DC converters and thicker, more expensive wiring

Reduce tracker costs through micro-optical designs with acceptance angle that permit the use of lower cost, coarse, 2-axis trackers for non-concentrating PV

Reduce installation costs by producing flat plate MEPV modules that are as easy or easier to pack, ship, handle, hoist, and mount as one-sun PV panels

Reduce O&M costs by producing systems that are reliable, weather-resistant, and autonomous

$$LCOE = \frac{NPV\left[\text{Module Cost} + \text{BOS Cost} + \text{Tracker Cost} + \text{Installation Cost} + \text{O\&M Cost}\right]}{NPV\left[\text{Energy generation}\right]}$$

Increase energy generation by boosting efficiency of MEPV cell stack and reducing losses in the optical system, tracker, sunlight-to-DC conversion, and DC-to-AC conversion

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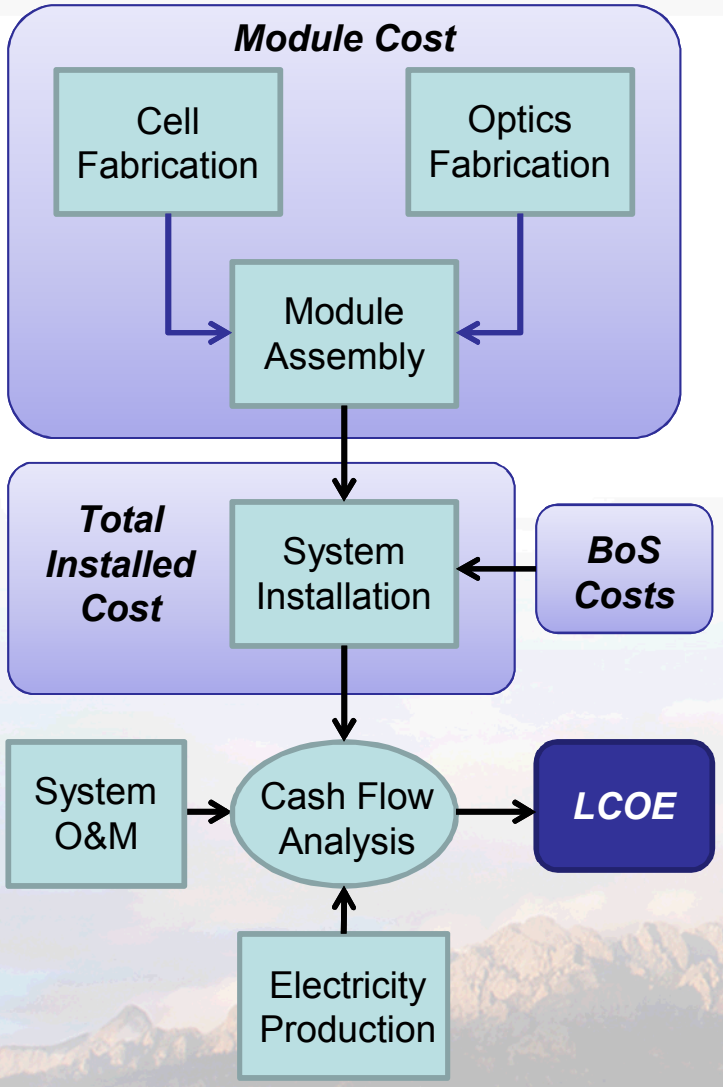
What We Sought to Accomplish in Year 1



- Produce a transparent, defensible model of cell, module, and system prices ($/$W_p$) and LCOE — including profit margins
- Apply that model to the Prototype 1 cell design and Prototype 2 optical designs
- Generate graphs that relate various component costs with MEPV cell size, level of concentration, and module efficiency
- Answer questions on the relationship between sun tracking costs and acceptance angles for the optical system
- Understand what others have done and are doing to make PV the most profitable electricity generation option for utilities

What We Did

- Built in Excel a cost model that is modular in structure — cell, module, system, operation
- Produced a series of graphs and contour plots that show the system cost impact of specific design choices based on explicit inputs, assumptions, and calculations
- Using PV industry data, generated graphs for our optics and system designers that relate sun tracking costs to acceptance angles
- Developed a clearer picture of the pathways and obstacles associated with achieving the $\$1/W_p$ PV system price by 2020

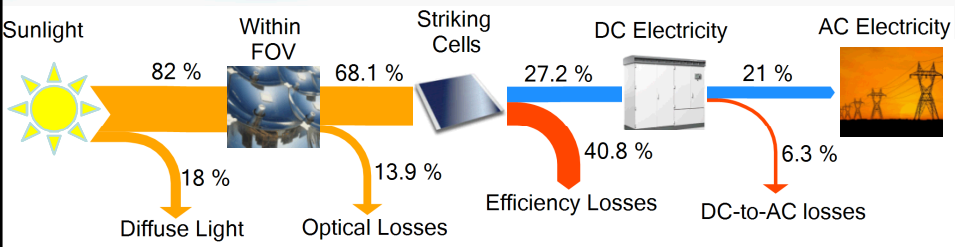
Iterative Interaction with MEPV Cells and Materials Unit

Iterative Interaction with MEPV Optics Unit

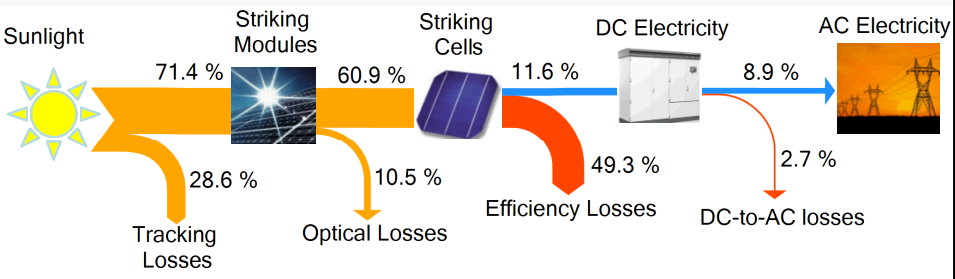
Iterative Interaction with MEPV Systems Unit

INPUT PARAMETERS		
Module Specifications	***Value***	***Units***
Module width	1.559	m
Module height	0.798	m
Concentration Ratio	100	X
Series losses in module	3%	-
Wafer Processing/Cell Production		
Cell efficiency	19%	-
Wafer diameter	200	mm
Diagonal of cells	250	µm
Gap between patterned cells on wafer	8	µm
% of wafer area patterned w/ cells	92%	-
Usable layers per wafer	13	-
Layers in cell stack	1	-
Wafer cost	$15.00	$/wafer
Wafer processing cost	$163.86	$/wafer layer
Optics		
Optical efficiency	90%	-
Width of inactive border on cell incircle	20	µm
Volume ratio of lens:fill material	2	-
Ratio of lens stack thickness to lens diameter	2.8	-
Adhesive layers	2	-
Adhesive thickness	0.2	mm
Glass layers	1	-
Glass thickness per layer	1	mm
Plastic lens materials cost	$8.00	$/kg
Plastic fill materials cost	$16.00	$/kg
Glass materials cost	$16.00	$/m^2
Adhesive cost per m^2	$3.85	$/m^2
Module Production		
Cell placement cost basis	$/cell	-
Cell placement cost - per part (Pick and Place)	$0.0010	$/cell
Cell placement cost - by area		$/module
PCB, mounting tape, and junction box	$9.50	$/module
Aluminum frame and edge seal	$20.00	$/module
EVA	$4.00	$/m^2
Back sheet film (Tedlar)	$8.00	$/m^2
Module assembly costs	$21.04	$/m^2

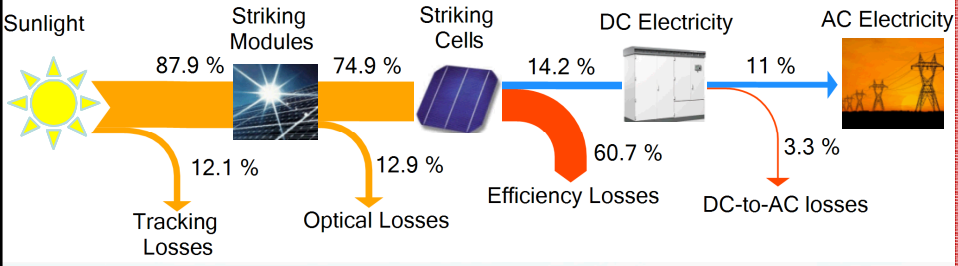
Maximizing Energy Generation in MEPV System



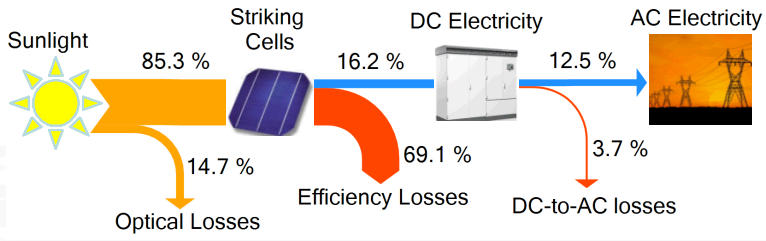
HCPV (cell η=40%, module η=33%)



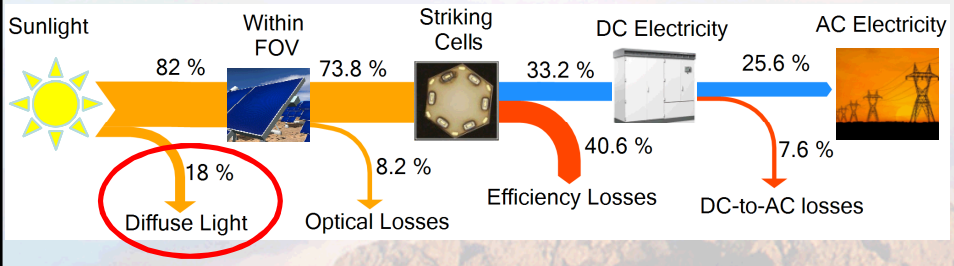
Fixed PV (cell η=19%, module η=16%)



1-axis PV (cell η=19%, module η=16%)



2-axis PV (cell η=19%, module η=16%)



MEPV (cell η=45%, module η=40%)

MEPV electricity generation:
- **20%** more than HCPV
- **100%** more than 2-axis Si PV
- **130%** more than 1-axis Si PV
- **180%** more than fixed mount Si PV

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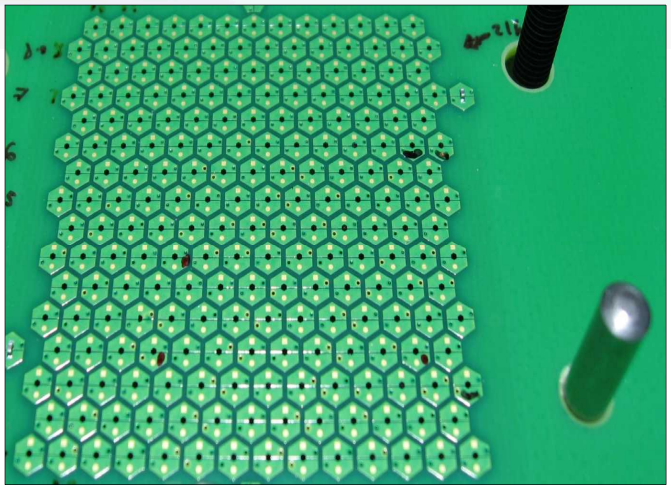
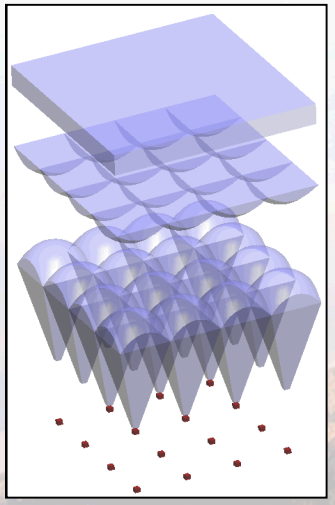
MEPV Cost Modeling with the Mind's Eye on the Prize



MEPV Prototype 1 Cell Array



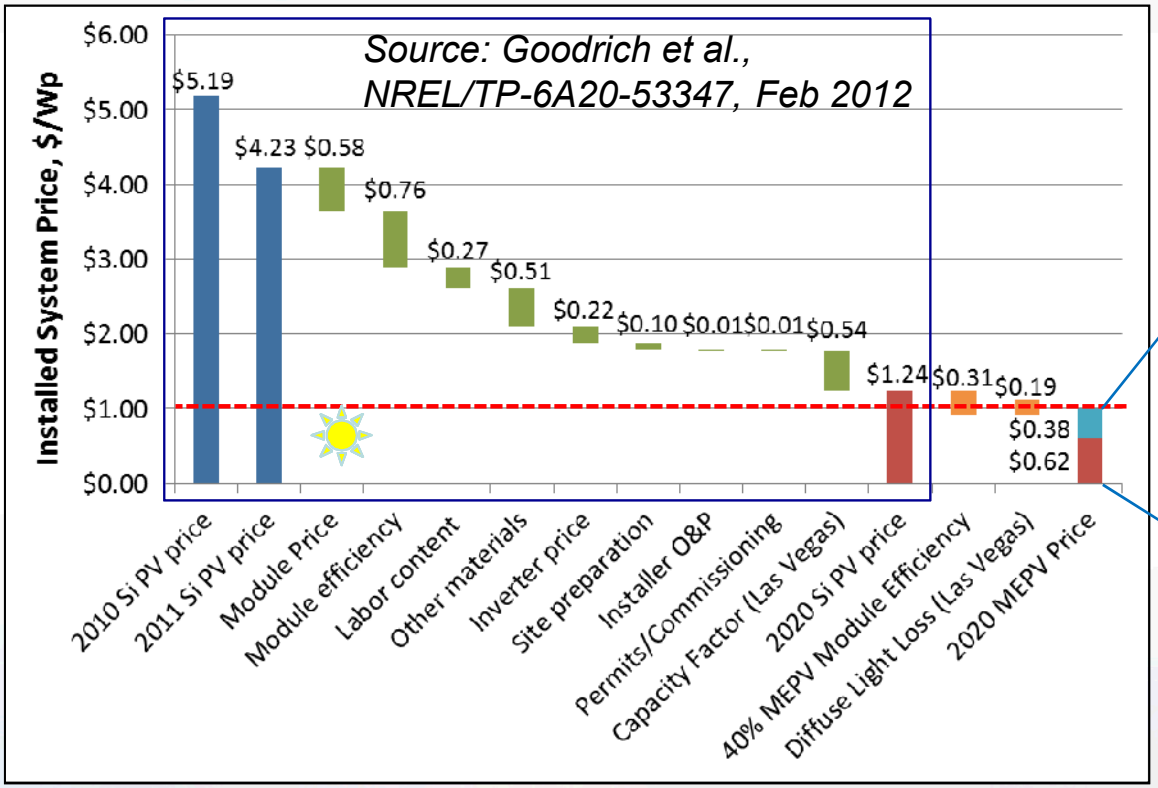
Generalized Diagram of MEPV Prototype 2 Optical System

- MEPV Prototype 1 Cell and Prototype 2 Optical Design Features:
  - 1 layer c-Si MEPV cell
  - ~100X concentration
  - 90% optical efficiency
  - >3^0 acceptance angle

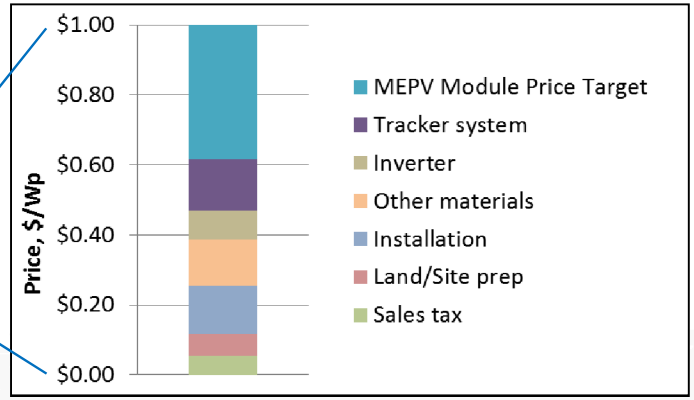
- The DOE SunShot Price Target (including profit) for a utility-scale, installed solar system is \$1/W_p by 2020

- At this price point and greater than 25 year operational life, wholesale electricity can be sold for \$0.06/kWh – without any government subsidies.

Three Step MEPV Path to the SunShot Target



Projected 2020 MEPV Price



Step 1: Take advantage of cost reductions in non-concentrating Si PV module and BOS components

Step 2: Boost MEPV module efficiency to 40%

Step 3: Decrease $/$W_p$ module costs through materials minimization, semiconductor processing, and microelectronics assembly

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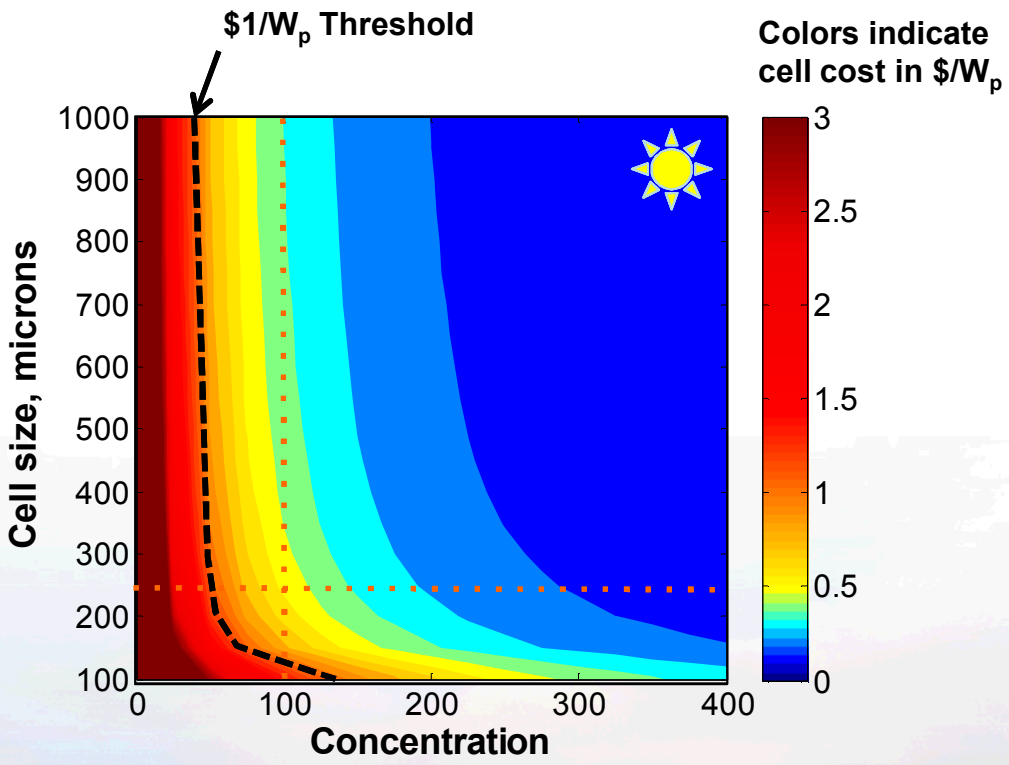
MEPV Cell Cost Model



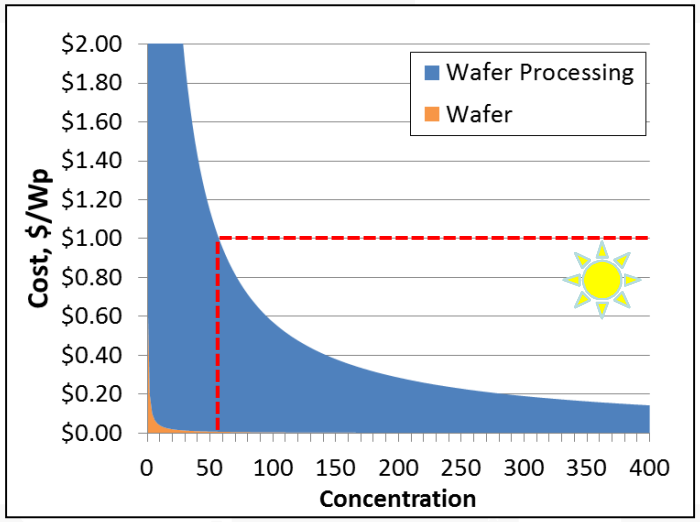
Costs calculated using 16% module efficiency

- **Design Choices:** Consider cell sizes of 100-1000 μm and concentration ratios of 1-400
- **Assumptions:** The maximum cost for each processing step is identical to the same step done by the semiconductor industry *(Source: IC Knowledge)*
- **Calculations:** Derived from the c-Si MEPV cell fabrication process laid out by our tech dev't team

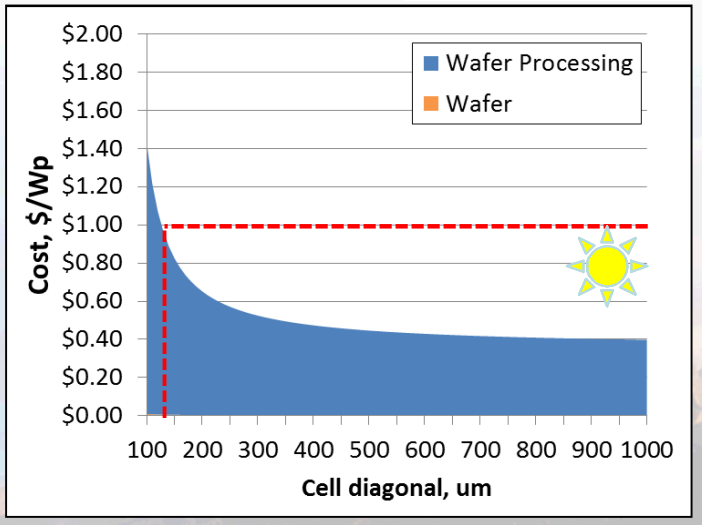
The concentration ratio needs to be greater than 60X

MEPV Cell Cost Model

250 µm Cells



100X Concentration



Calculations based on 16% MEPV module efficiency

- **Design Choices:** Consider cell size of 250 µm and 100X concentration

- **Inputs:**
  - Re-use yields 13 layers of 20 µm thick cells per wafer
  - Cells are sized with a 20 µm inactive border to accommodate cell & lens stack tolerances

- **Observations:**
  - c-Si wafer costs (shown as an orange sliver) effectively disappear
  - c-Si use is less than 0.1 g/W_p for MEPV at η = 16.0% and 20 µm cell thickness vs. 7.0 g/W_p for commercial c-Si* at η = 16.7% and 180 µm wafer thickness

With c-Si material costs for MEPV lowered dramatically, our tech dev't team has much more influence on reducing cell costs through innovations in wafer processing

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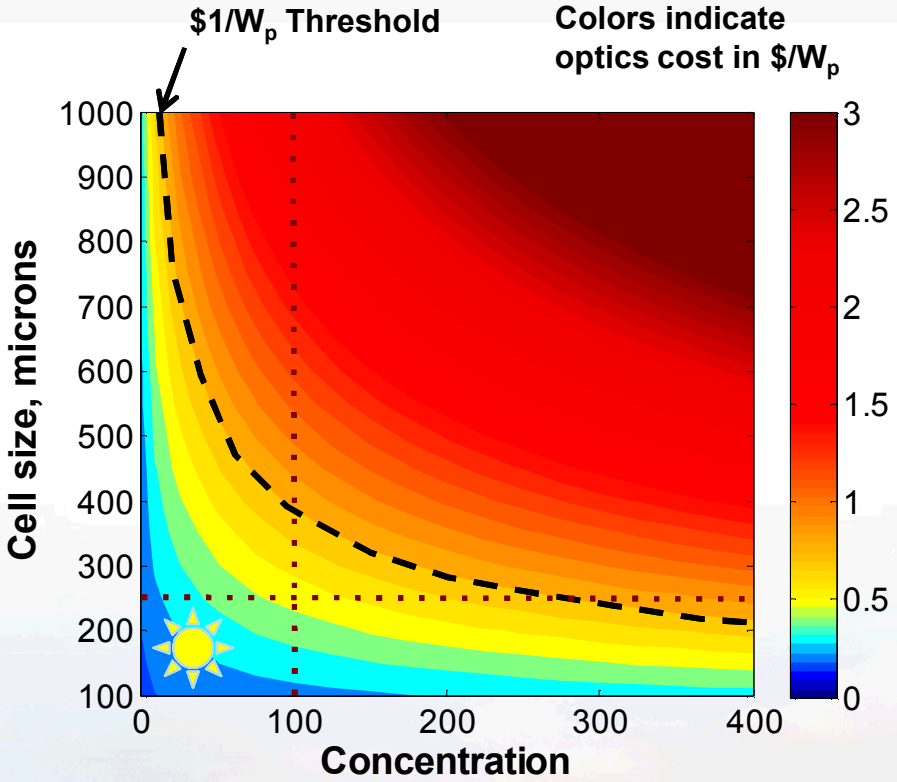
*Source: NREL c-Si Roadmap (unpublished), May 2012

MEPV Optics Cost Model



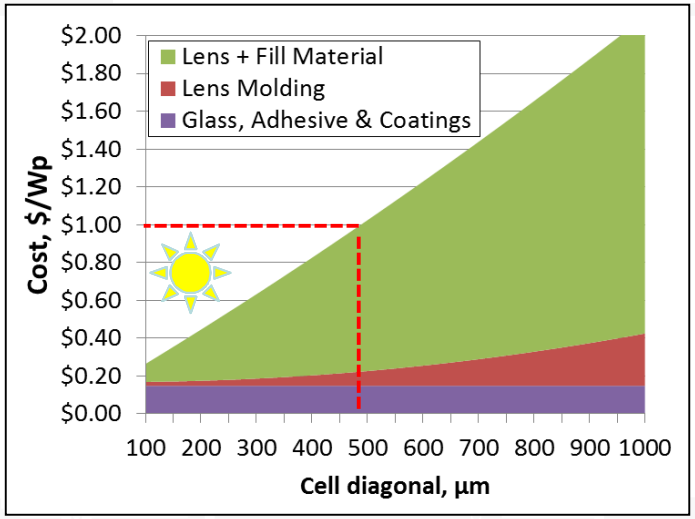
Costs calculated using 16% module efficiency

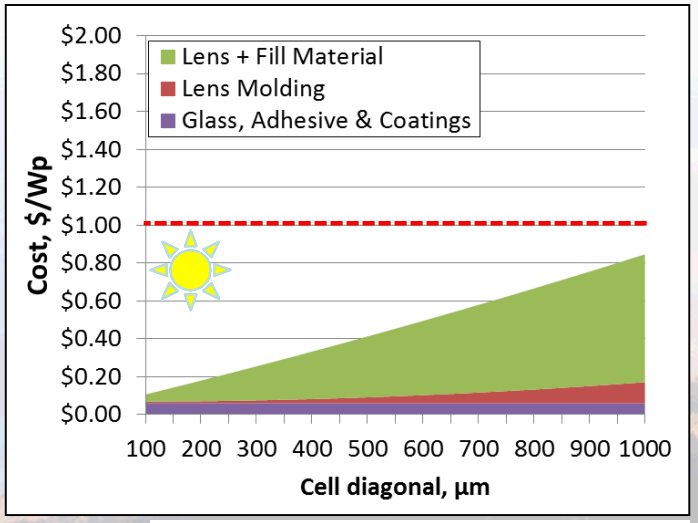
- **Design Choices:** Consider costs for Prototype 2 lens "sandwich" design at cell sizes of 100-1000 μm and concentration ratios of 1-400
- **Inputs:**
  - PC lens ($8/kg), PDMS fill ($16/kg)
  - 2:1 ratio of lens:fill volume
  - 2.8 ratio of optics thickness to lens diameter
- **Calculations:** Derived from the materials specs for Prototype 2 design and fabrication of lenses using a high-volume injection molding process

The contour plot sets a clear boundary for the cell size and concentration for the MEPV Prototype 2 Optical System to stay below the $1/$W_p$ threshold

MEPV Concentrating Optics Cost Related to Cell Size

100X Concentration, 16% Module Efficiency





100X Concentration, 40% Module Efficiency

- **Design Choices:** Prototype 2 lens "sandwich" design with 100X concentration ratio at 16% and 40% module efficiency

- **Inputs:**
  - PC lens ($8/kg), PDMS fill ($16/kg)
  - 2:1 ratio of lens:fill volume
  - 2.8 ratio of optics thickness to lens diameter

- **Calculations:** Derived from the materials specs for Prototype 2 design and fabrication of lenses using a high-volume injection molding process

MEPV cell size needs to be in the 100-300µm range to keep MEPV Prototype 2 optical system cost well below $1/$W_p$

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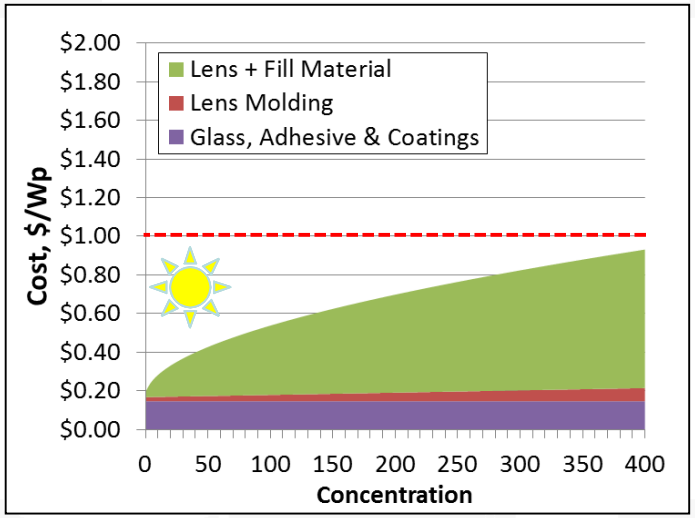
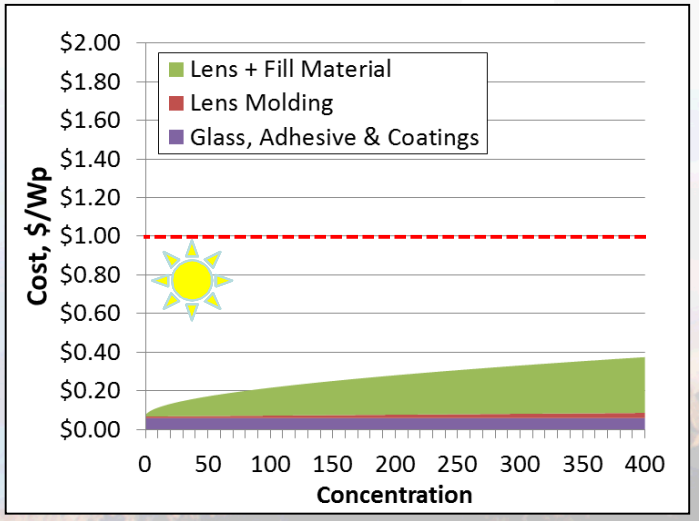
MEPV Concentrating Optics Cost Related to Concentration

250 µm Wide Cells, 16% Module Efficiency





250 µm Wide Cells, 40% Module Efficiency

- **Design Choices:** Prototype 2 lens "sandwich" design with 250 µm wide cells at 16% and 40% mod efficiency

- **Inputs:**
  - PC lens ($8/kg), PDMS fill ($16/kg)
  - 2:1 ratio of lens:fill volume
  - 2.8 ratio of optics thickness to lens diameter

- **Observations:** $/$W_p$ increase diminishes at 100-200X

At 40% module efficiency, the costs for the MEPV Prototype 2 optical system are at $0.20-$0.30/W_p between 100-200X

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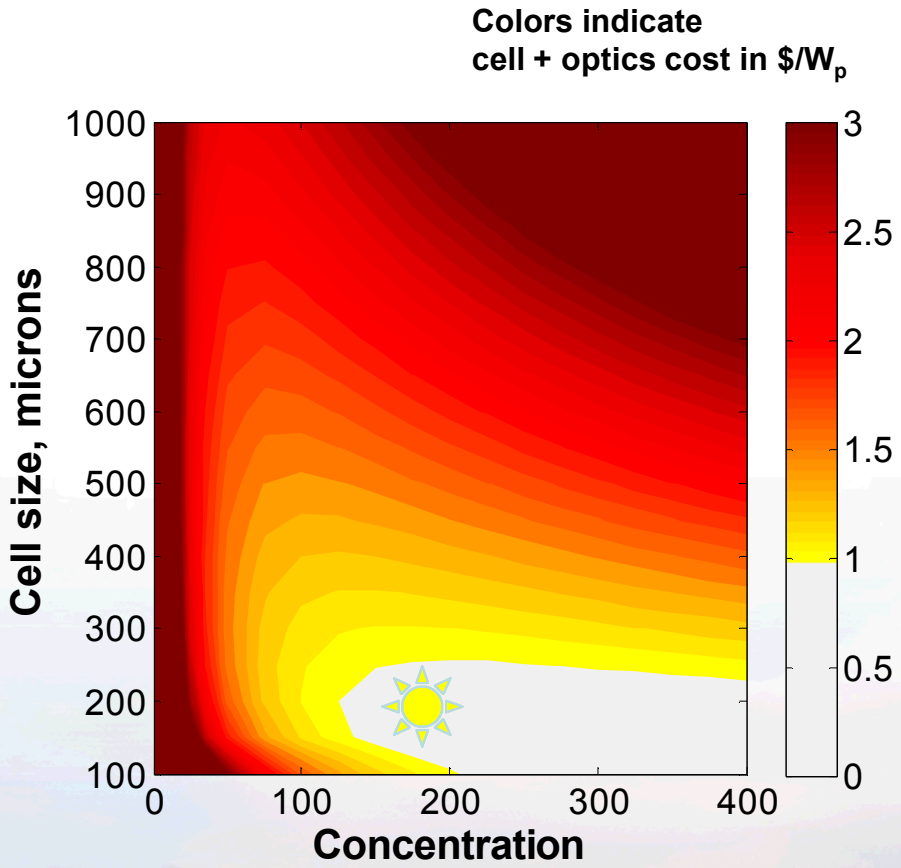
MEPV Cell + Optics Costs Related to Cell Size and Concentration

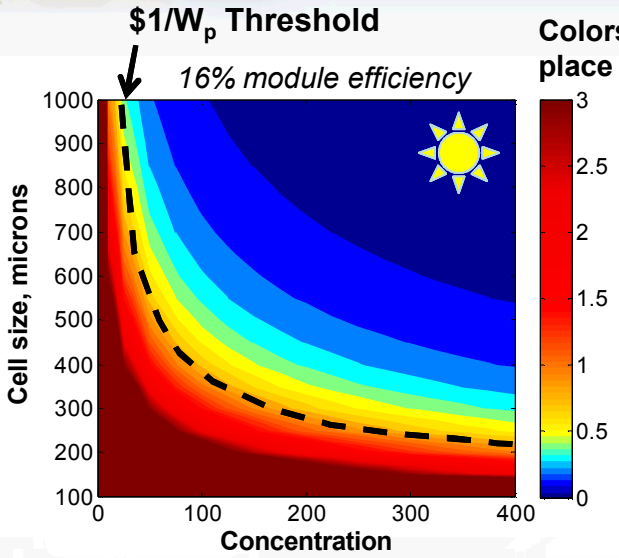


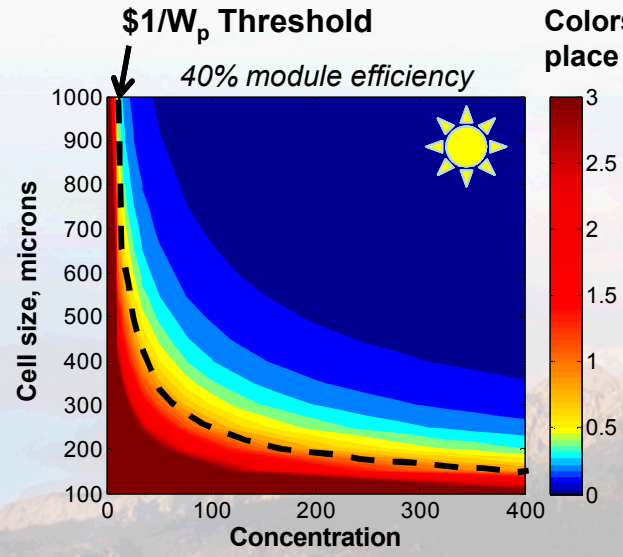
Costs calculated using 16% module efficiency

- **Design Choices:** Consider cell sizes of 100-1000 μm and concentration of 1-400
- **Assumptions:** Costs do not include module components or assembly
- **Calculations:** Cell and optics costs are added for each combination of cell size and concentration

The white area denoted by the sun shows a cell size range of 100-250 μm and concentration of greater than 125X stays within the $1/W$_p$ threshold

MEPV Pick-and-Place Costs Related to Cell Size and Concentration



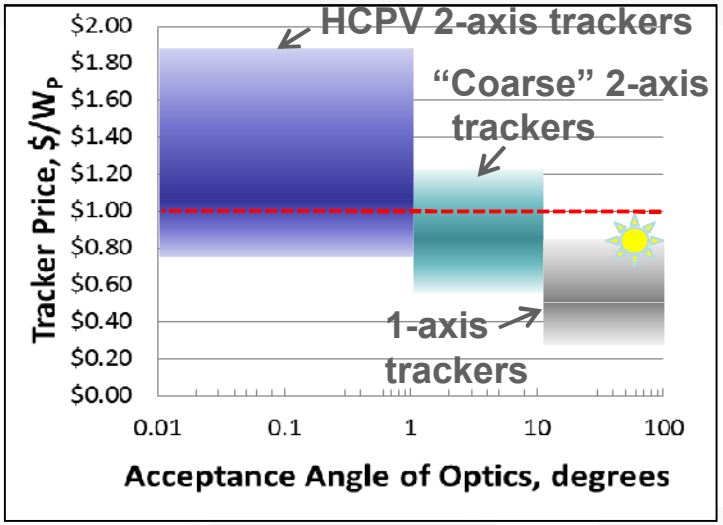


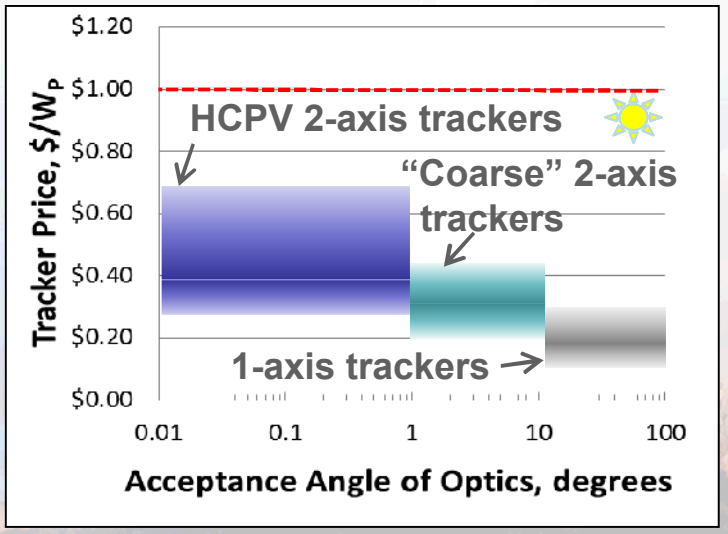
- **Design Choices:** Consider cell sizes of 100-1000 µm and concentration of 1-400
- **Inputs:** $0.001/part, independent of cell size
- **Calculations:** Density of cells (per m^2) is a function of concentration and cell size
- **Observation:** Even with module efficiency more than doubling, pick-and-place cost contours shift only slightly

As with microscale cells and optics, there is an opportunity to reduce costs significantly by developing massively parallel cell-to-module assembly tools to replace pick-and-place tools.

MEPV Tracker Cost Related to Acceptance Angle

16% module efficiency





40% module efficiency

- Researched tracker performance and costs
- Conducted survey of different tracker products (with significant contribution from *Perspectives*)

At 16% module efficiency, the concentrating optics need to be designed at acceptance angles suitable for coarse 2-axis or 1-axis tracking

At 40% module efficiency, the price for coarse 2-axis trackers can be reduced to \$0.20-\$0.45/W_p at an acceptance angle of 1^0-10^0

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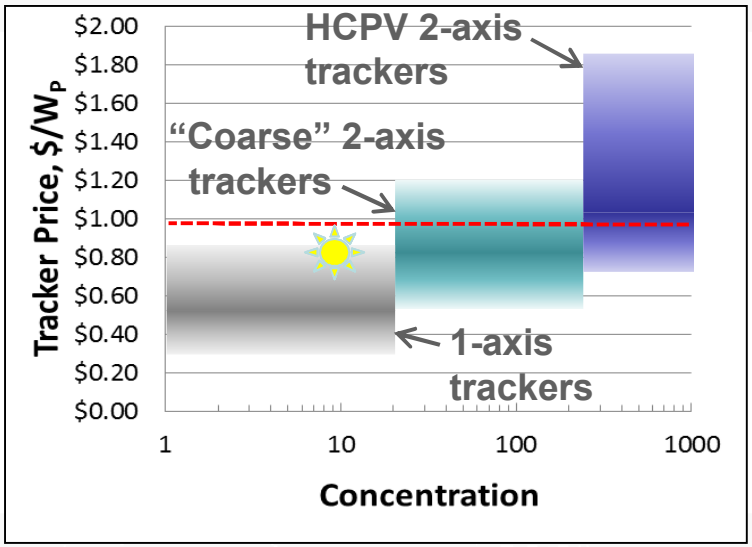
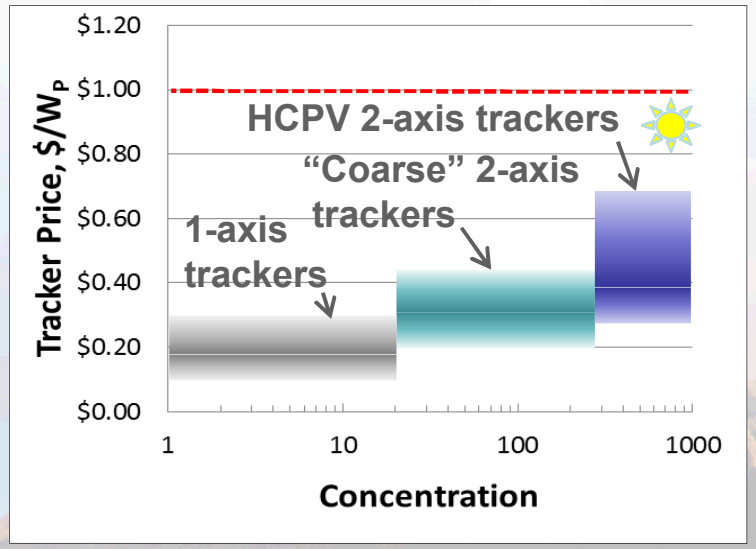
Sources: PV News, July 2011; NREL presentation at CPV Workshop, Santa Barbara, July 2012.

MEPV Tracker Cost Model Related to Concentration

16% module efficiency





40% module efficiency

- Converted maximum acceptance angle to level of concentration
- Developed MATLAB code to calculate energy output throughout year as a function of acceptance angle

At 16% MEPV module efficiency, the optics need to be designed at less than 20-200X to keep tracker prices below the $1/$W_p$ system price threshold

At 40% module efficiency, the price for coarse 2-axis trackers can be reduced to $0.25-$0.45/W_p at a concentration level of 20-200X

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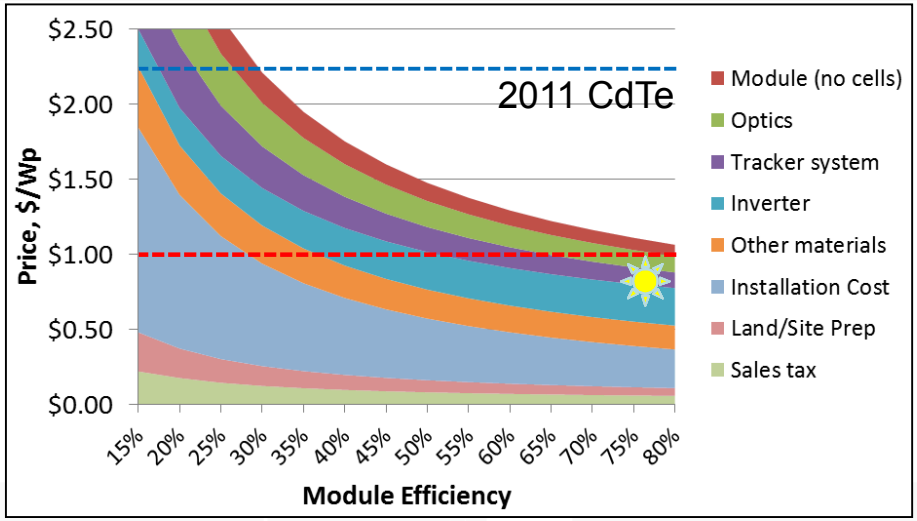
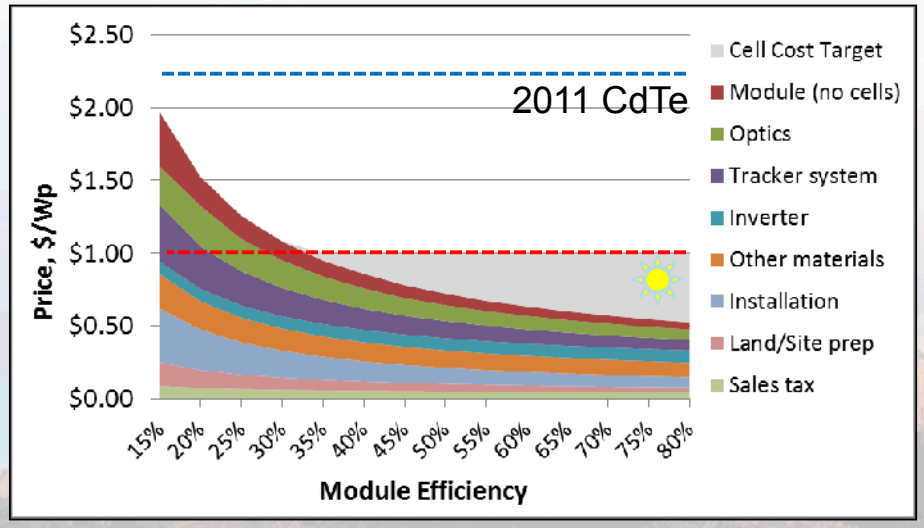
Sources: PV News, July 2011; NREL presentation at CPV Workshop, Santa Barbara, July 2012.

System Price Breakdown Without MEPV Cells 2012 and 2020

2012 Cost Estimates – 100X Concentration, 250 µm cells



2020 Cost Estimates – 100X Concentration, 250 µm cells



- System price breakdown minus MEPV cells as function of module efficiency
- Calculation done capacity factors in Las Vegas, NV
- Price done for a power utility obtaining a turn key MEPV system

While it is impossible to attain the $1/W$_p$ system price target today, it is possible to do so by the year 2020 by hitting specific efficiency and cost targets

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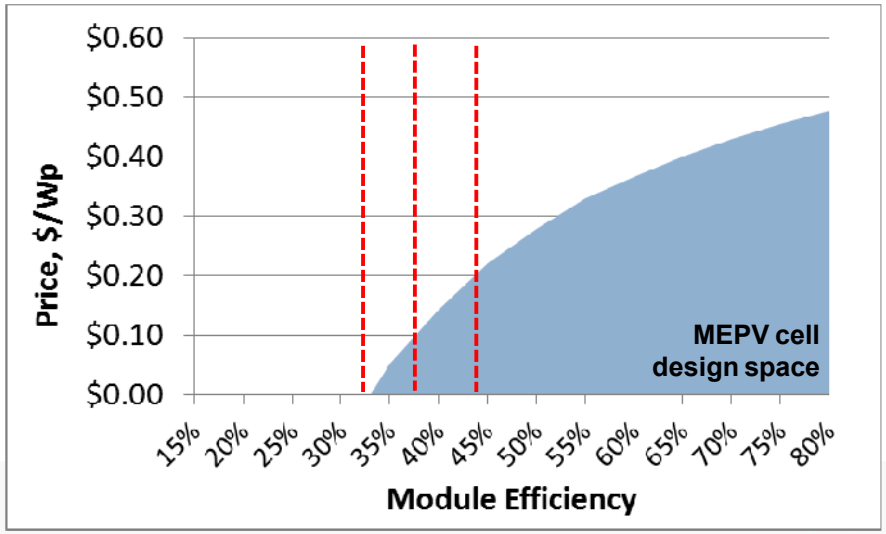
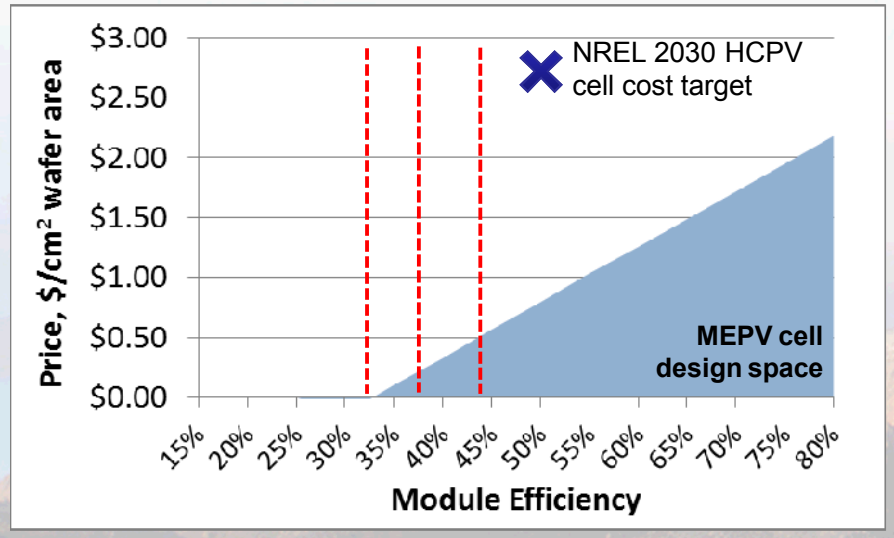
Capacity factor of 0.201 for fixed CdTe modules, 0.249 for CdTe modules on 1-axis trackers, and 0.288 for MEPV on 2-axis trackers

Maximum MEPV Cell Prices to Achieve $1/W$_p$ SunShot System Price Target

100X concentration, 250 μm cells





- For each MEPV cell stack design, these plots set the boundaries for the maximum $/W$_p$ prices as a function of module efficiency
- Also useful for assessing the merits and demerits of each MEPV cell layer in the stack
- Only applicable for utility-scale CPV applications; MEPV cell design space is larger for weight and area constrained applications (e.g., outer space, military)

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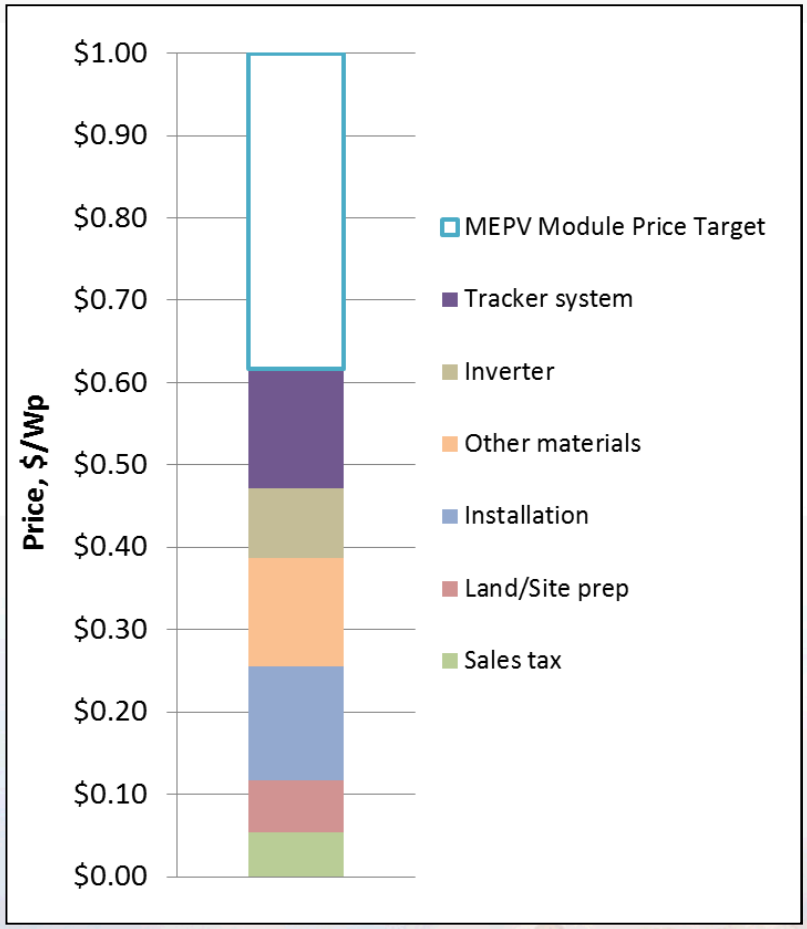
Year 2 Pursuits in Cost Modeling



MEPV System Price Breakdown

- Quantify the $\$/W_p$ and LCOE system impact of different MEPV cell stack designs
- Produce MEPV multi-junction cell cost vs. efficiency graphs for system designers
- Estimate the impact of capturing diffuse light
- Conduct an "audit" of the calculations within the MEPV Modular Cost Model
- Publish and present MEPV Prototype 1 & 2 Cost Modeling to peers
- Model cost impact of MEPV-enabled inverter designs as well as BoS components simplified by MEPV
- Set cost boundaries on Prototype 3 design through iterative wrestling