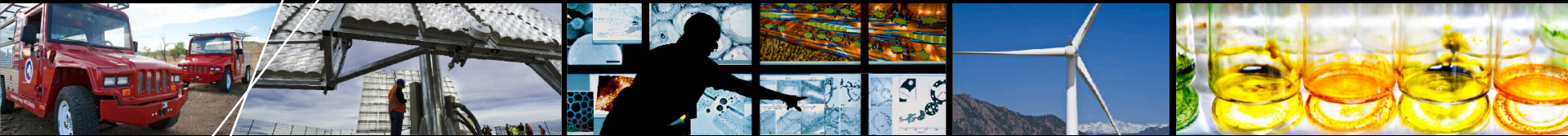


# Cost Model Results for Several PV Technologies



**Michael Woodhouse, Robert Margolis,  
Ted L James, David Feldman, and Alan Goodrich**

**Analysis Results from The Strategic Energy Analysis  
Center and The National Center for Photovoltaics**

**2012 Scialog Workshop at Biosphere 2**

# Analysis Disclaimer

## DISCLAIMER AGREEMENT

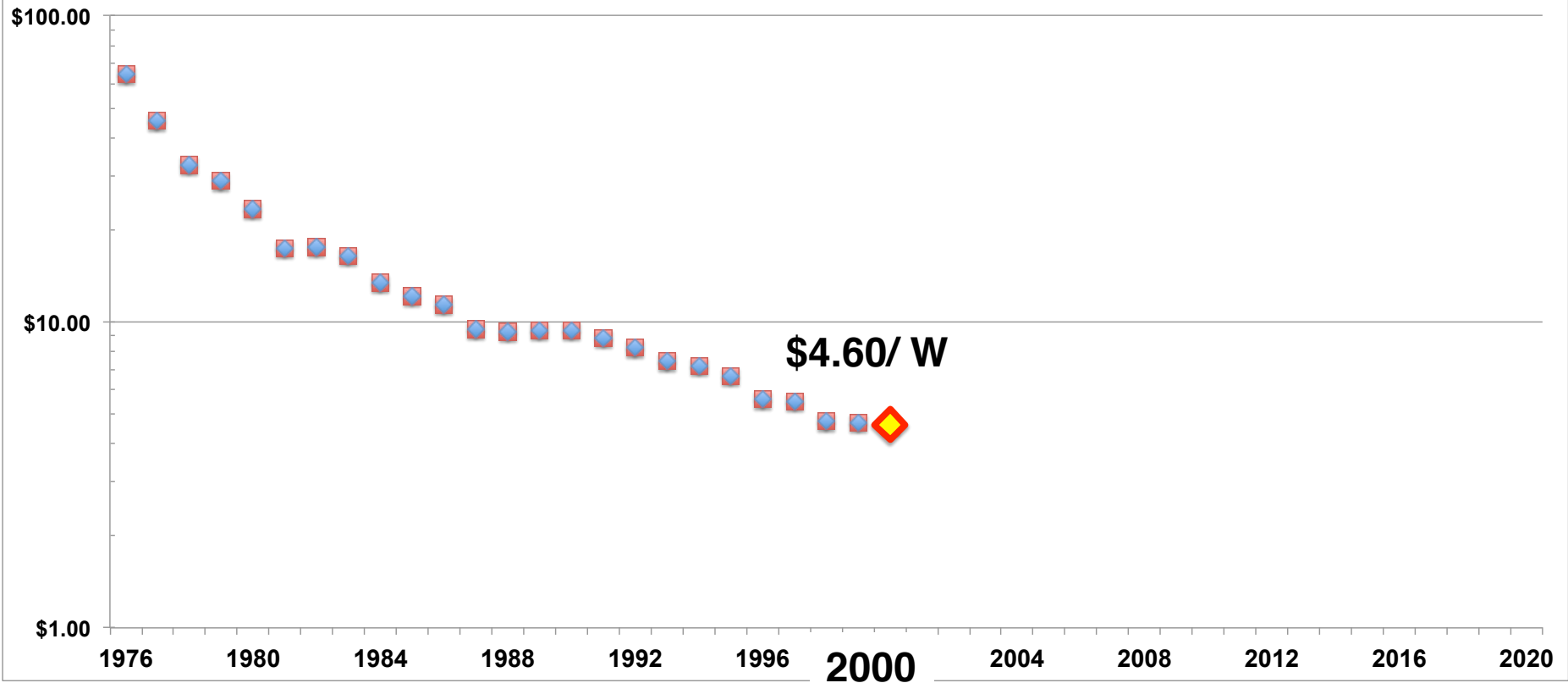
These manufacturing cost model results (“Data”) are provided by the National Renewable Energy Laboratory (“NREL”), which is operated by the Alliance for Sustainable Energy LLC (“Alliance”) for the U.S. Department of Energy (the “DOE”).

It is recognized that disclosure of these Data is provided under the following conditions and warnings: (1) these Data have been prepared for reference purposes only; (2) these Data consist of forecasts, estimates or assumptions made on a best-efforts basis, based upon present expectations; and (3) these Data were prepared with existing information and are subject to change without notice.

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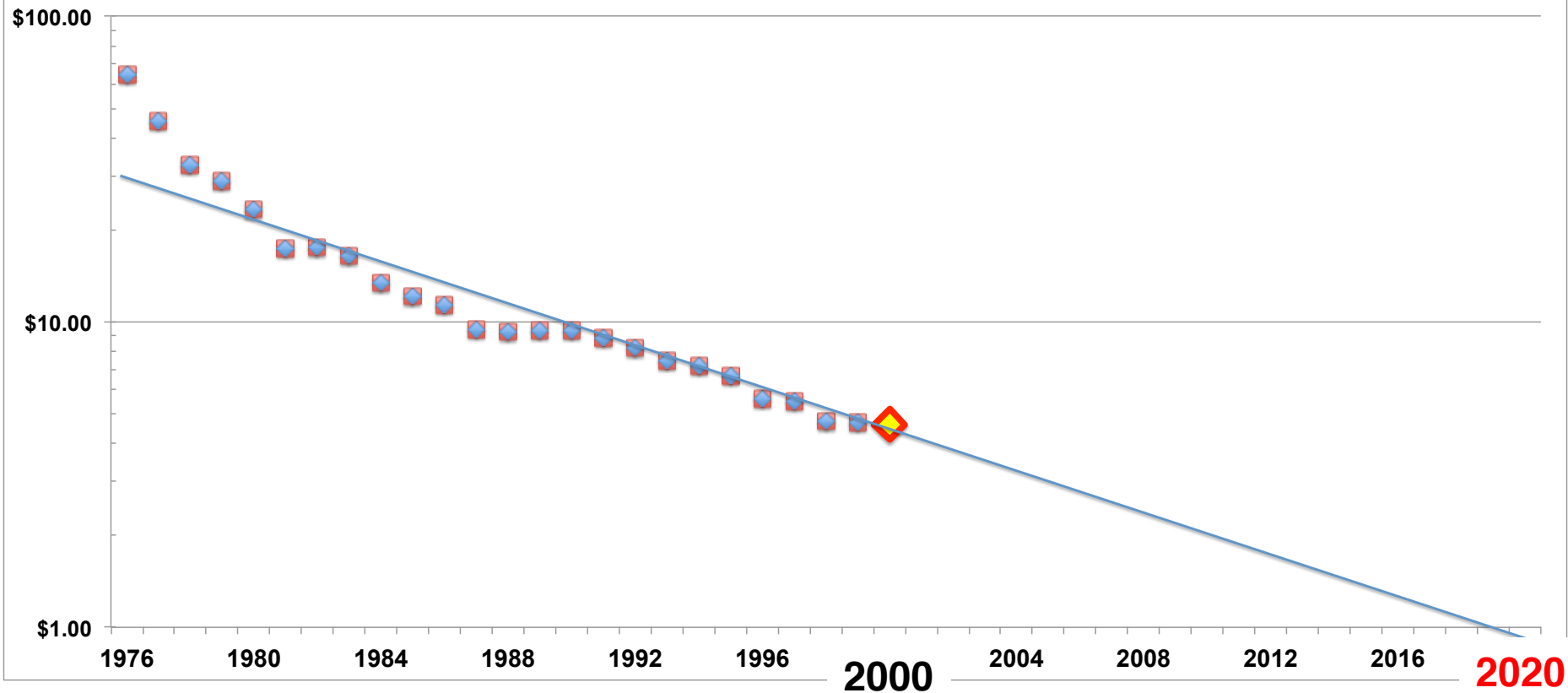
**YOU AGREE TO INDEMNIFY DOE/NREL/ALLIANCE, AND ITS AFFILIATES, OFFICERS, AGENTS, AND EMPLOYEES AGAINST ANY CLAIM OR DEMAND, INCLUDING REASONABLE ATTORNEYS' FEES, RELATED TO YOUR USE, RELIANCE, OR ADOPTION OF THESE DATA FOR ANY PURPOSE WHATSOEVER. THESE DATA ARE PROVIDED BY DOE/NREL/ALLIANCE "AS IS" AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE EXPRESSLY DISCLAIMED. IN NO EVENT SHALL DOE/NREL/ALLIANCE BE LIABLE FOR ANY SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES OR ANY DAMAGES WHATSOEVER, INCLUDING BUT NOT LIMITED TO CLAIMS ASSOCIATED WITH THE LOSS OF DATA OR PROFITS, WHICH MAY RESULT FROM AN ACTION IN CONTRACT, NEGLIGENCE OR OTHER TORTIOUS CLAIM THAT ARISES OUT OF OR IN CONNECTION WITH THE USE OR PERFORMANCE OF THESE DATA.**

Historical Prices for PV Modules from a 2000 Vantage Point

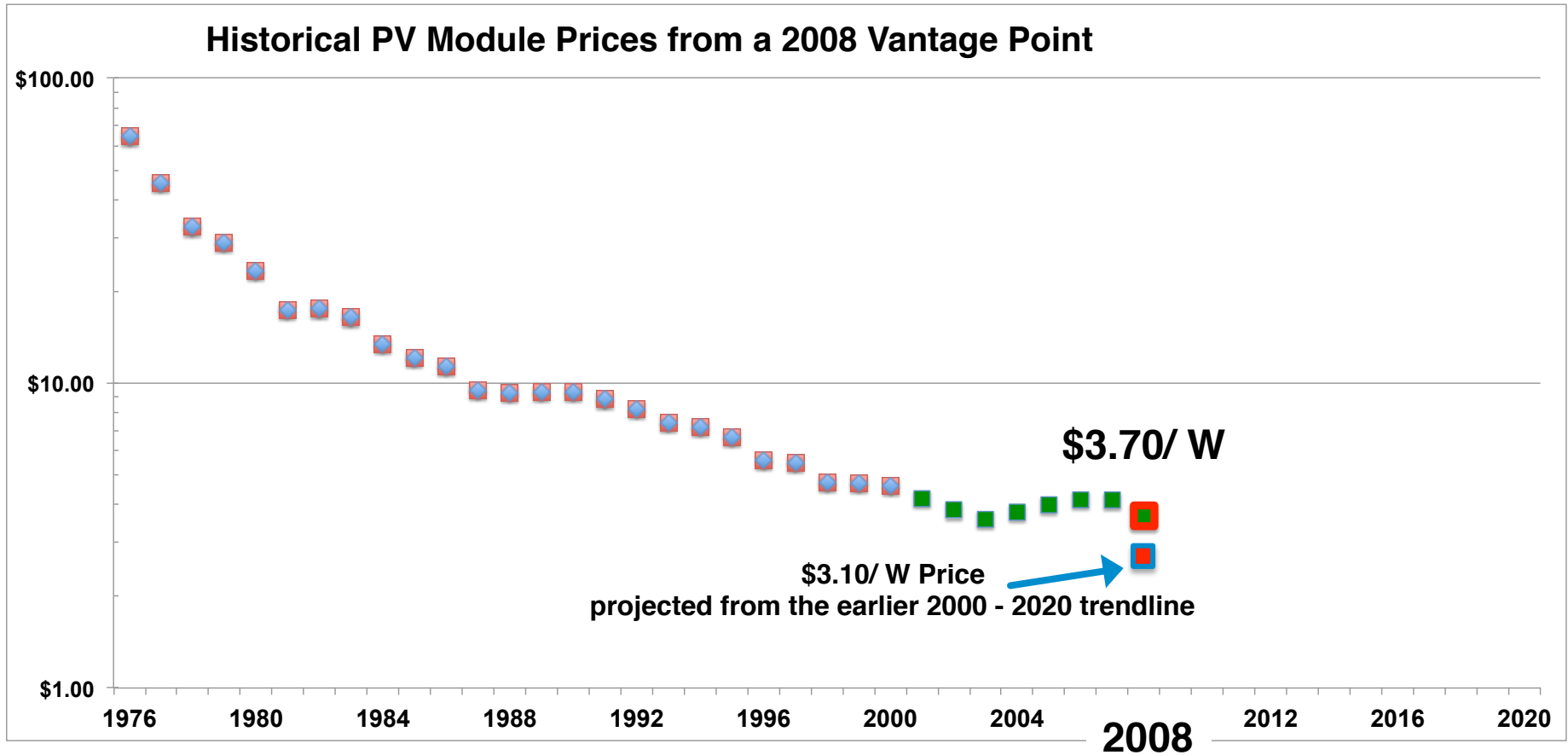


A logical strategy question for the time: When will the prevailing market price for PV modules be  $\approx \$1/W$ ?

## Historical and Conceivable PV Module Prices from a 2000 Vantage Point

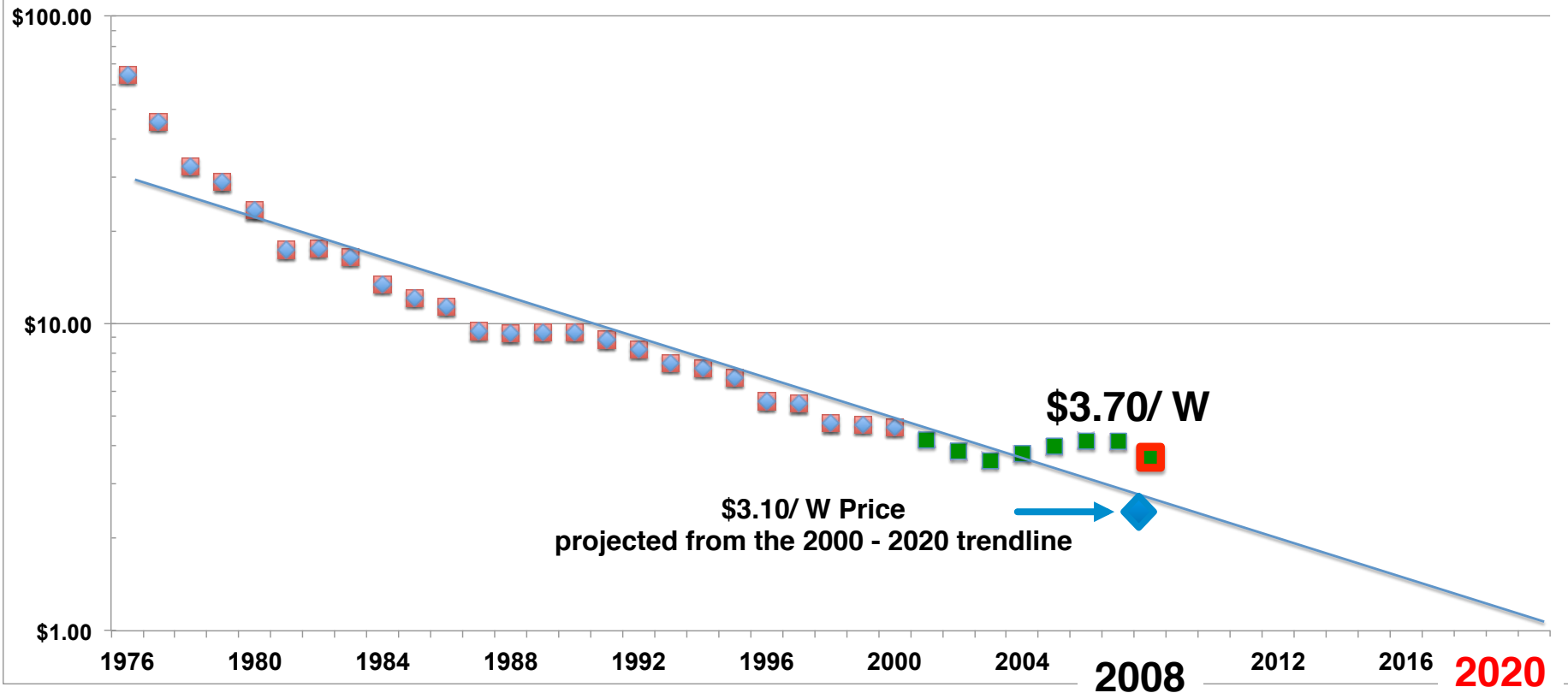


**Answer: Looks like circa 2020.**



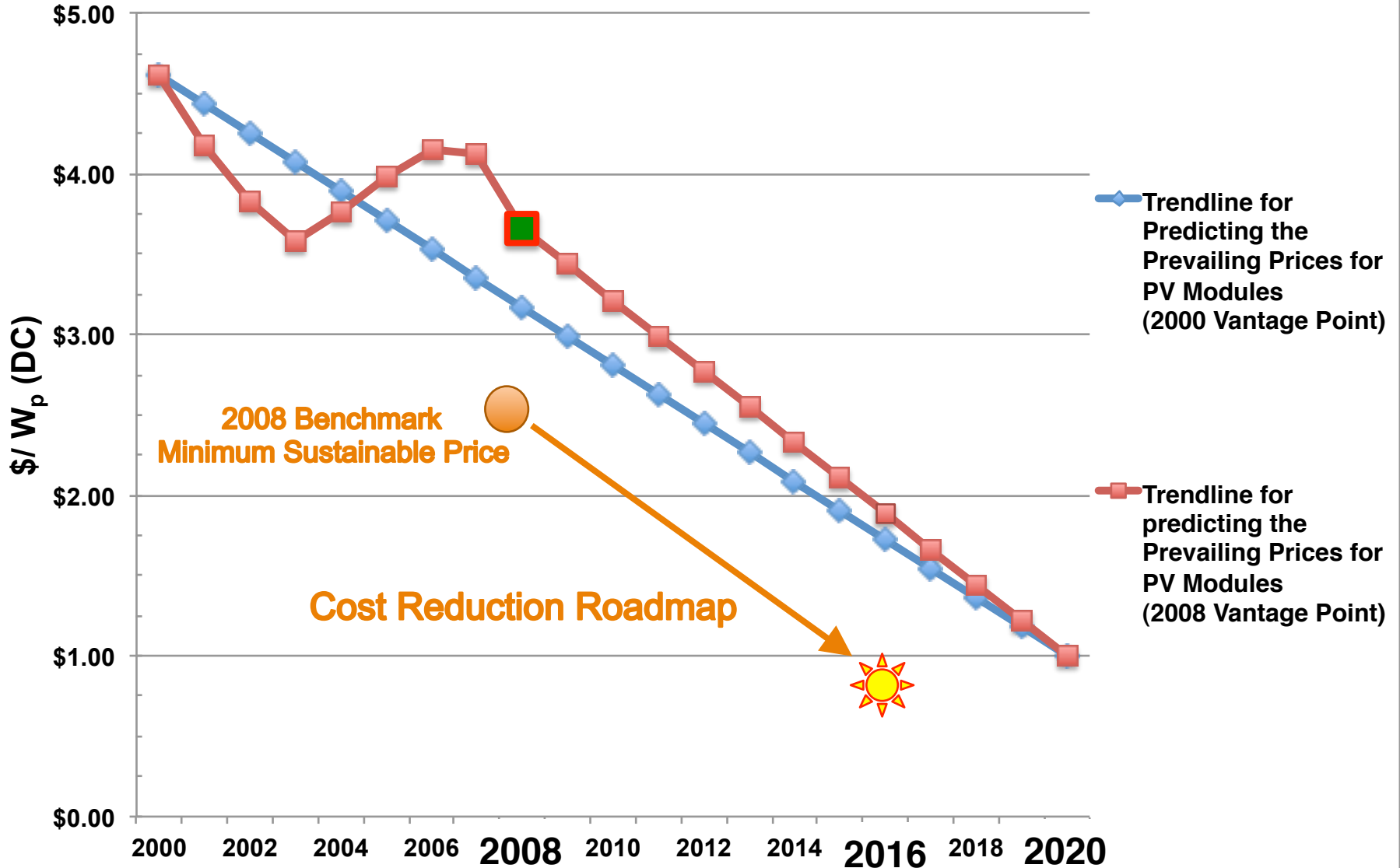
**The same logical strategy question at the time: When will the prevailing market price for PV modules be  $\approx$ \$1/ W?**

# Historical and Conceivable PV Module Prices from a 2008 Vantage Point

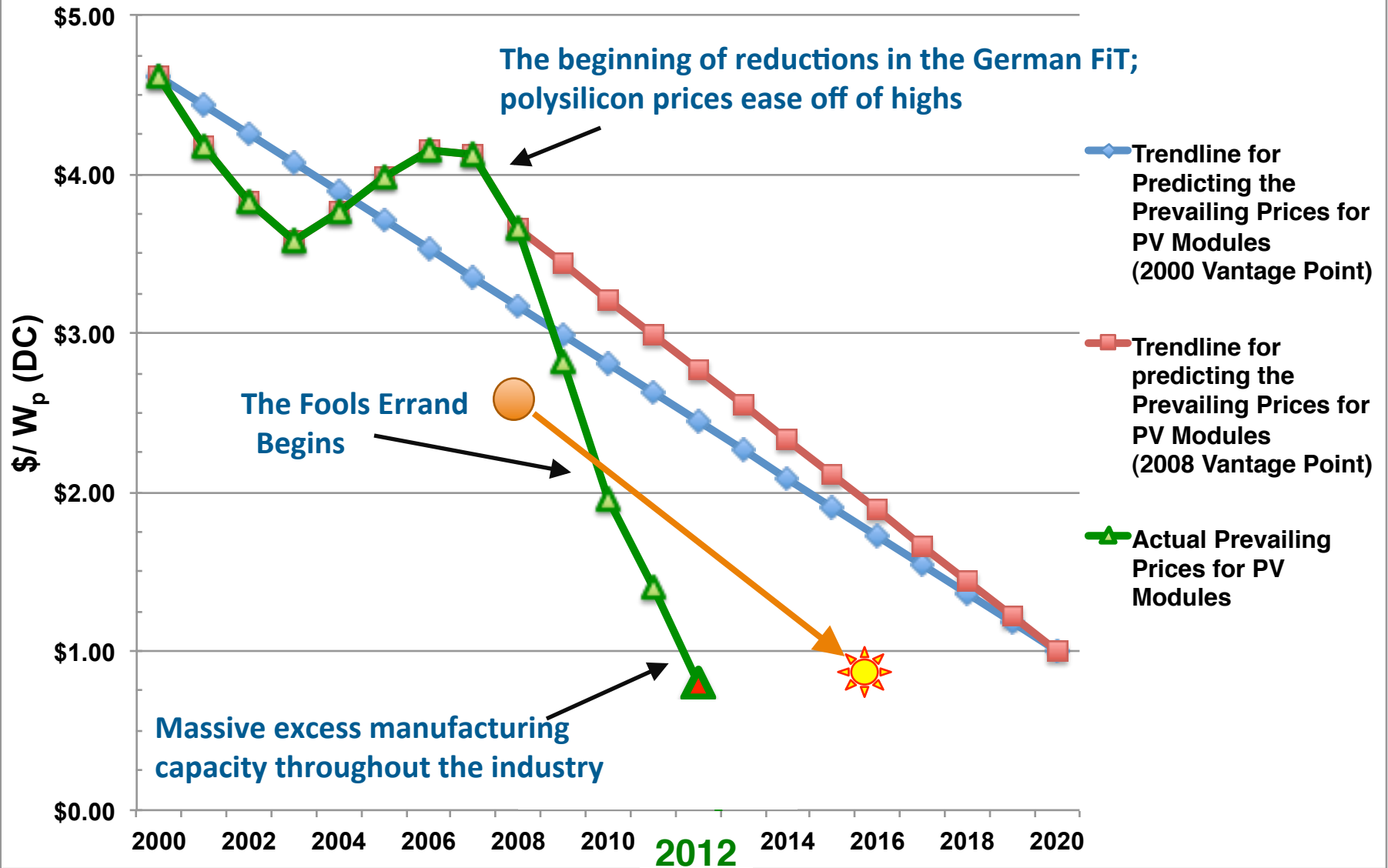


**Answer: Looks like circa 2020.**

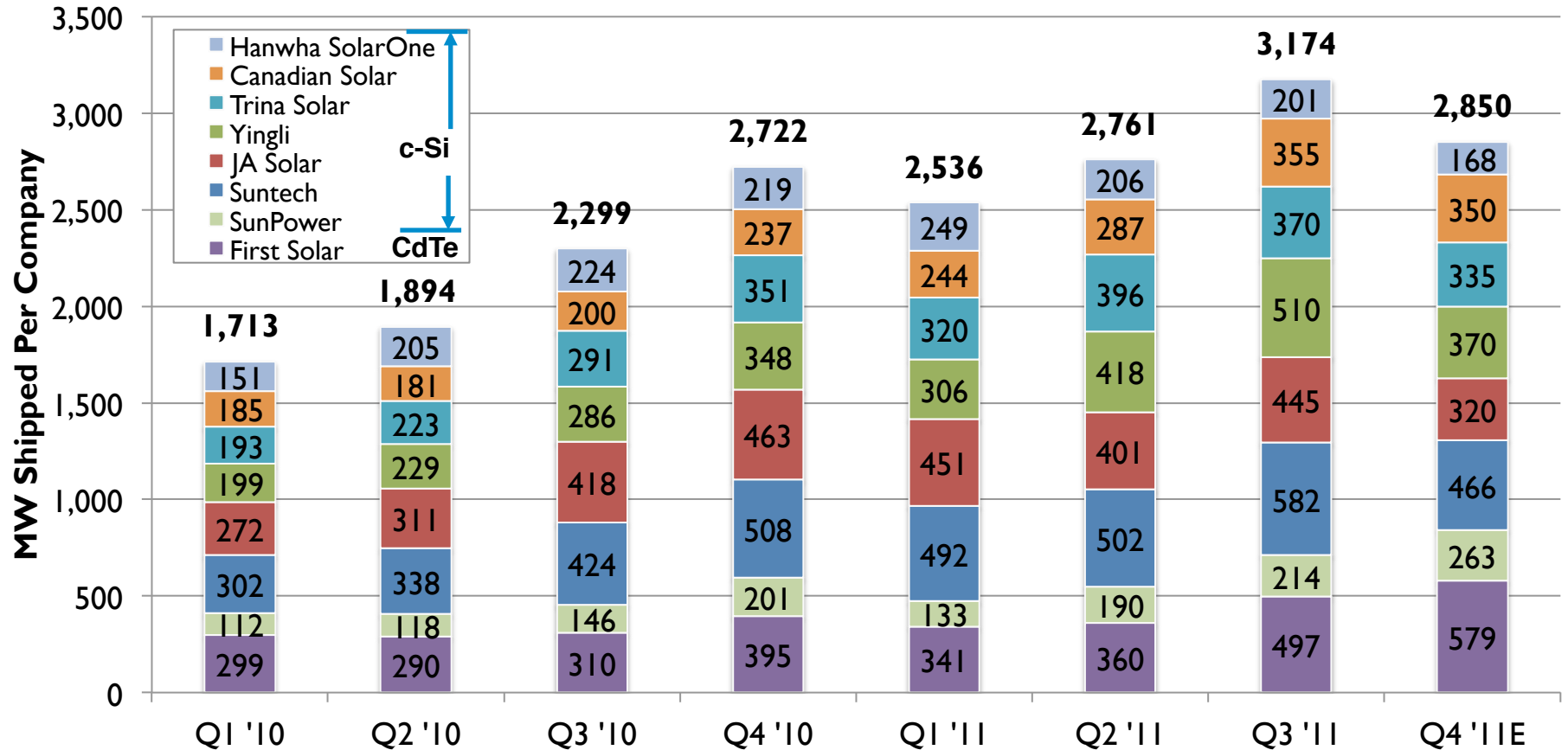
# A Perfectly Reasonable Business Plan for 2008



# And Then the Unexpected Happened

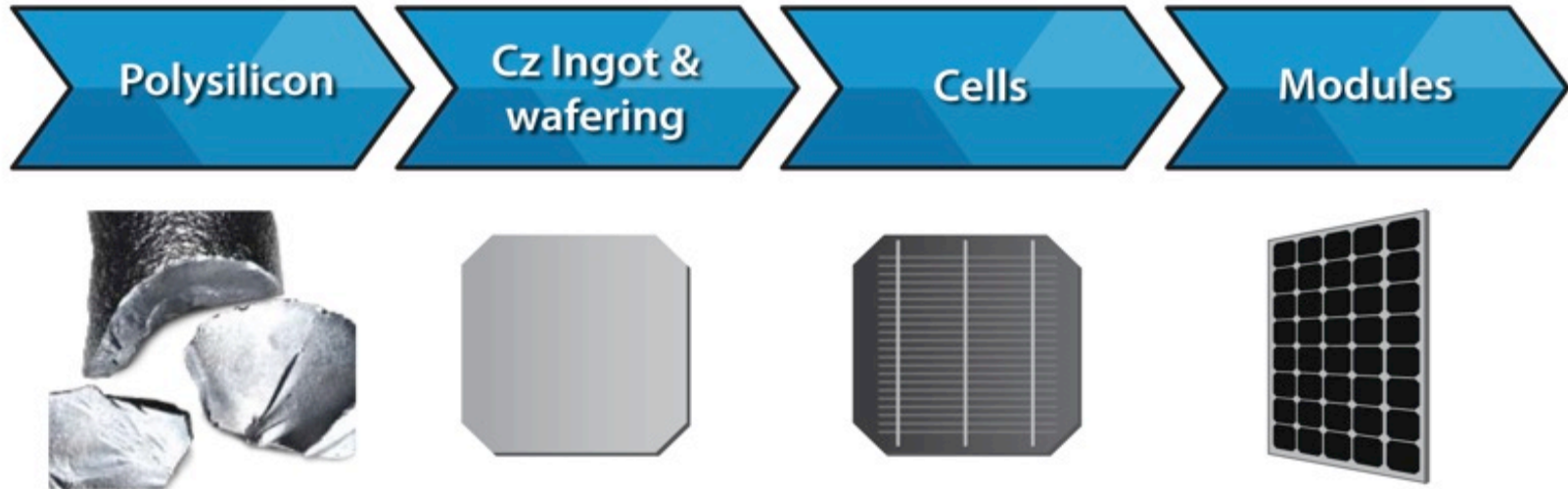


# The leading PV Cell/Module Manufacturers in 2010 and 2011



All figures are based on SEC filings by the respective companies, except for First Solar in Q4 '11. Q4 '11 First Solar shipments based on medium of projections from Citi (11/4/11), Cowen & Co. (11/4/11), Deutsche Bank (11/4/11), Piper Jaffray (11/4/11), Stifel Nicolaus (11/4/11), UBS (11/4/11).

# The c-Si Module Supply Chain

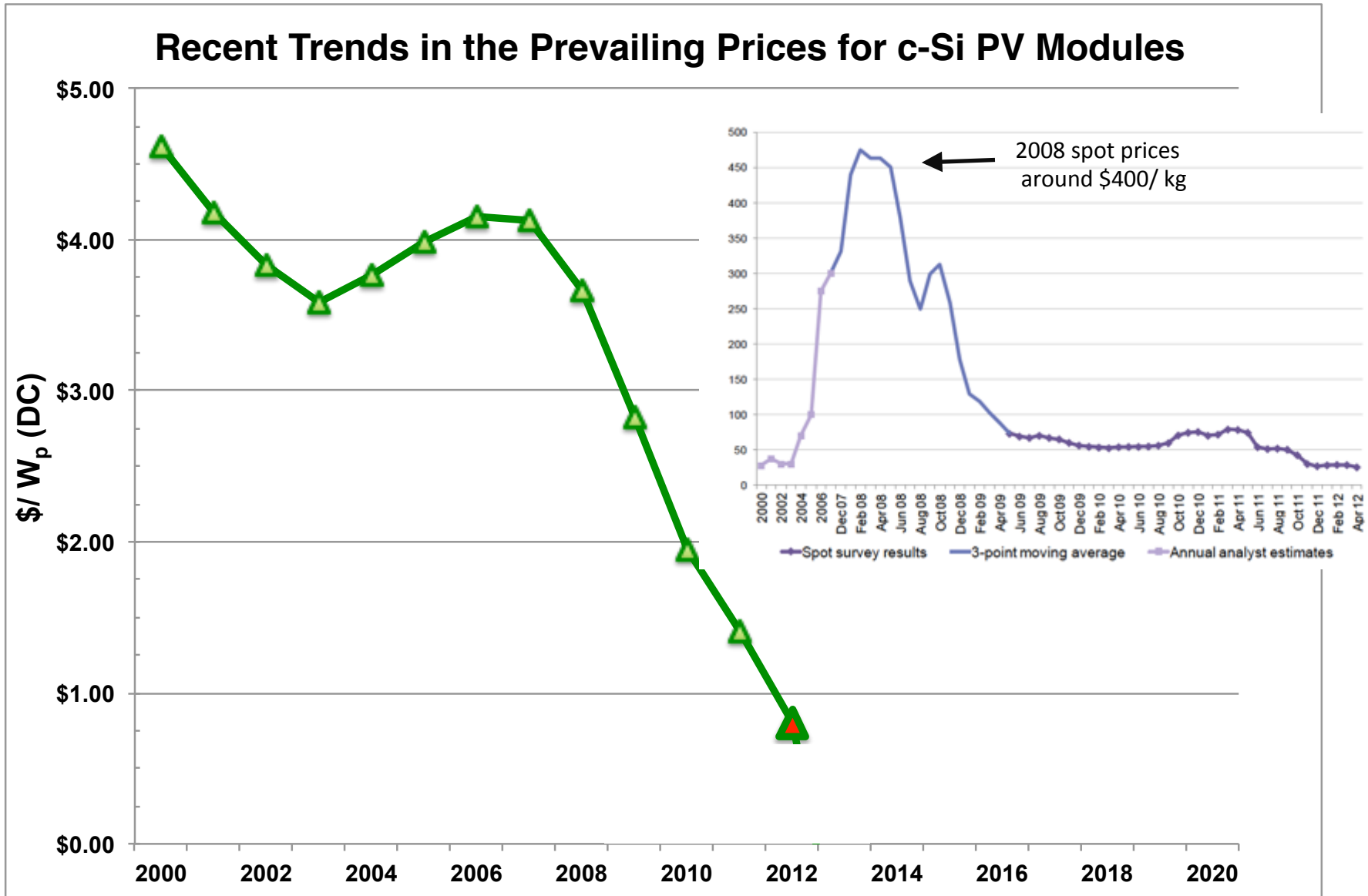


**Total Module Costs =  $\sum$  Minimum Sustainable Prices for Each Upstream Material**

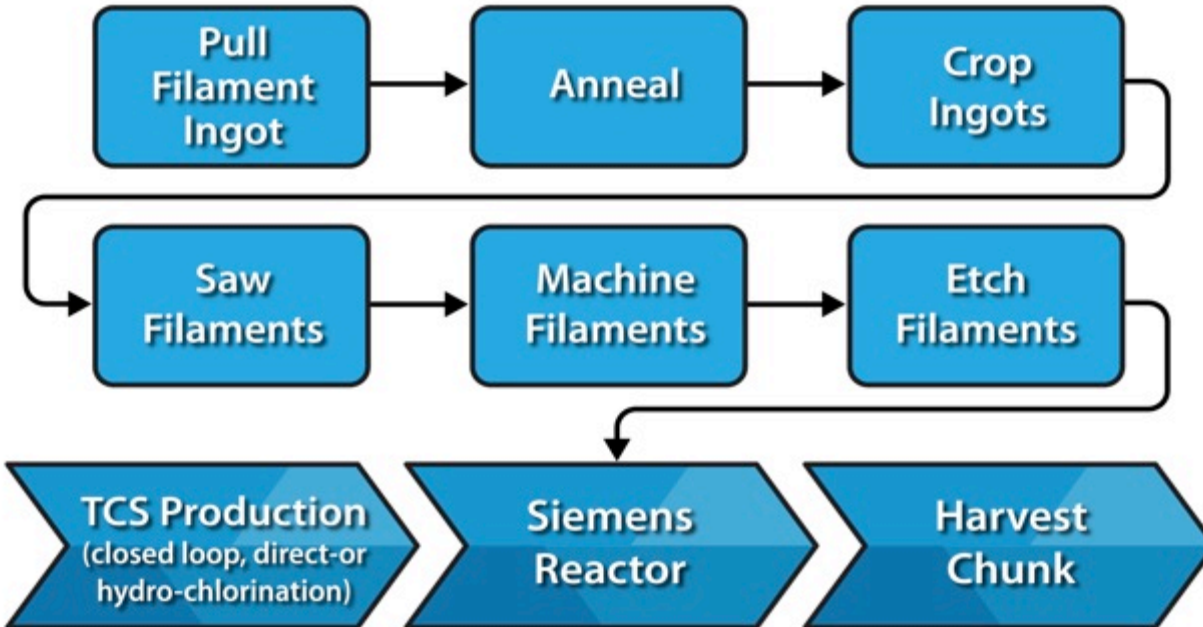
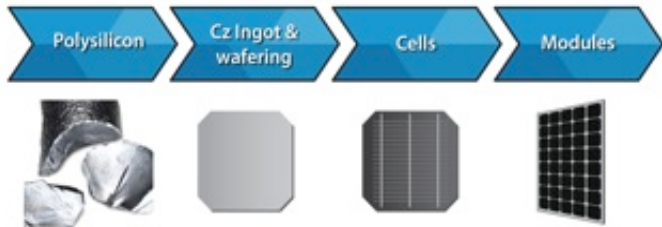
Goodrich, A.; Hacke, P.; Wang, Q.; Sopori, B.; Margolis, R.; James, T.; Woodhouse, M.,  
***“A Wafer-Based Monocrystalline Silicon Photovoltaics Road Map: Utilizing Known Technology Improvement Opportunities for Further Reductions in Manufacturing Costs,”***  
provisionally accepted by *Solar Energy Materials and Solar Cells*.

Also available if requested by email: [alan.goodrich@nrel.gov](mailto:alan.goodrich@nrel.gov), [michael.woodhouse@nrel.gov](mailto:michael.woodhouse@nrel.gov)

# The c-Si Module Supply Chain: Polysilicon



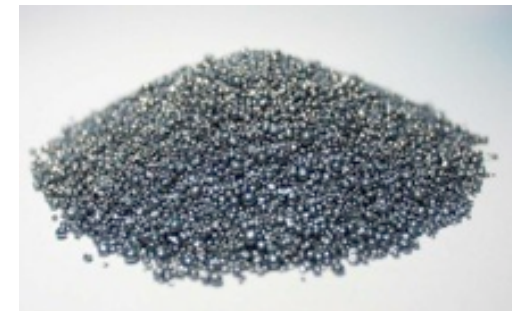
# The c-Si Module Supply Chain: Polysilicon



Siemens Chunk

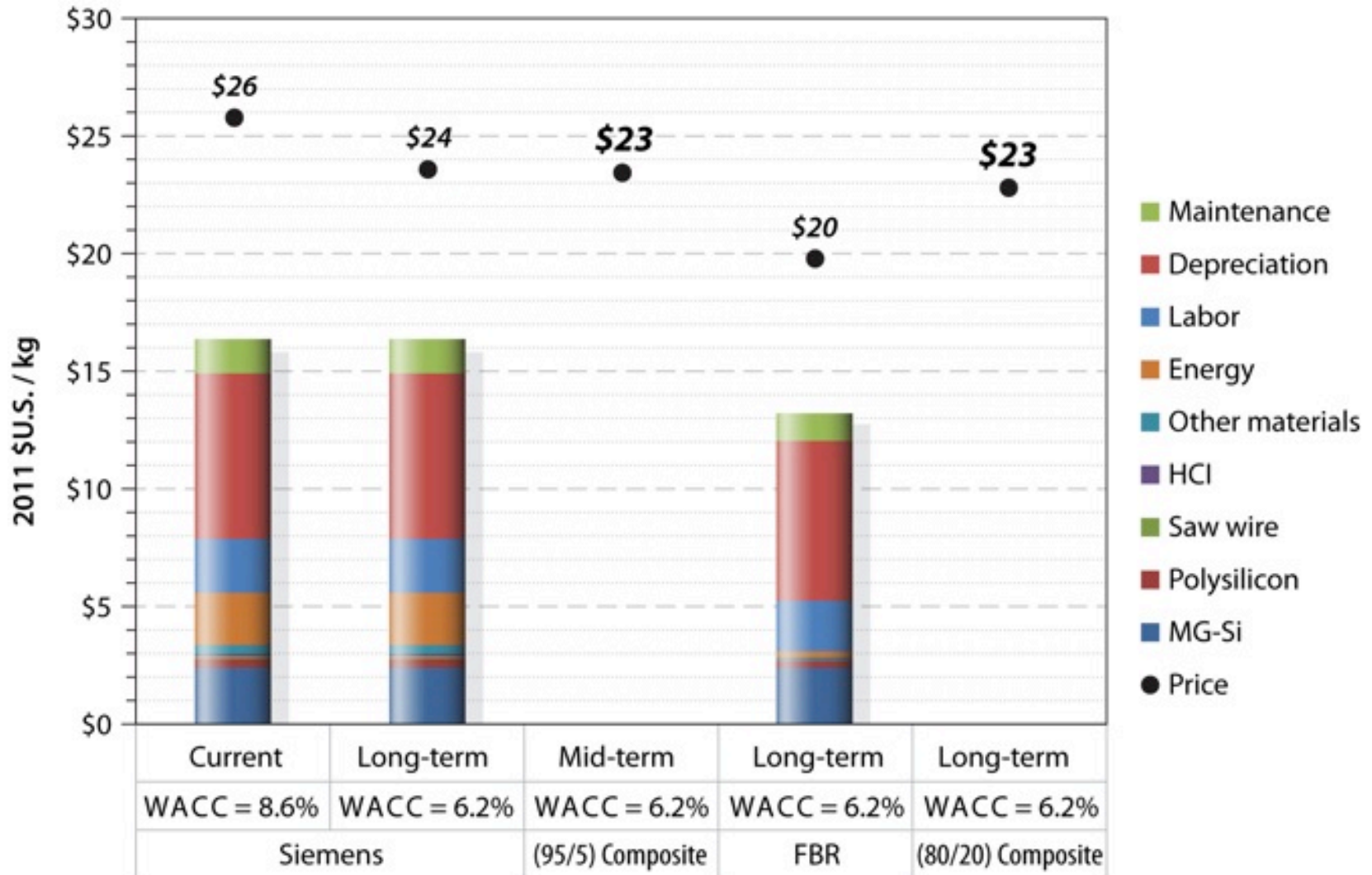


Fluidized bed granules

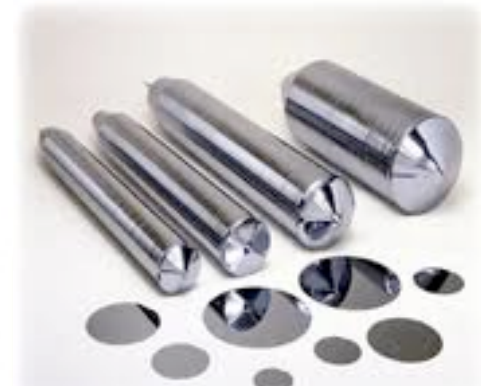
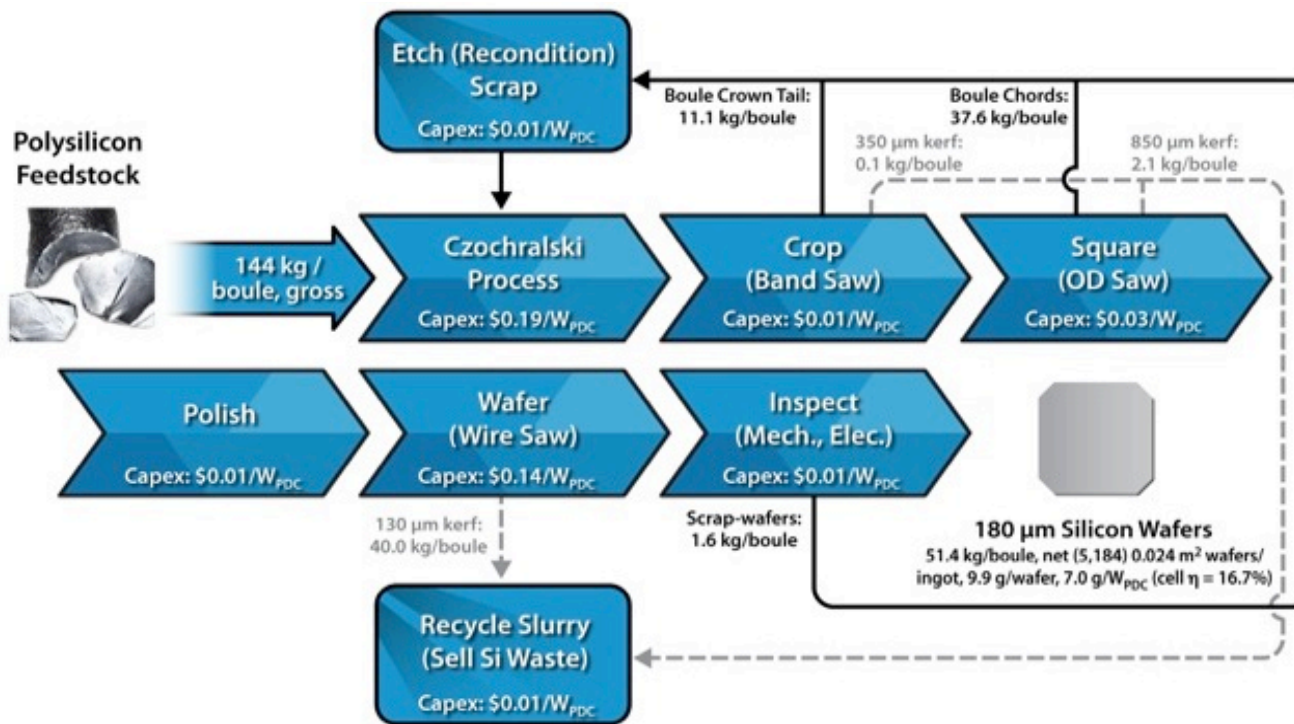


# The c-Si Module Supply Chain: Polysilicon

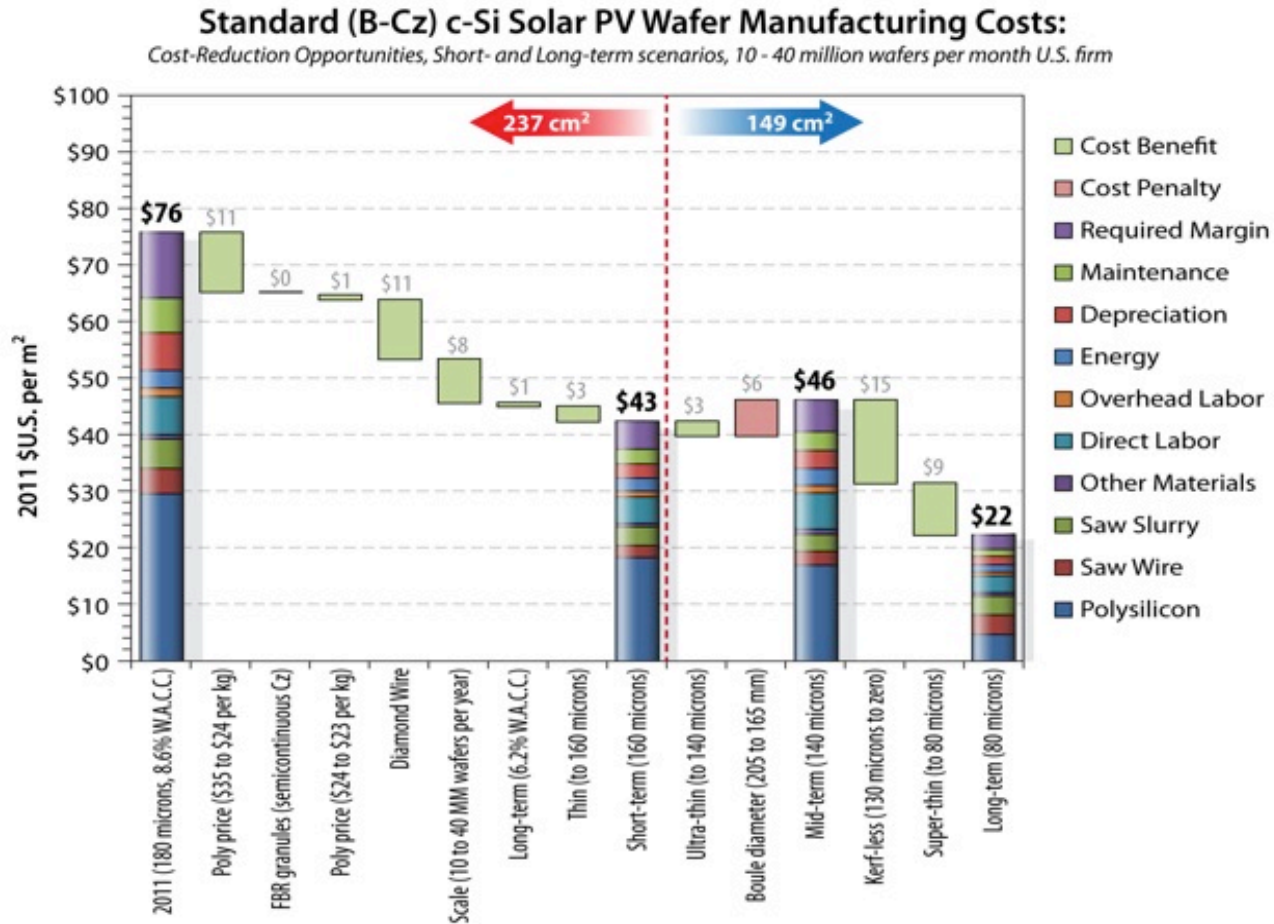
## U.S. Solar Grade Polysilicon: Direct Manufacturing Costs



# The c-Si Module Supply Chain: Wafers

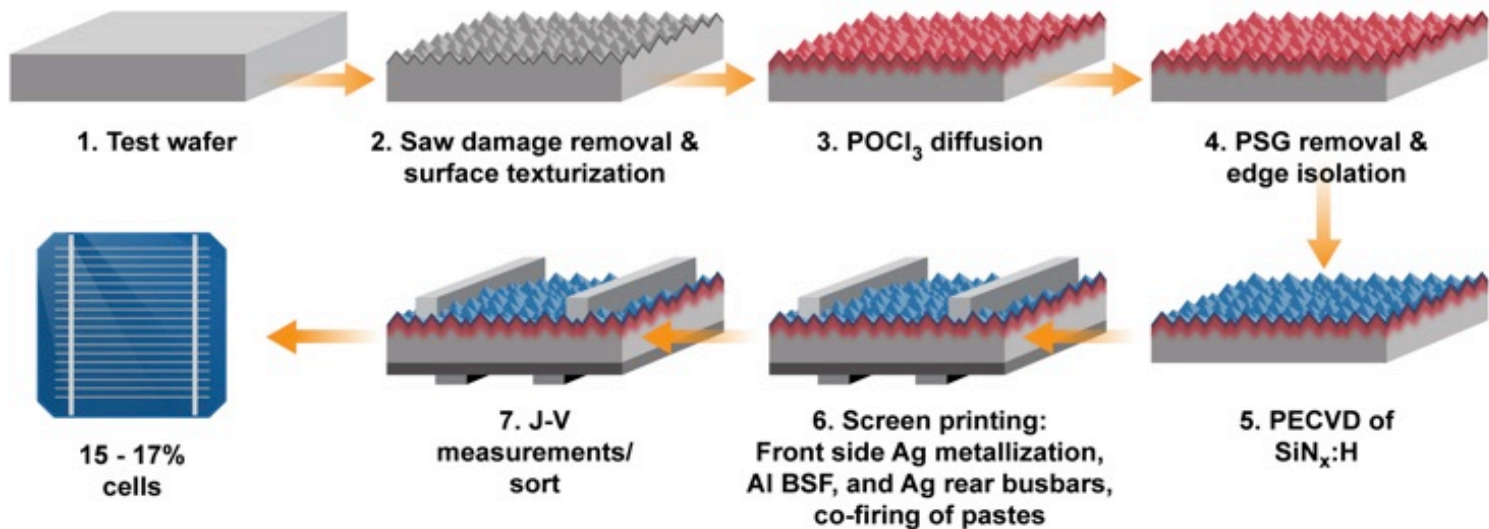


# The c-Si Module Supply Chain: Wafers

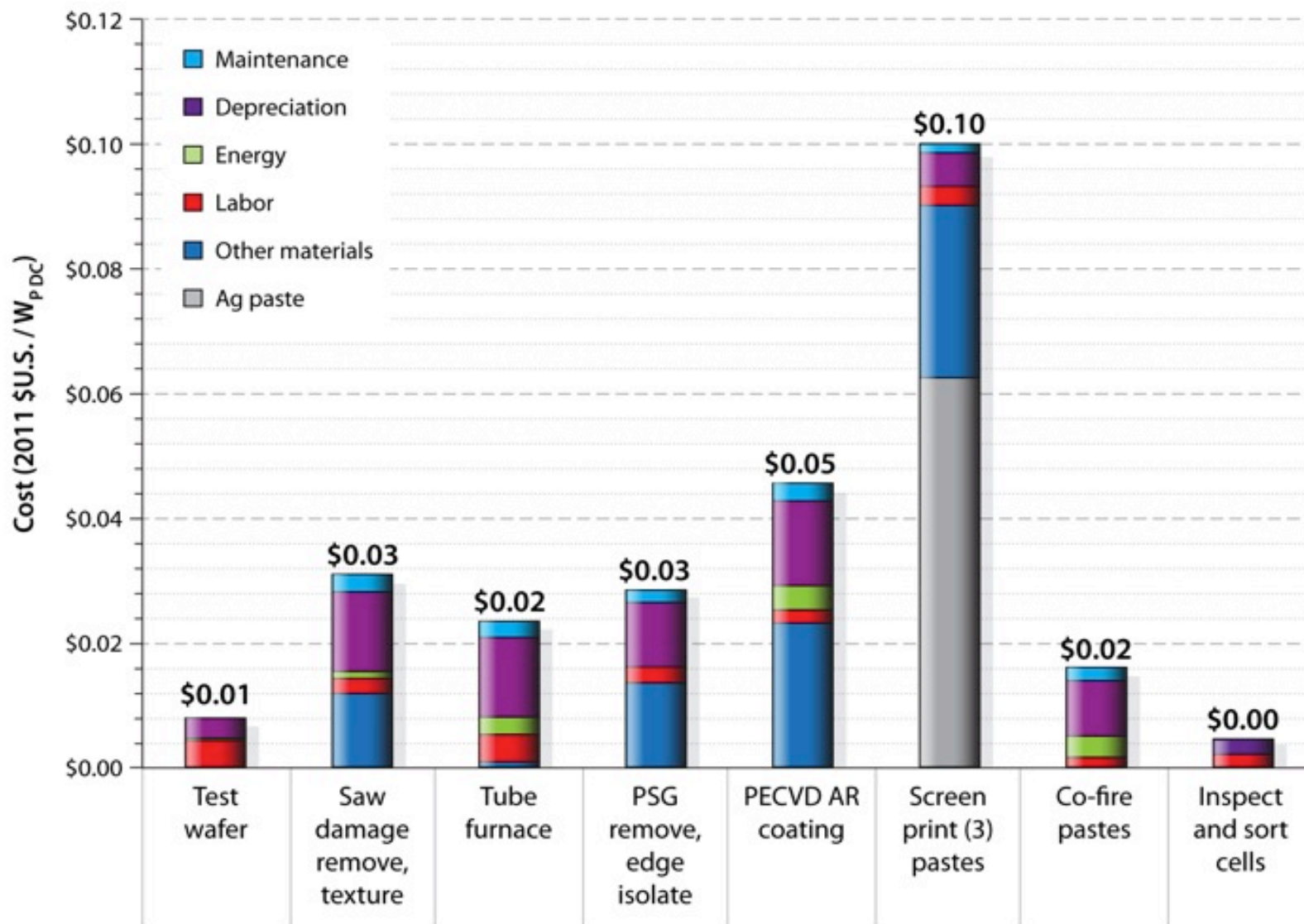


- Assumes perfect transfer of minimum sustainable polysilicon prices (e.g., a vertically integrated firm or consortium)
- Savings by eliminating kerf  $\approx$  \$15/ m<sup>2</sup> of wafers produced
- Savings for moving from 180  $\mu$ m to 80  $\mu$ m wafers  $\approx$  \$9/ m<sup>2</sup> of wafers produced.

# The c-Si Module Supply Chain: Making Standard Cells ( $\approx 17\%$ Efficiency)

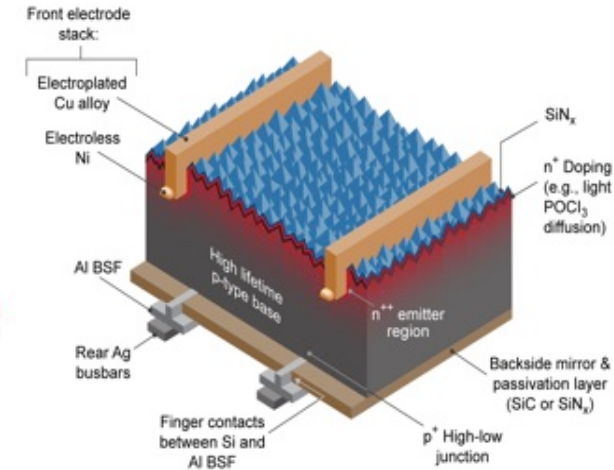
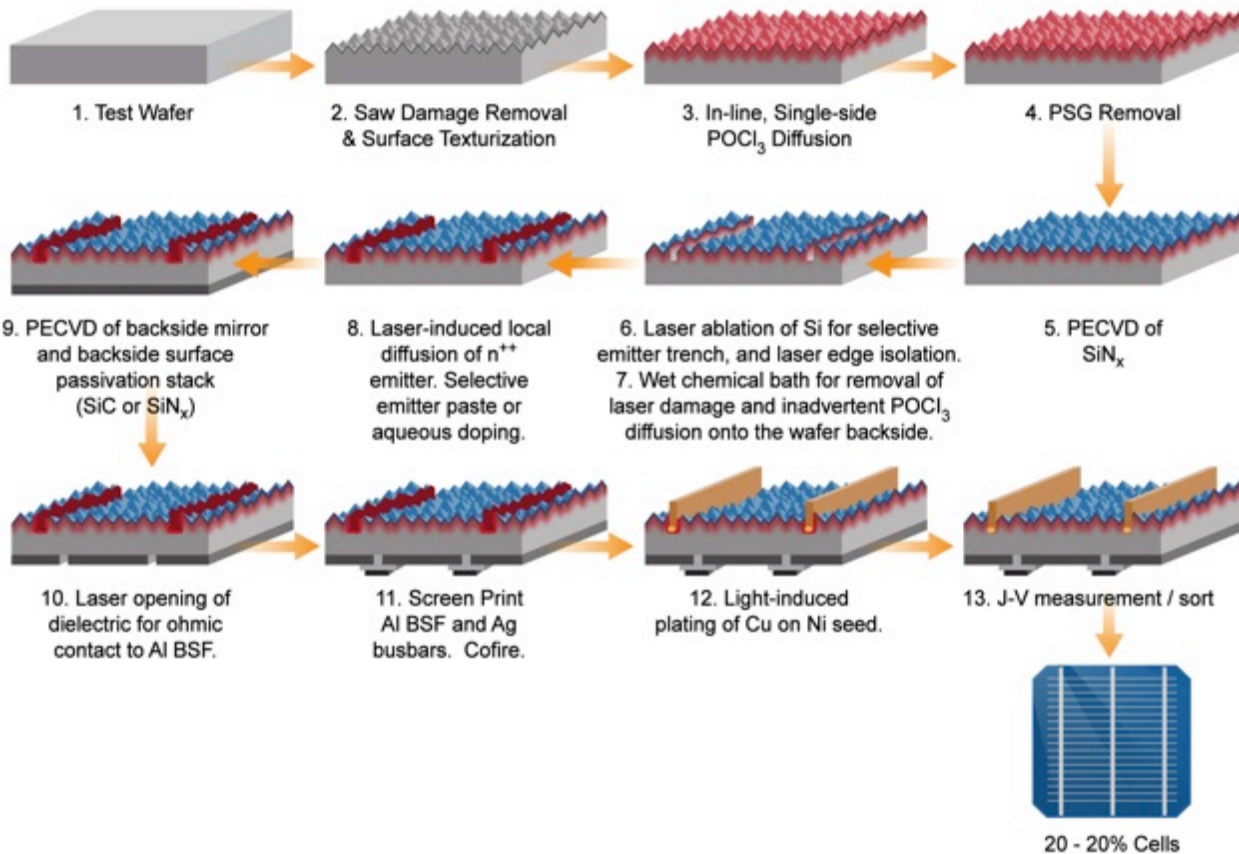


# Calculated Cost of Ownership for each step in the fabrication of Standard c-Si Solar Cells



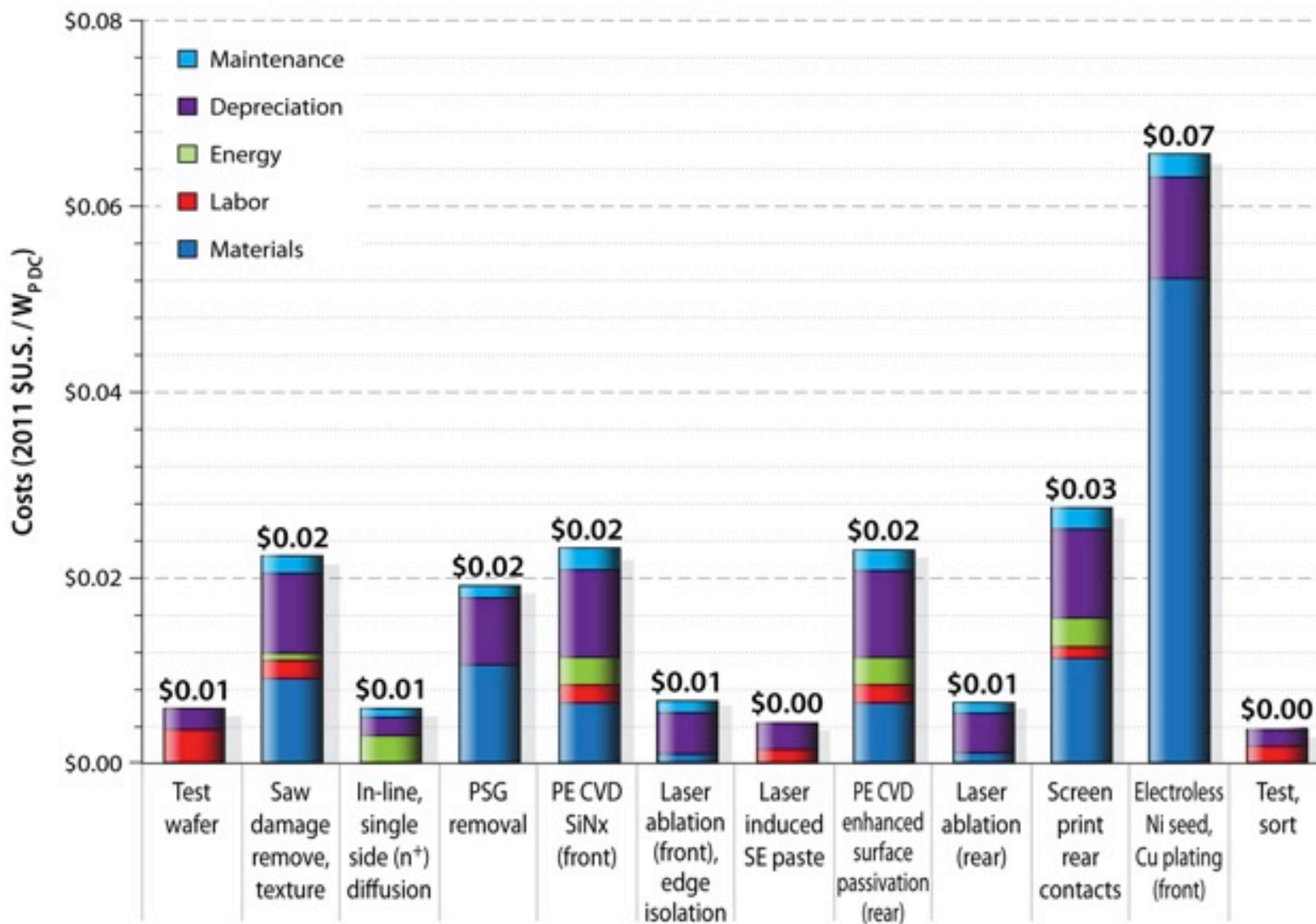
# The c-Si Module Supply Chain: Making Technology Group 1 Cells (20 - 22% Efficiency)

## Process Flow

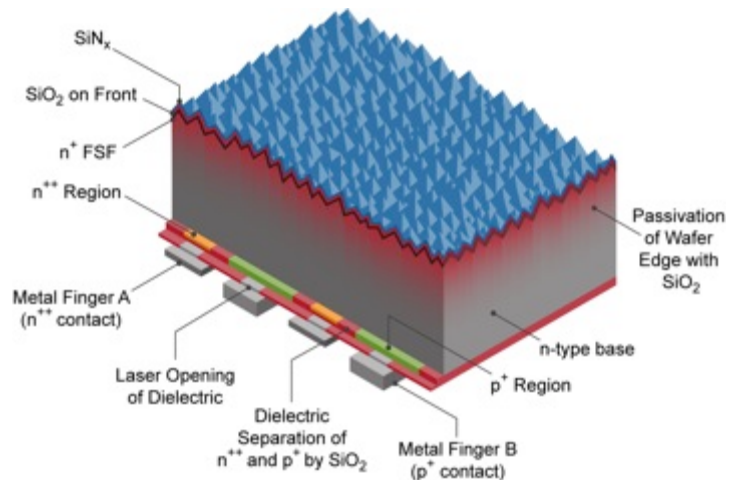


## Cell Architecture (PERC-like, with Selective Emitter)

# Calculated Cost of Ownership for each step in the fabrication of Technology Group 1 c-Si Solar Cells

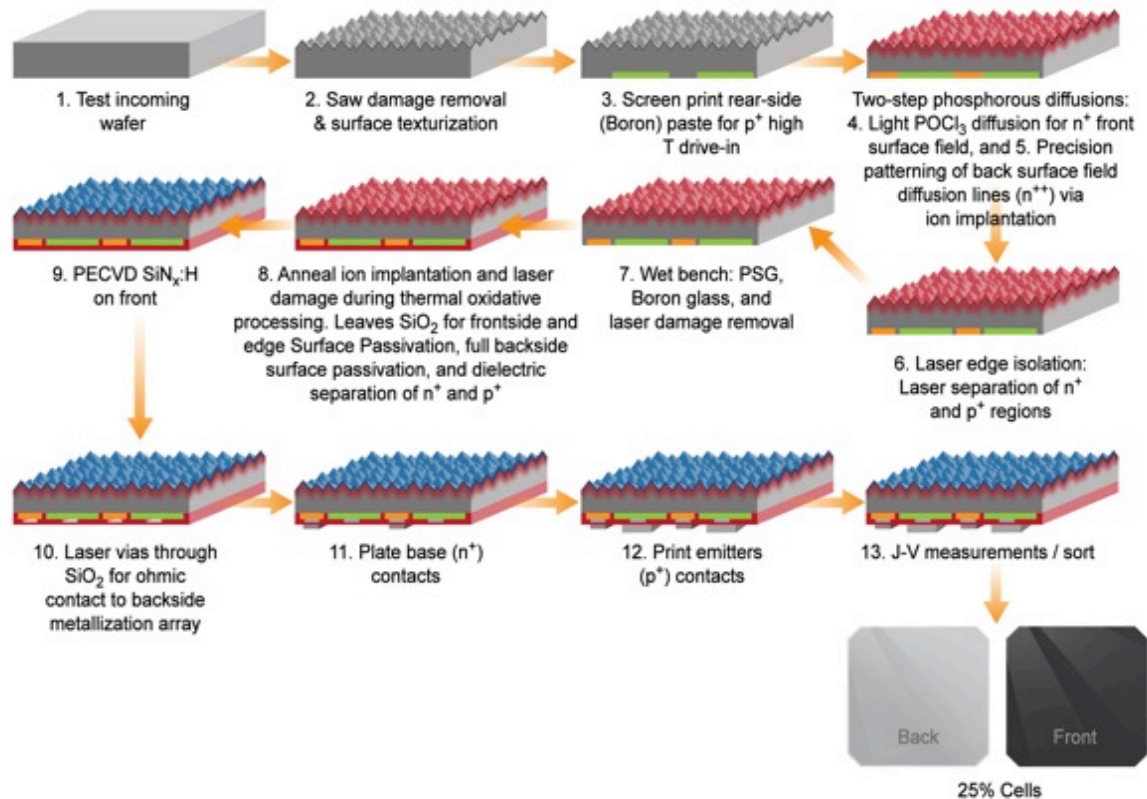


# The c-Si Module Supply Chain: Making Technology Group 2 Cells ( $\approx 25\%$ Efficiency)

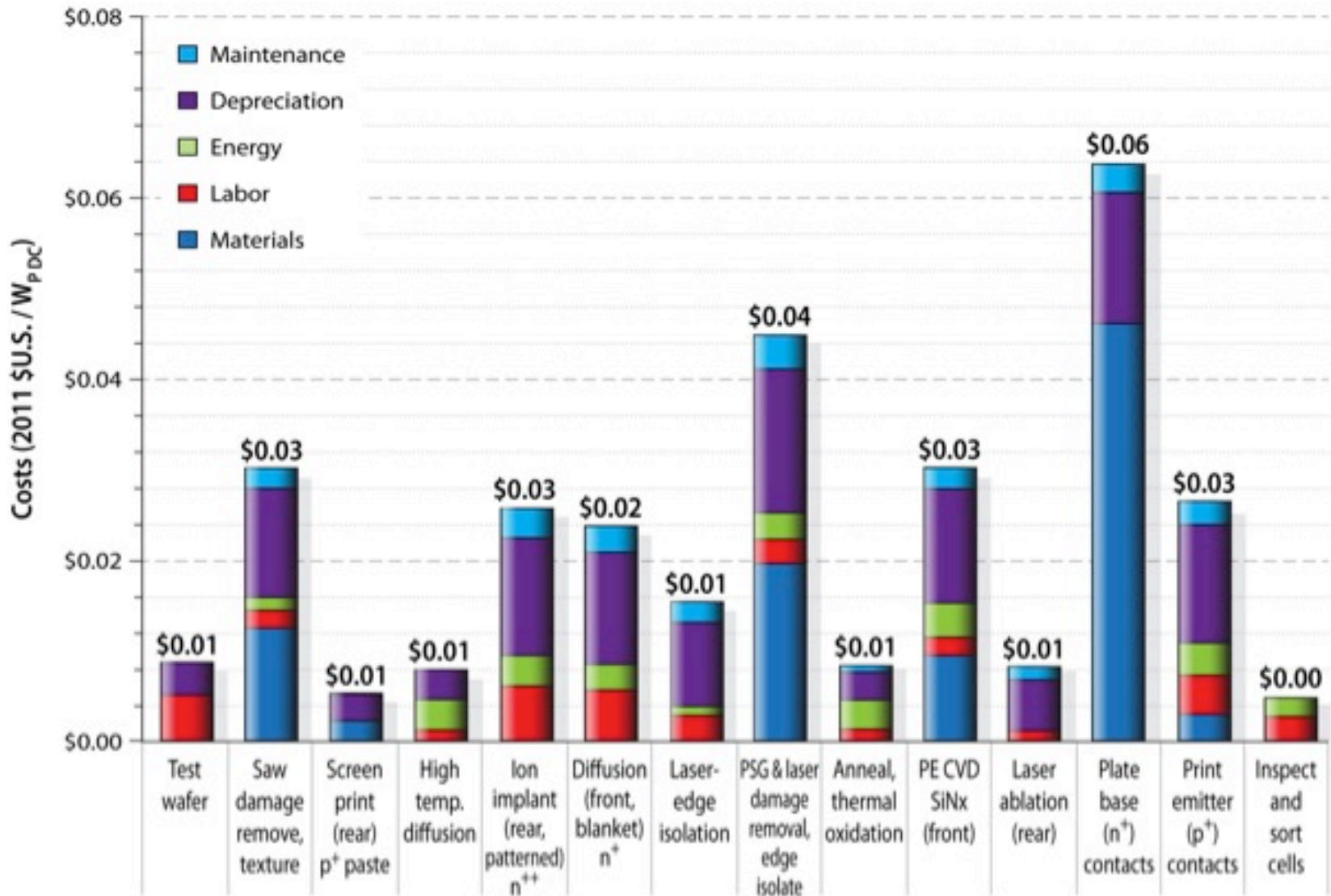


## Cell Architecture (Interdigitated Back Contact, or 'IBC')

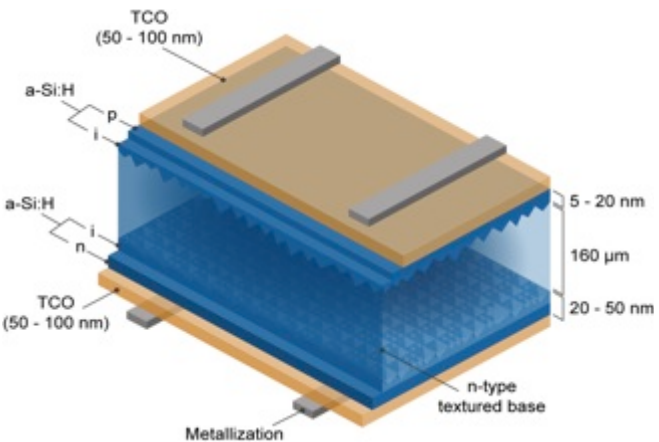
## Process Flow



# Calculated Cost of Ownership for each step in the fabrication of Technology Group 2 c-Si Solar Cells

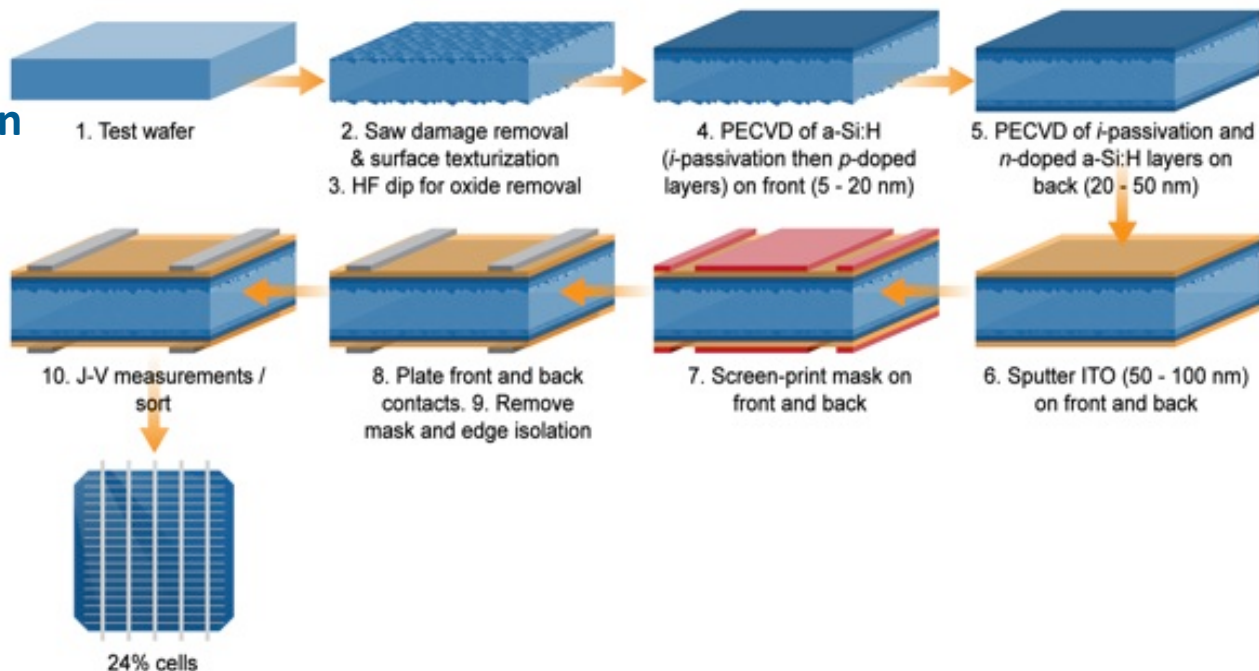


# The c-Si Module Supply Chain: Making Technology Group 3 Cells ( $\approx 24\%$ Efficiency)

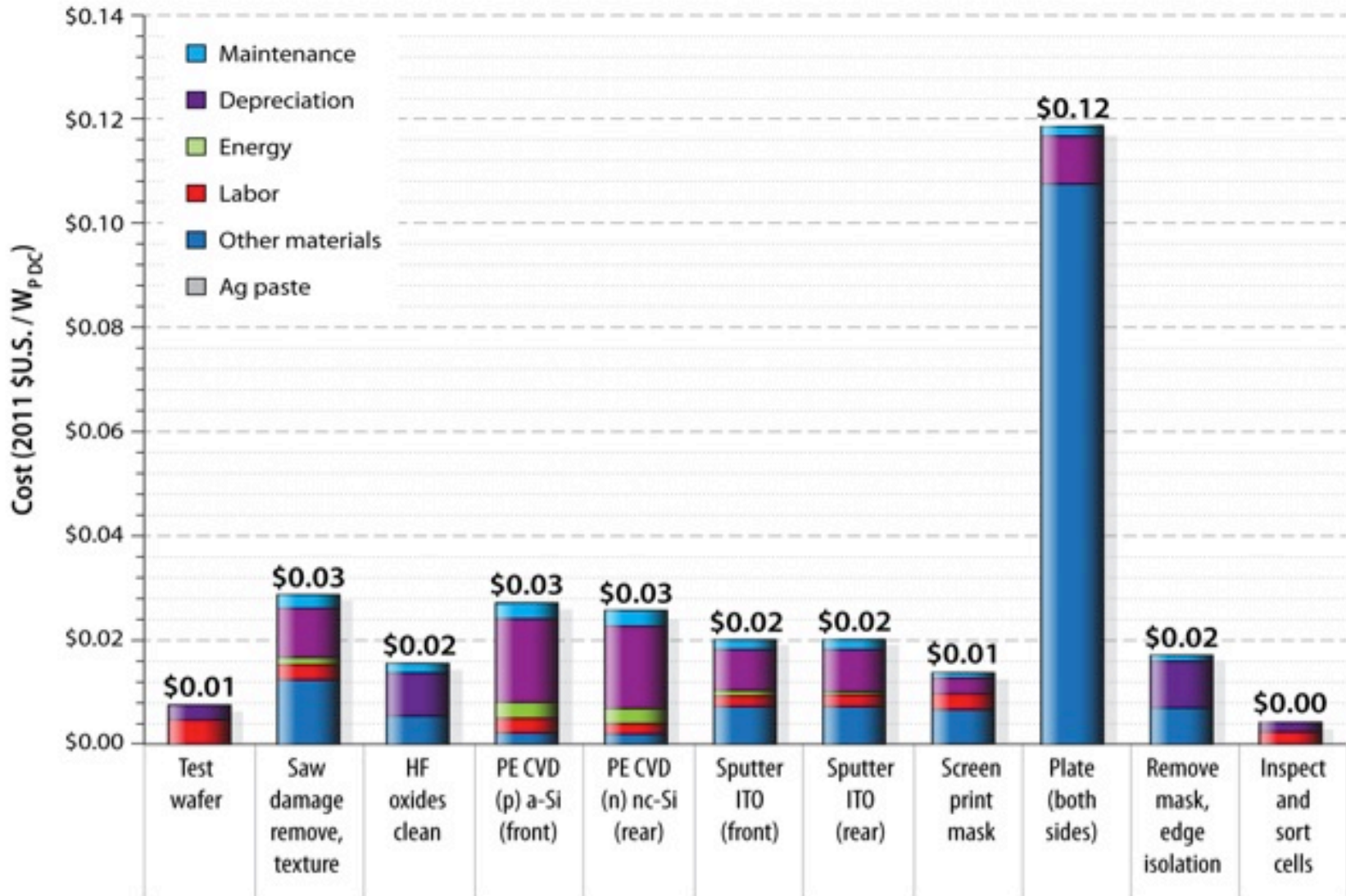


## Cell Architecture (Heterojunction Intrinsic Thin Layer, or 'HIT')

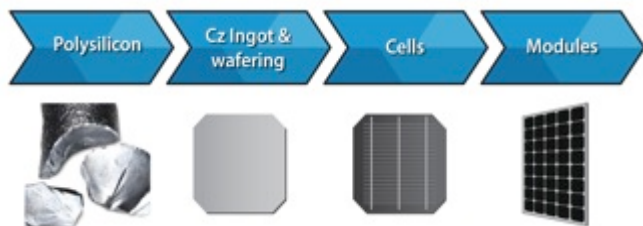
## Process Flow



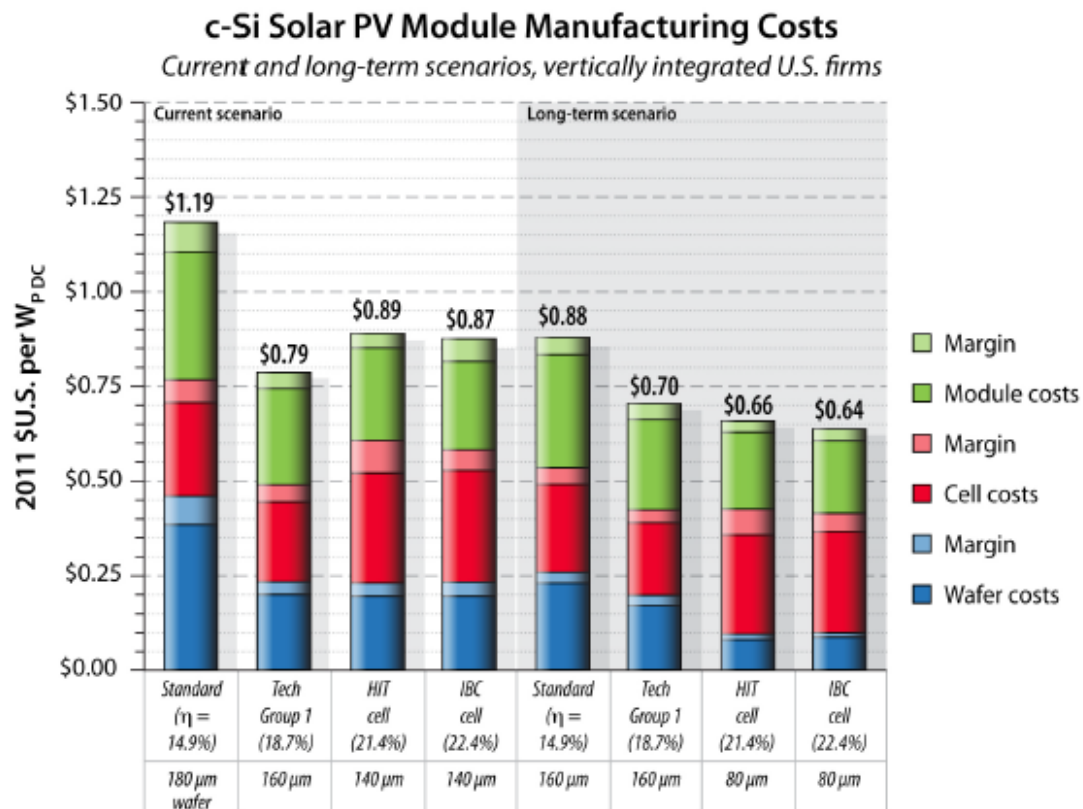
# Calculated Cost of Ownership for each step in the fabrication of Technology Group 3 c-Si Solar Cells



# The c-Si Module Supply Chain: Complete Module Costs



Balance of Material Costs for Modules	
Material	2011 Costs
Cells (See fig. 11)	\$0.54 - \$0.37 / $W_p$
Bus bars and tabbing ribbon	\$0.80/ module
PCB, mounting tape, and junction box containing the bypass diodes	\$9.50/ module
Aluminum frame and edge seal	\$20/ module
EVA (2 sheets needed)	\$4 / $m^2$ for each sheet
Back sheet film	\$8 / $m^2$
Front Glass (4.0 mm, low [Fe], tempered)	\$16 / $m^2$
<b>Estimated module materials costs</b>	<b>\$0.82 - \$0.57 / <math>W_p</math></b>



Assumed cell-to-module derate of 11%

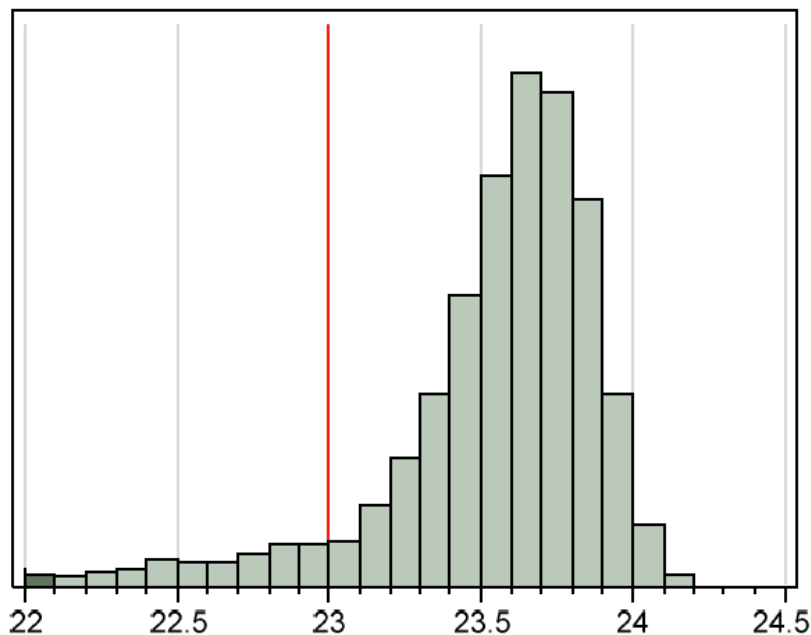
Goodrich, A.; Hacke, P.; Wang, Q.; Sopori, B.; Margolis, R.; James, T.; Woodhouse, M., **“A Wafer-Based Monocrystalline Silicon Photovoltaics Road Map: Utilizing Known Technology Improvement Opportunities for Further Reductions in Manufacturing Costs,”** provisionally accepted by *Solar Energy Materials and Solar Cells*.

Also available if requested by email: [alan.goodrich@nrel.gov](mailto:alan.goodrich@nrel.gov), [michael.woodhouse@nrel.gov](mailto:michael.woodhouse@nrel.gov)

# Conclusions on c-Si:

## Benchmarks for other PV technologies to consider

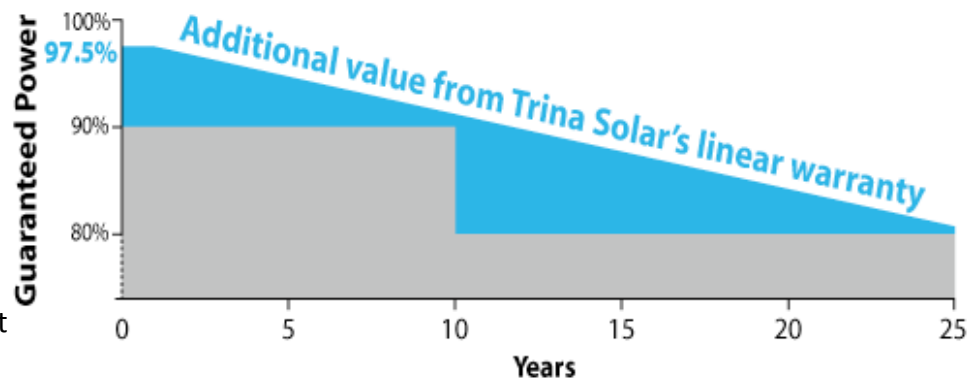
Efficiency:  
20 - 25%



- Efficiency distribution for SunPower's Maxeon Gen 3 Cells with **23.6%** average commercial production efficiencies.
- See D. D. Smith et al. (2012), Proceedings of the 38<sup>th</sup> IEEE PVSC, pp. 001594.
- Low efficiency c-Si companies are generally the first ones being shut down during the 2012 downturn.

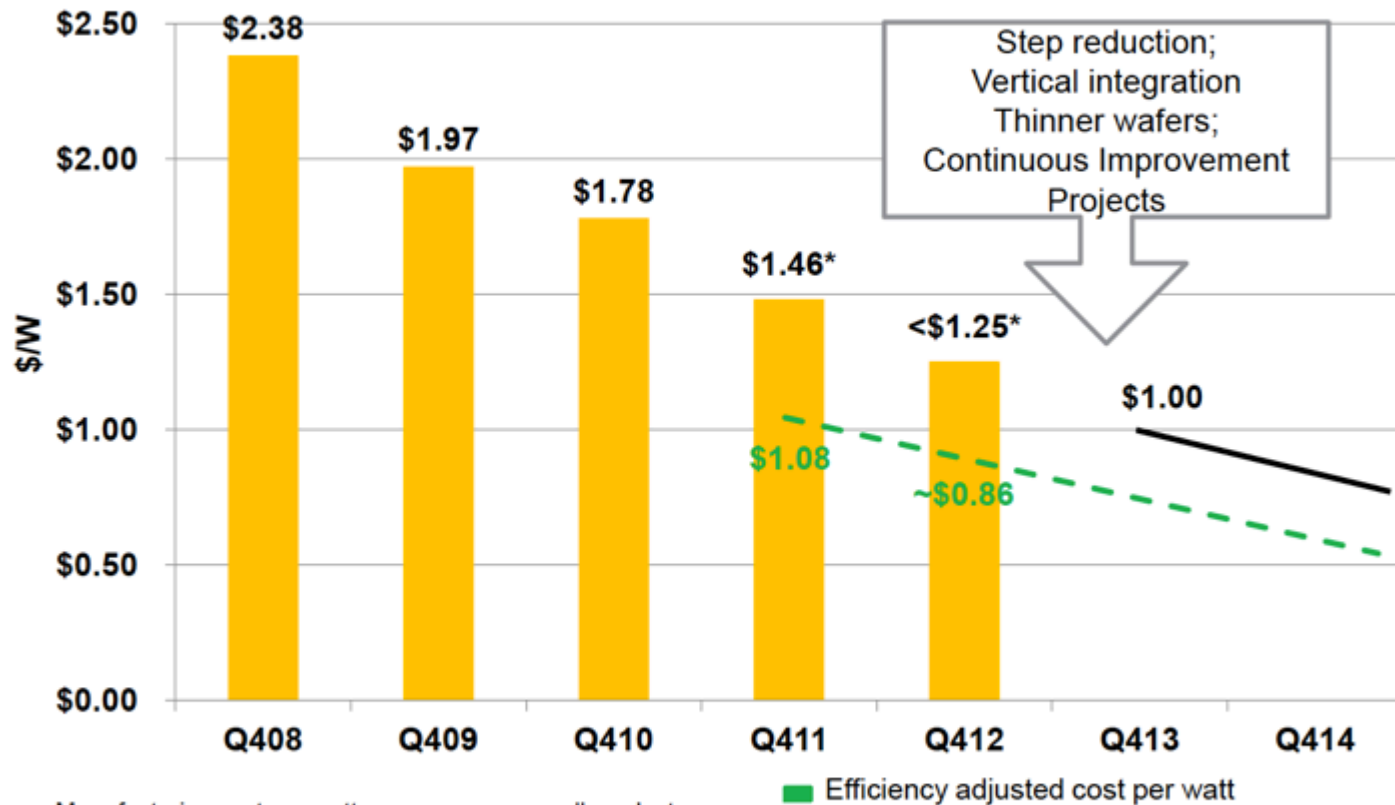
Stability:  
T80 of 25 years

Trina Solar's linear performance warranty



<http://www.trinasolar.com/eu/products/product-resources/product-warranty>

## Manufacturing Cost Reduction Roadmap



\*Manufacturing cost per watt – average across all products, excludes freight, underutilization and inventory charges

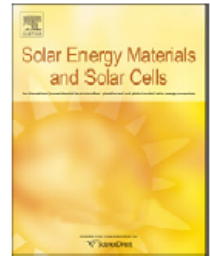
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10

SunPower Q4 2011 Earnings Call and

[http://www.pv-tech.org/news/sunpower\\_next\\_capex\\_spending\\_cycle\\_not\\_until\\_2014\\_touts\\_cell\\_cost\\_reduction](http://www.pv-tech.org/news/sunpower_next_capex_spending_cycle_not_until_2014_touts_cell_cost_reduction).



### Perspectives on the pathways for cadmium telluride photovoltaic module manufacturers to address expected increases in the price for tellurium

Michael Woodhouse<sup>a,\*</sup>, Alan Goodrich<sup>a,\*</sup>, Robert Margolis<sup>a</sup>, Ted James<sup>a</sup>, Ramesh Dhere<sup>c</sup>, Tim Gessert<sup>c</sup>, Teresa Barnes<sup>c</sup>, Roderick Eggert<sup>b</sup>, David Albin<sup>c,\*</sup>

<sup>a</sup> The National Renewable Energy Lab, Strategic Energy Analysis Center, 1617 Cole Blvd, Golden, CO 80401, United States

<sup>b</sup> Colorado School of Mines, United States

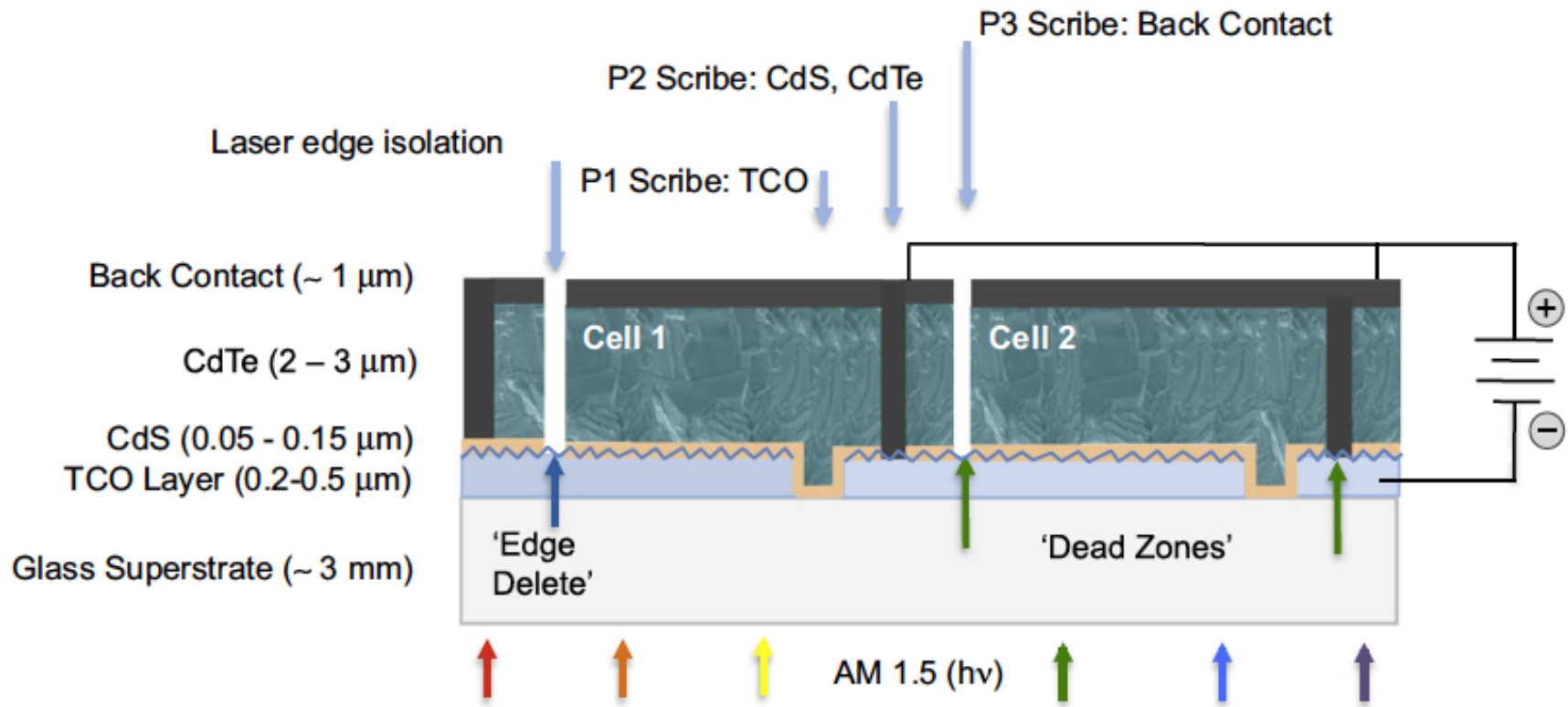
<sup>c</sup> The National Renewable Energy Laboratory, National Center for Photovoltaics, 1617 Cole Blvd, Golden, CO 80401, United States

### Supply-Chain Dynamics of Tellurium, Indium, and Gallium Within the Context of PV Module Manufacturing Costs

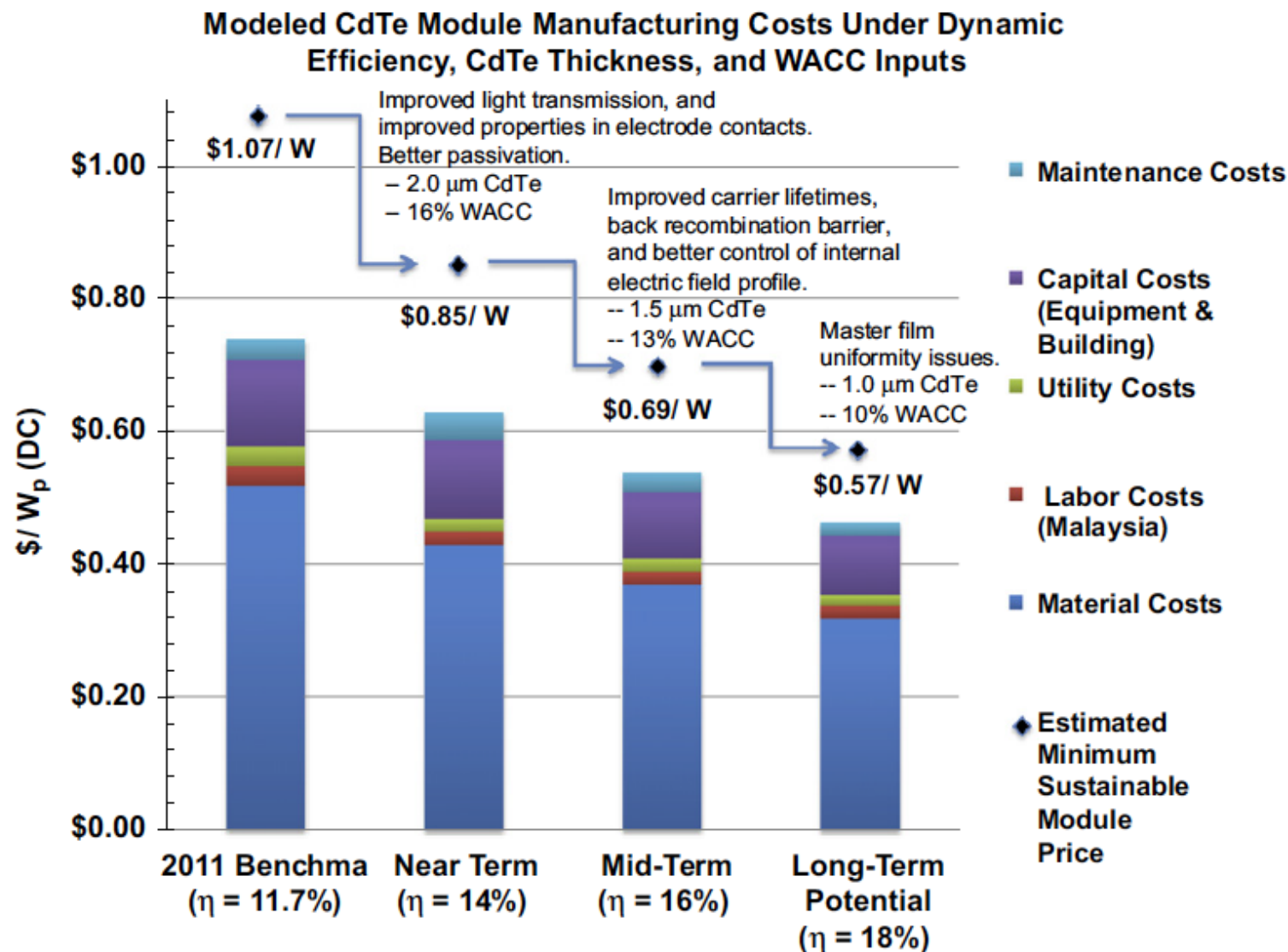
Michael Woodhouse<sup>1</sup>, Alan Goodrich<sup>1</sup>, Robert Margolis<sup>1</sup>, Ted L James<sup>1</sup>, Martin Lokanc<sup>2</sup>, and Roderick Eggert<sup>2</sup>

2012 IEEE PVSC Conference proceedings, and accepted by the *Journal of Photovoltaics*.

# Single-Junction Polycrystalline CdTe in a Monolithically-Integrated Format



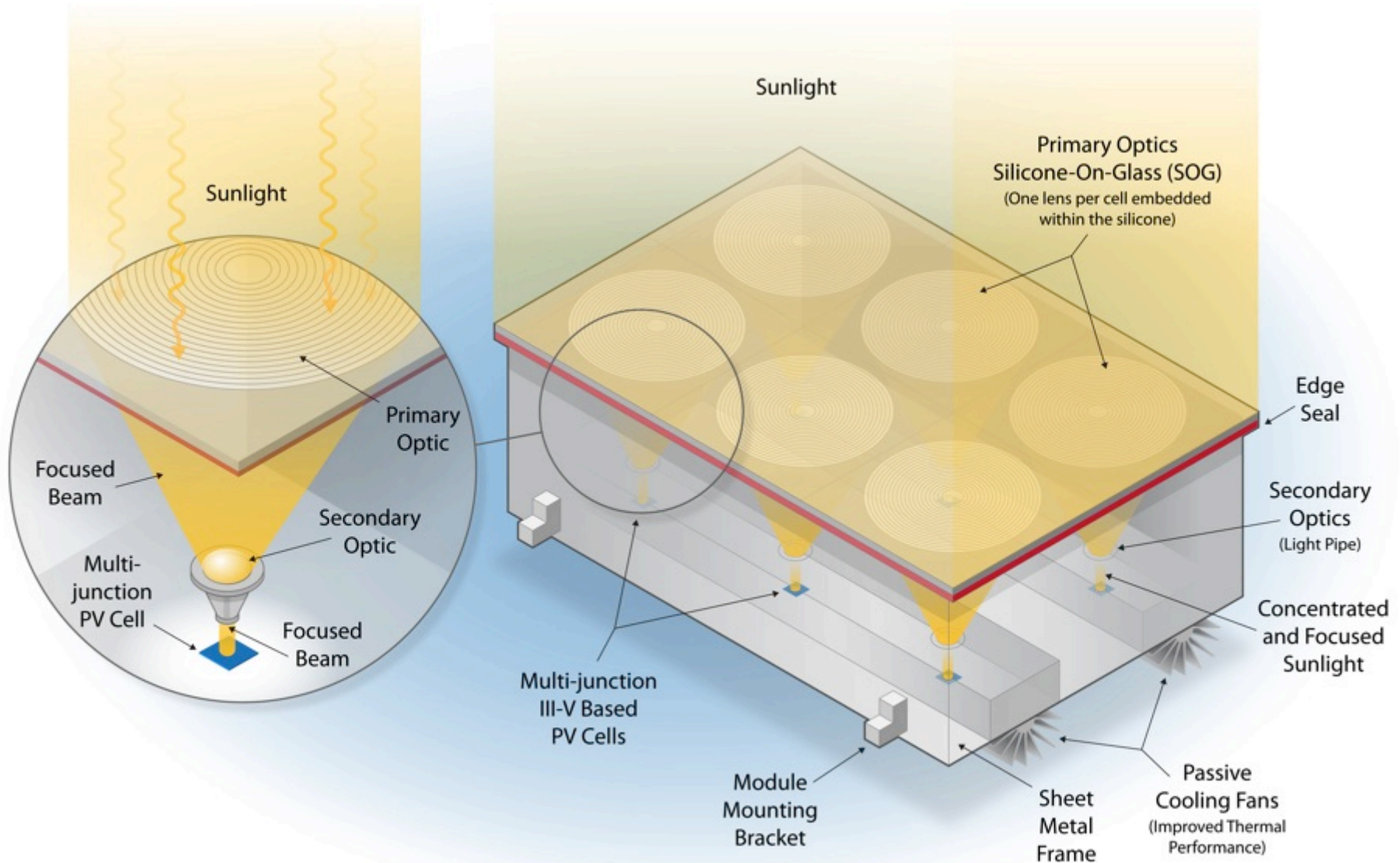
# Single-Junction Polycrystalline CdTe in a Monolithically-Integrated Format



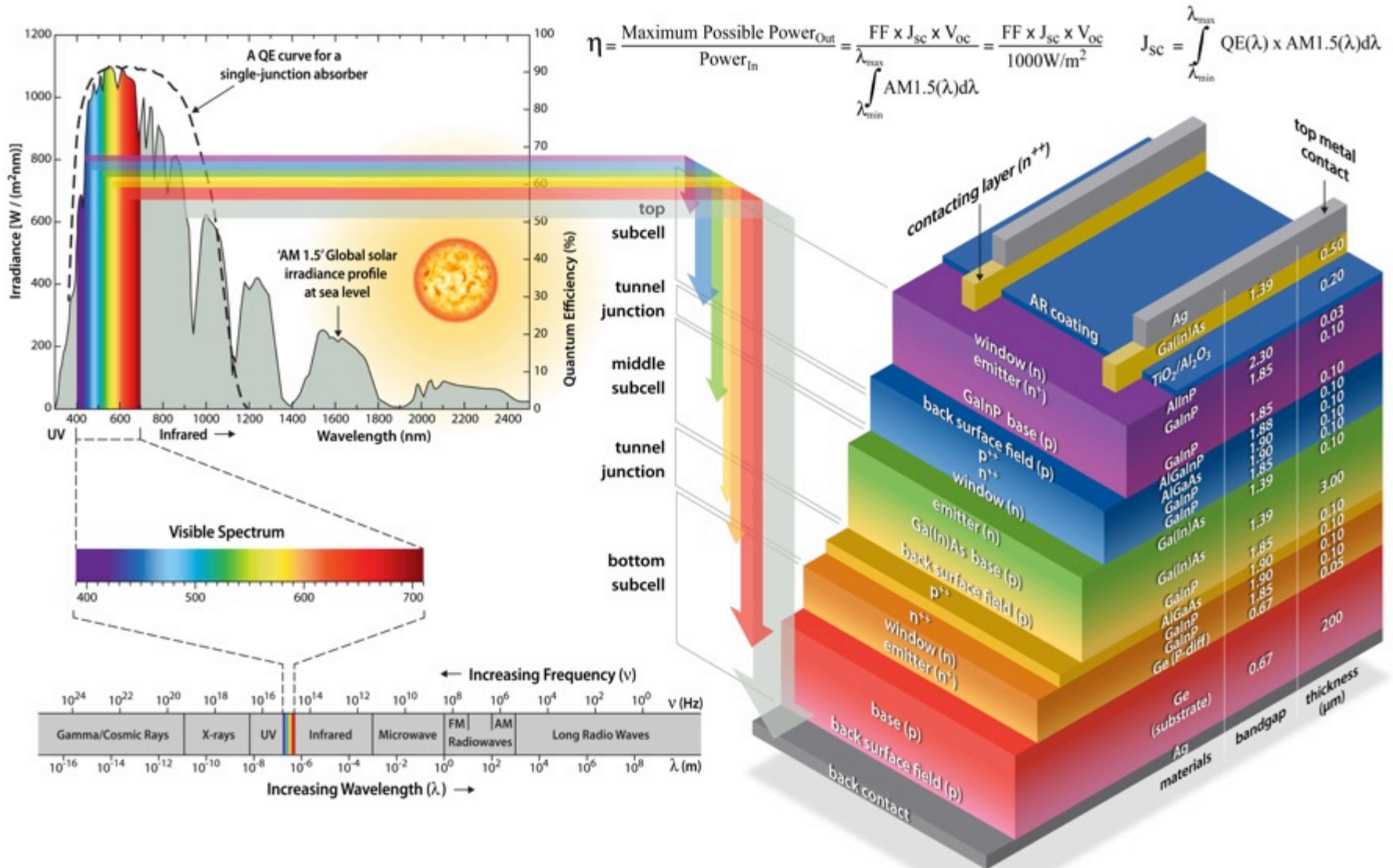
Assumes constant prices for all materials, as well as constant labor and capital equipment requirements.

# Some III-Vs Stuff

# Where the III-V Cost Modeling Effort Will Eventually Go: The Fresnel Lens Box



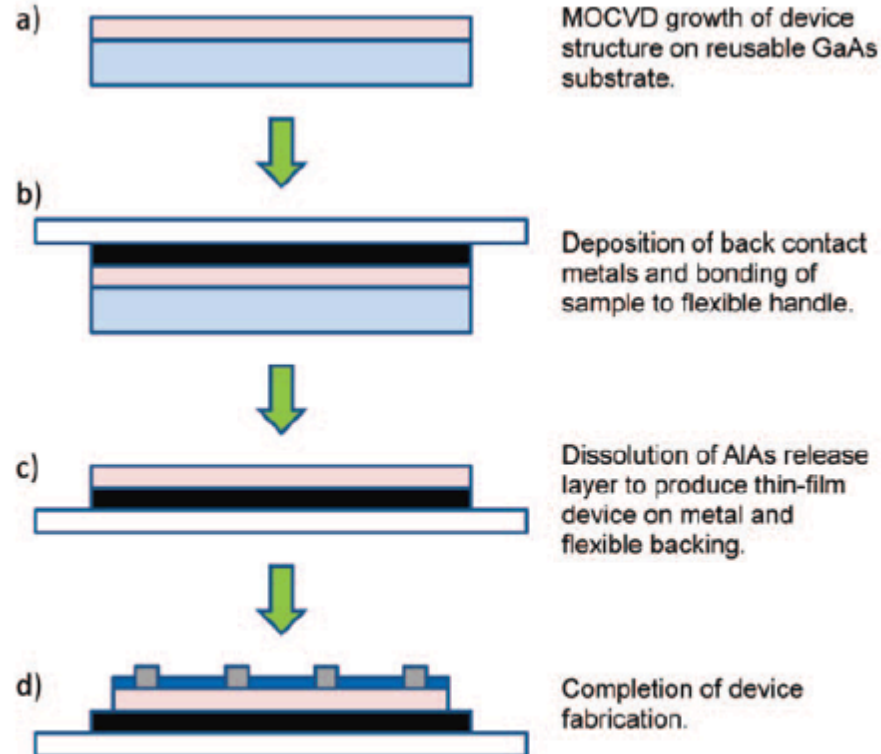
# Where the III- V Cost Modeling Effort Will Eventually Go: Multi-Junction Solar Cells



Figures adapted from D J Friedman, J M Olson, S Kurtz, High Efficiency III-V Multijunction Solar Cells, in Handbook of Photovoltaic Science and Engineering, 2<sup>nd</sup> ed. (2011). Note: The optical penetration depth for each color is not represented to scale within the figure.

# But First the Single-Junction Case

One representative single-junction GaAs cell processing sequence



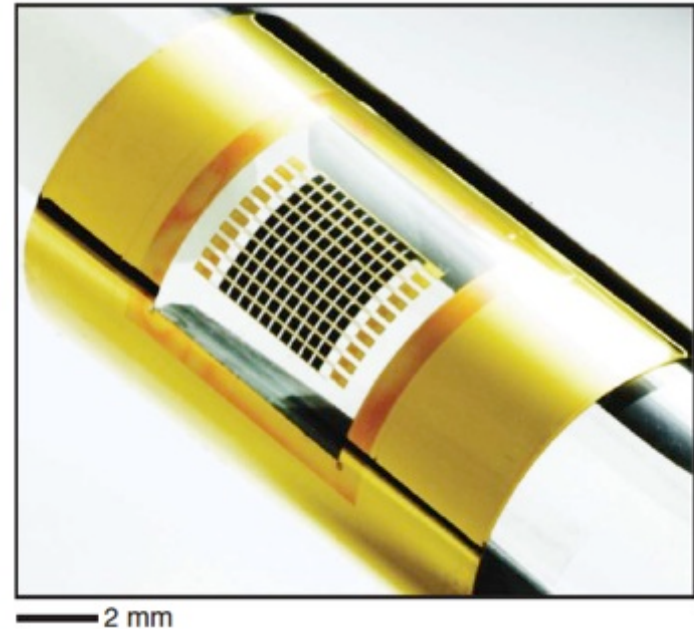
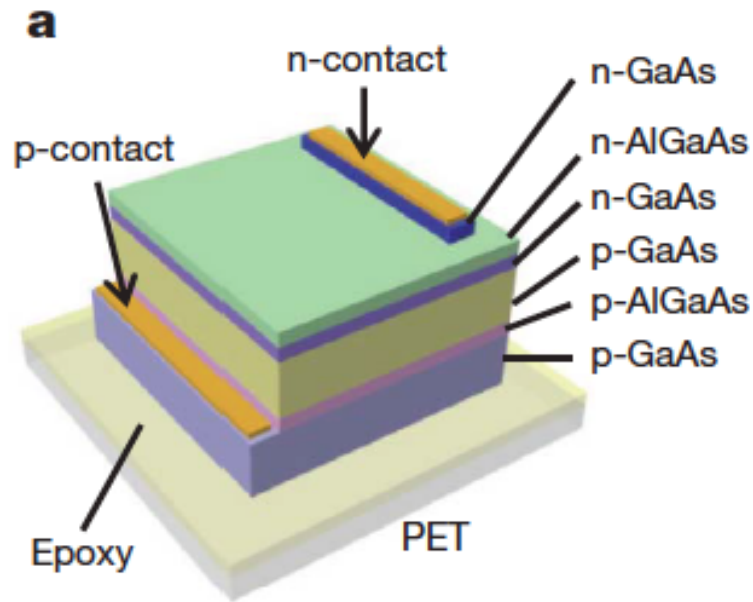
A process flow from: **27.6% CONVERSION EFFICIENCY, A NEW RECORD FOR SINGLE-JUNCTION SOLAR CELLS UNDER 1 SUN ILLUMINATION**

Brendan M. Kayes, Hui Nie, Rose Twist, Sylvia G. Spruytte, Frank Reinhardt, Isik C. Kizilyalli, and Gregg S. Higashi [1]

Alta Devices, Inc., Santa Clara, CA, USA

2011 IEEE PVSC Conference Proceedings

# Another Analogous Case

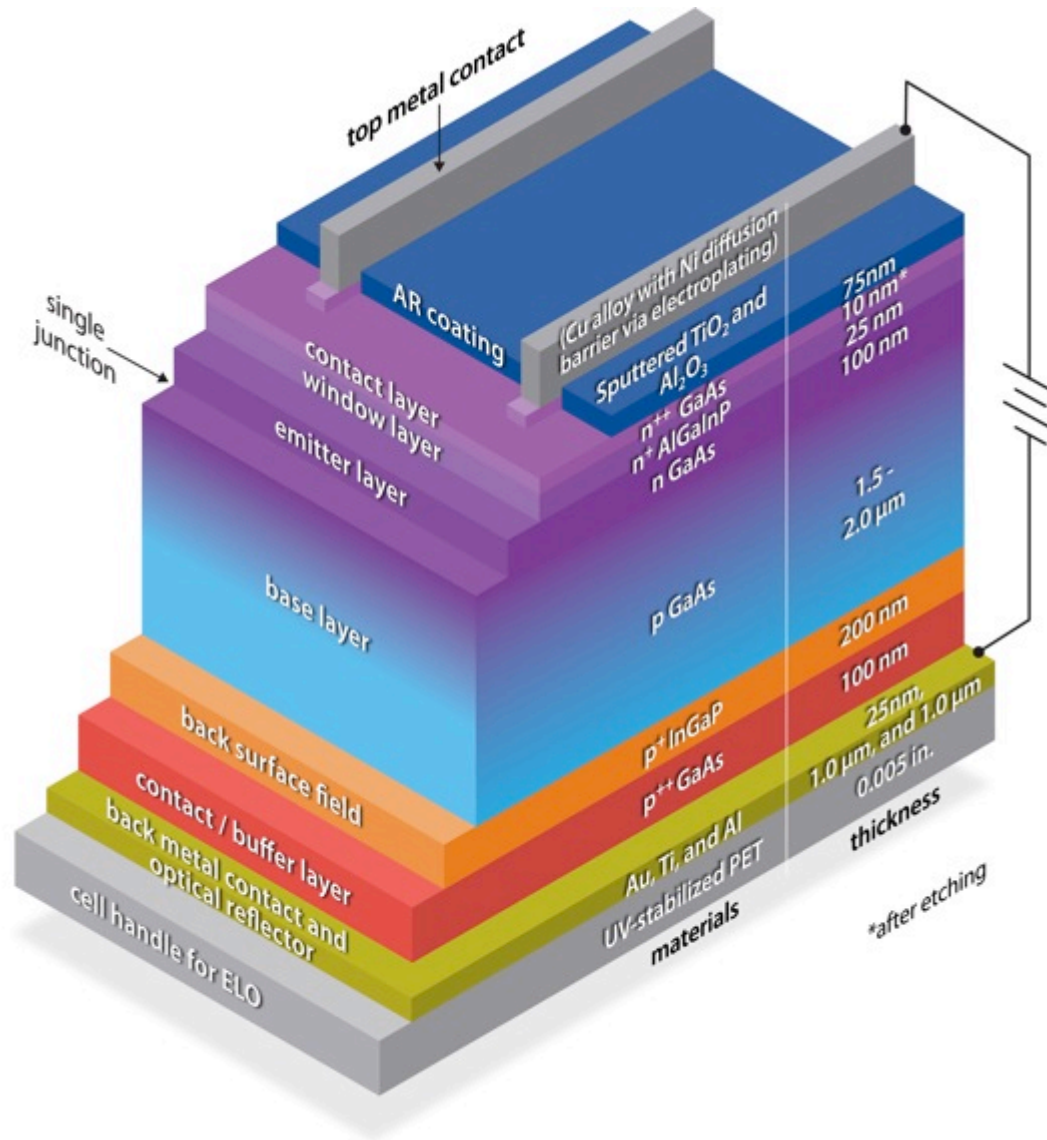


## GaAs photovoltaics and optoelectronics using releasable multilayer epitaxial assemblies

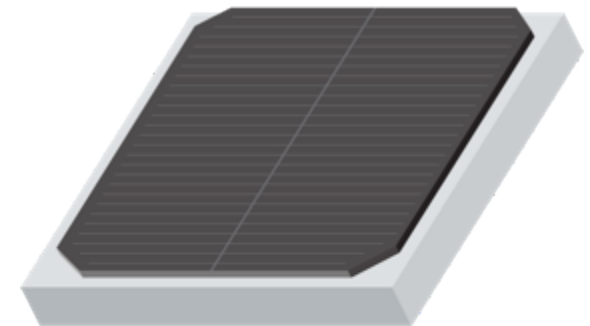
Jongseung Yoon<sup>1\*</sup>, Sungjin Jo<sup>1,4\*</sup>, Ik Su Chun<sup>2</sup>, Inhwa Jung<sup>1</sup>, Hoon-Sik Kim<sup>1</sup>, Matthew Meitl<sup>3</sup>, Etienne Menard<sup>3</sup>, Xiuling Li<sup>2</sup>, James J. Coleman<sup>2</sup>, Ungyu Paik<sup>4</sup> & John A. Rogers<sup>1,2</sup>

*Nature*, (2010), 465, pp. 329.

# Representative Single-Junction GaAs Device for the Cost Model, Designed in Consultation with NREL Researchers

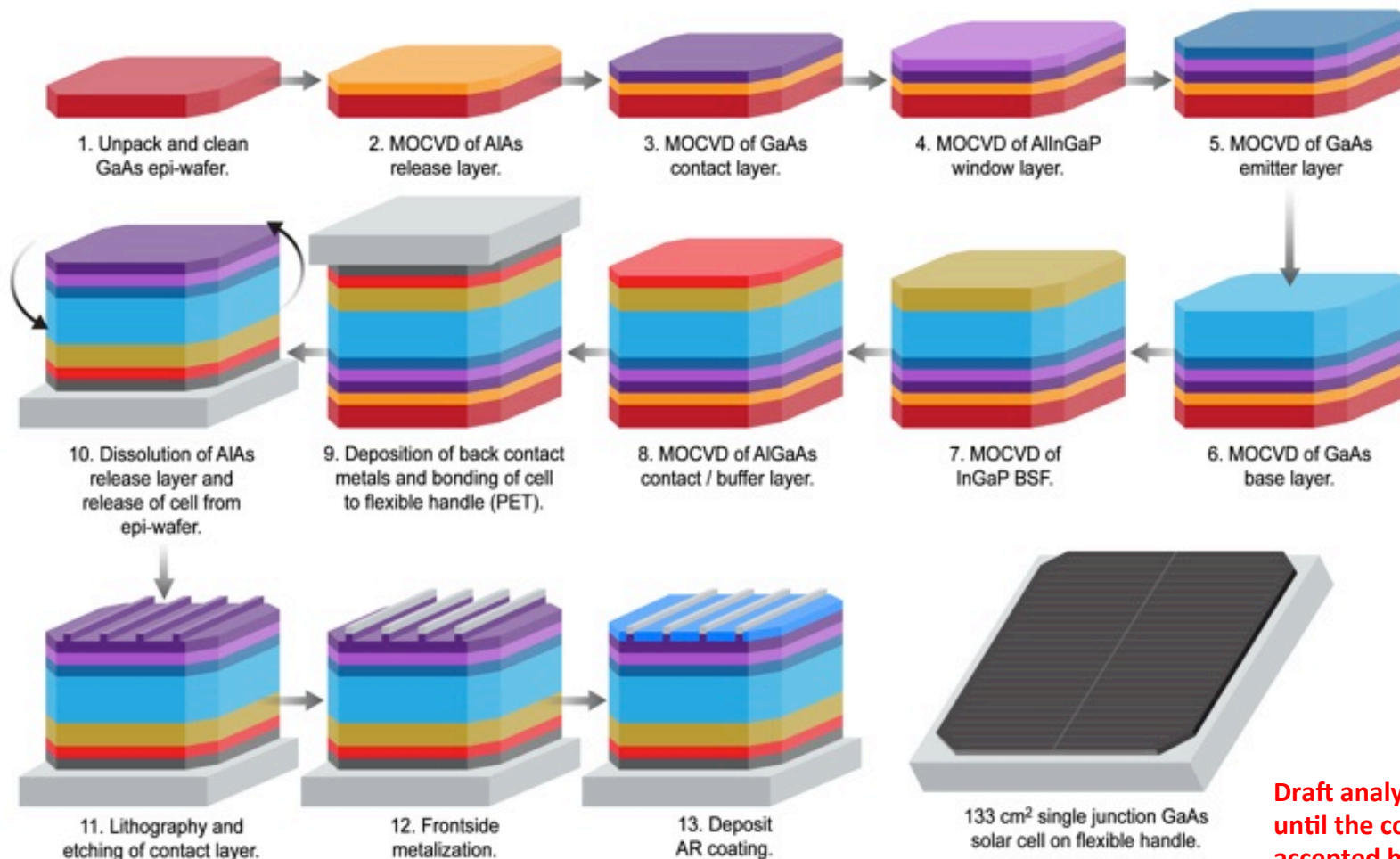


Draft analysis. Do not cite until the corresponding paper is accepted by a peer-reviewed journal.



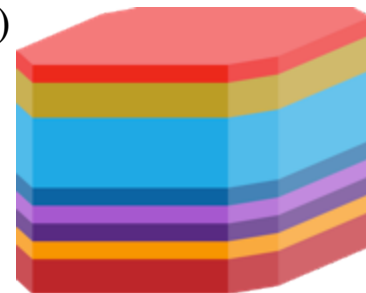
133 cm<sup>2</sup> single junction GaAs solar cell on flexible handle.

# Representative Process Flow for Making the Device



Draft analysis. Not to be cited until the corresponding paper is accepted by a peer-reviewed journal.

# Sample Cost Calculation for a Particular Step



8. MOCVD of AlGaAs contact / buffer layer.

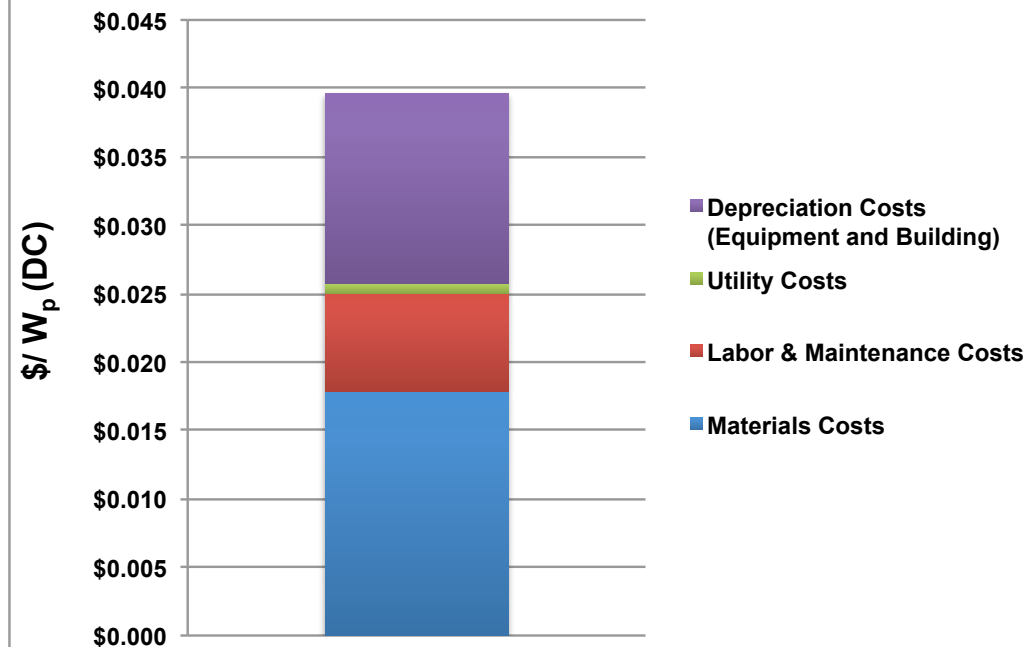
Precursor	Al(CH <sub>3</sub> ) <sub>3</sub>	Ga(CH <sub>3</sub> ) <sub>3</sub>	AsH <sub>3</sub>
Molar Reaction Coefficient (x, 1-x)	0.05	0.95	1
Molecular Weight (g mol <sup>-1</sup> )	72.09	114.82	77.94
Material Utilization (%)	30%	30%	8%
Precursor Price (\$/g)	\$18.00	\$2.50	\$0.44
Reclamation value of spent precursor (\$/g)	\$0.00	\$0.00	\$0.00

AlGaAs film Thickness: 100 nm  
 AlGaAs Density: 4.52 g/cm<sup>3</sup>

	Al	Ga	As
Mass of Material in GaAs film (g m <sup>-2</sup> )	0.004	0.210	0.238
Required Mass of Precursor (g m <sup>-2</sup> )	0.038	1.153	3.090
Precursor Costs (\$ m <sup>-2</sup> )	\$0.69	\$2.88	\$1.36
Precursor Costs (\$ cell <sup>-1</sup> )	0.01	\$0.04	\$0.02
Precursor Costs (\$ W <sup>-1</sup> )	0.00	\$0.01	\$0.00
Percent of Total Cost	14%	58%	28%

**Draft analysis. Not be cited until the corresponding paper is accepted in a peer-reviewed journal.**

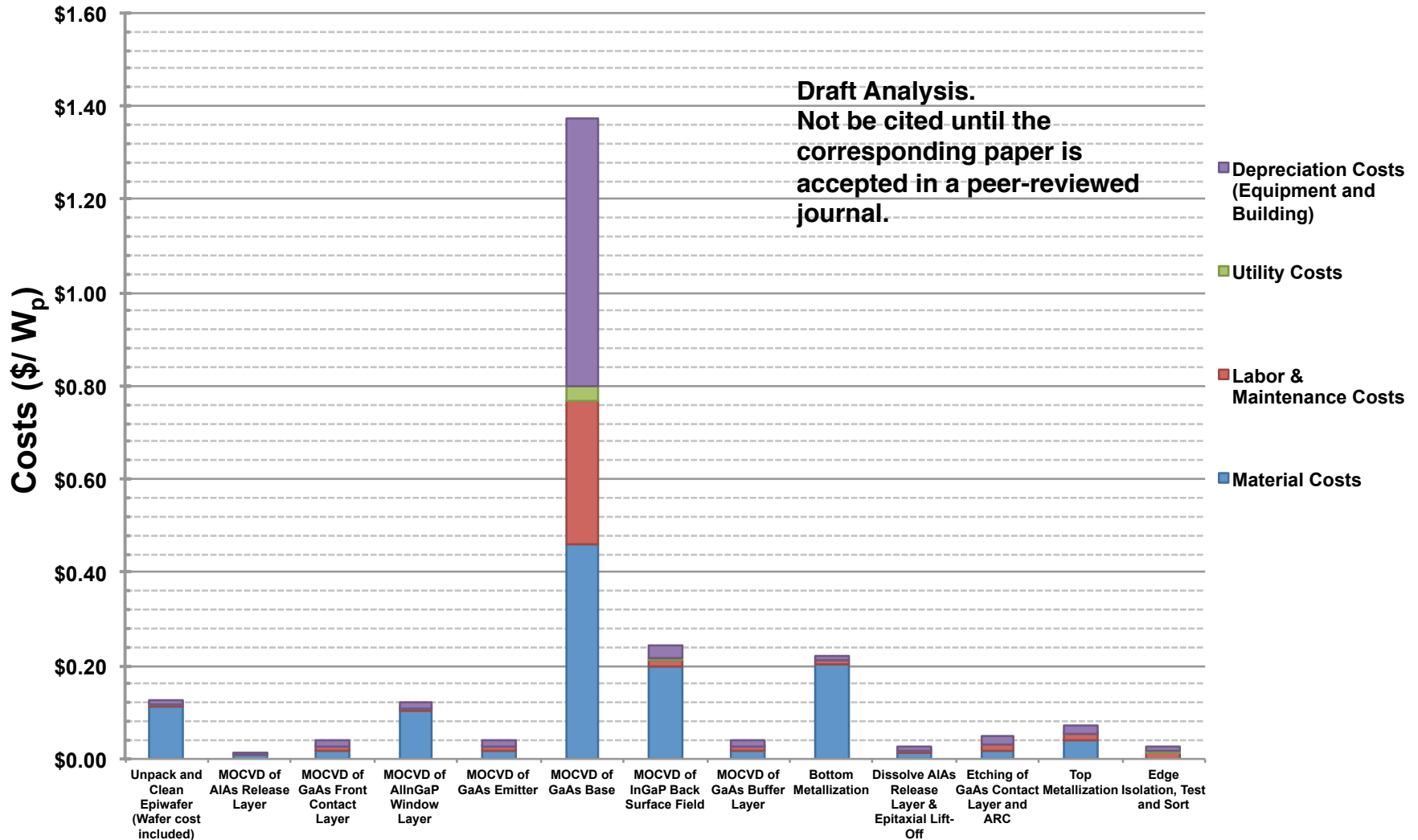
**Initial Cost Estimates for AlGaAs Buffer Layer**  
 500 MWp U. S. Facility, 28% Cell Efficiency, 0.25 μm/ min Dep Rate



# Calculated Cost of Ownership for each step in the fabrication of Single-Junction GaAs Solar Cells (2012 Inputs)

## Estimated Step-by-Step Costs for MOCVD of Single-Junction GaAs

500 MW<sub>p</sub> U.S. Facility, 28% Cell Efficiency, 0.25 μm/ min Deposition Rate



**Note: 500 substrate re-usages are assumed in order to keep y-axis reasonable.**

# Total Summary of Costs with 2012 Inputs

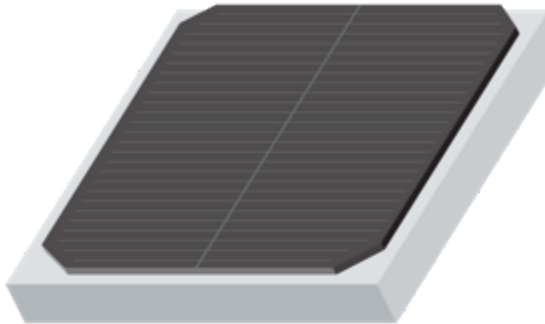
Assumes 500 growth cycles from each epi-wafer, and equal cell performance from all growth cycles

## Direct Manufacturing Cost Summary

Assumed Cell Efficiency: 28.0%

Assumed Facility Size (MW): 500

	\$/W <sub>p</sub>	\$/cell	\$/year	percent	investment
<b>VARIABLE COST ELEMENTS</b>					
Material Cost	\$1.13	\$4.21	\$565,278,707.82	42.22%	\$0.00
Direct Labor Cost	\$0.19	\$0.70	\$93,965,829.15	7.02%	\$0.00
Utility Cost	\$0.04	\$0.16	\$21,462,958.34	1.60%	\$0.00
<b>FIXED COST ELEMENTS</b>					
Equipment Cost	\$0.71	\$2.66	\$356,790,285.71	26.65%	\$2,497,532,000.00
Tooling Cost	\$0.00	\$0.00	\$0.00	0.00%	\$0.00
Building Cost	\$0.00	\$0.00	\$41,739.33	0.00%	\$626,090.00
Maintenance Cost	\$0.20	\$0.75	\$100,310,451.60	7.49%	\$0.00
Overhead Labor Cost	\$0.03	\$0.10	\$13,092,989.88	0.98%	\$0.00
Cost of Capital	\$0.38	\$1.40	\$188,090,938.85	14.05%	\$0.00
<b>TOTAL COSTS</b>	<b>\$2.68</b>	<b>\$9.97</b>	<b>\$1,339,033,901</b>	<b>100.00%</b>	<b>\$2,498,158,090</b>

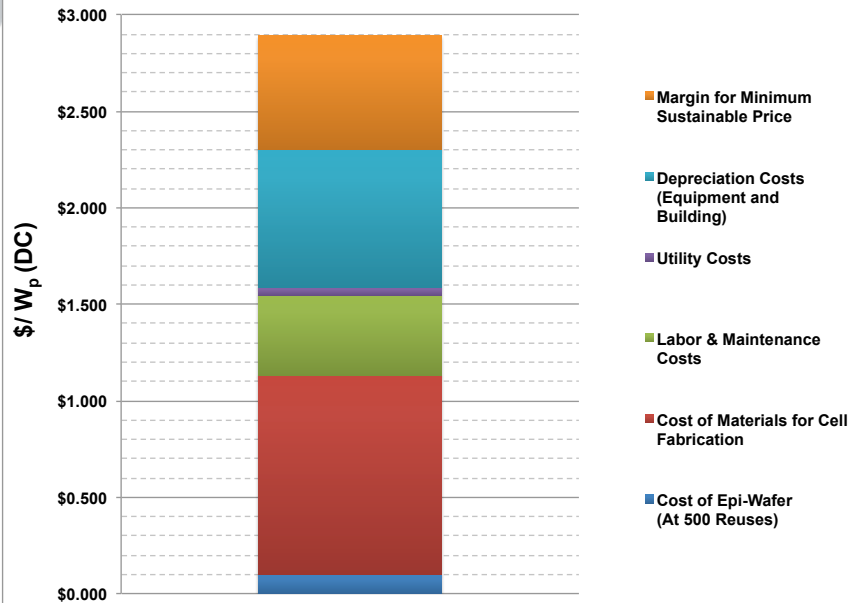


133 cm<sup>2</sup> single junction GaAs solar cell on flexible handle.

Draft analysis. Not be cited until the corresponding paper is accepted in a peer-reviewed journal.

### Estimates of Single-Junction GaAs Solar Cell Manufacturing Costs

500 MW<sub>p</sub> U. S. Facility, 28% Cell Efficiency, 0.25 μm/ Dep Rate, 7 cells per Batch

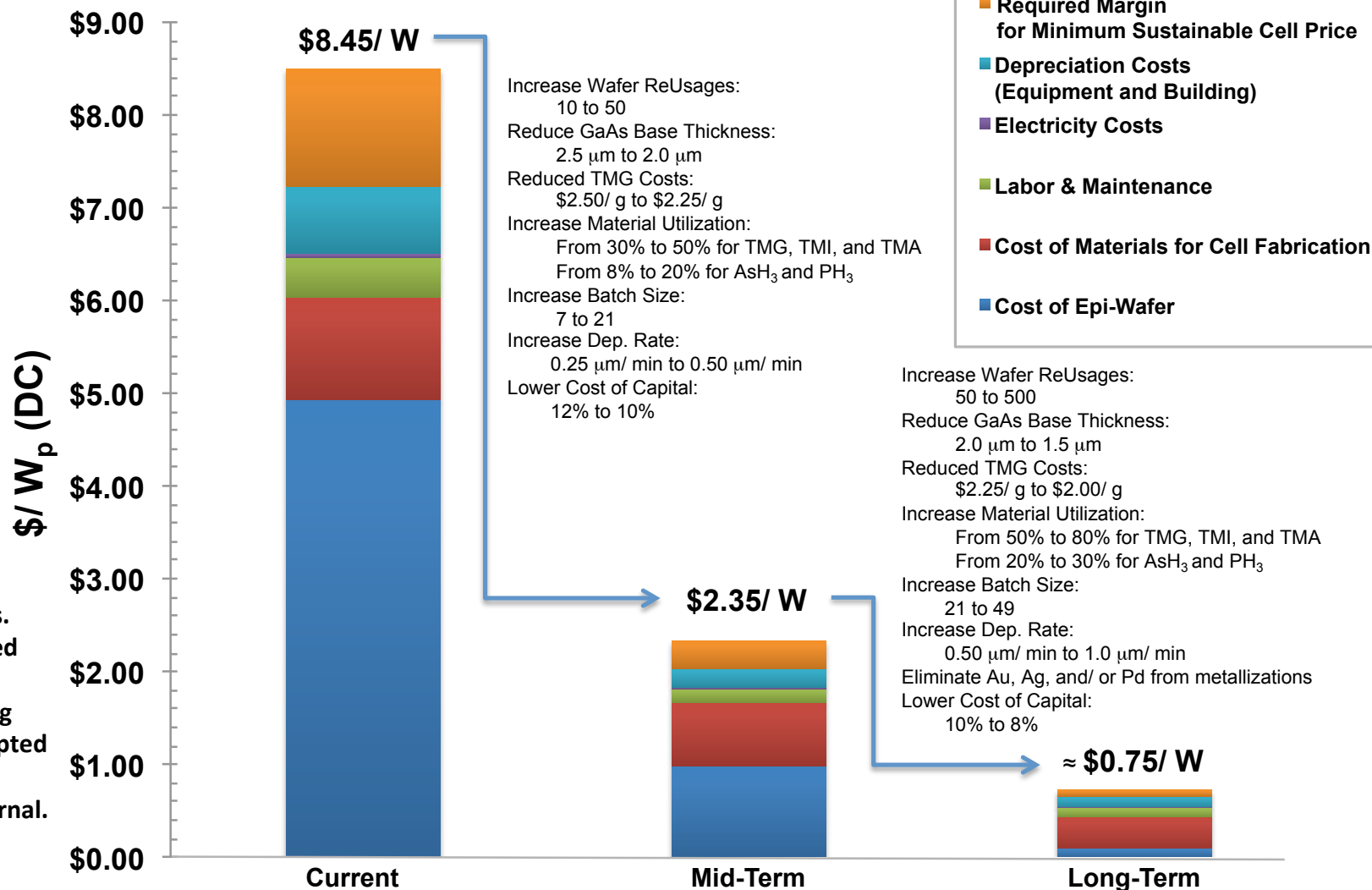


Estimated 'CapEx' For Plant:  
\$2.5 Billion/ 500 MW  
= \$5/ W

# Pathways for Reducing the Manufacturing Costs for Single-Junction III-V Solar Cells via MOCVD

## Cost Model Results for MOCVD of Single Junction GaAs Solar Cells

$\eta = 28\%$  for all cases; \$180 for 133 cm<sup>2</sup> Substrates; 0.25 Laborers per Reactor; U.S. Manufacturing



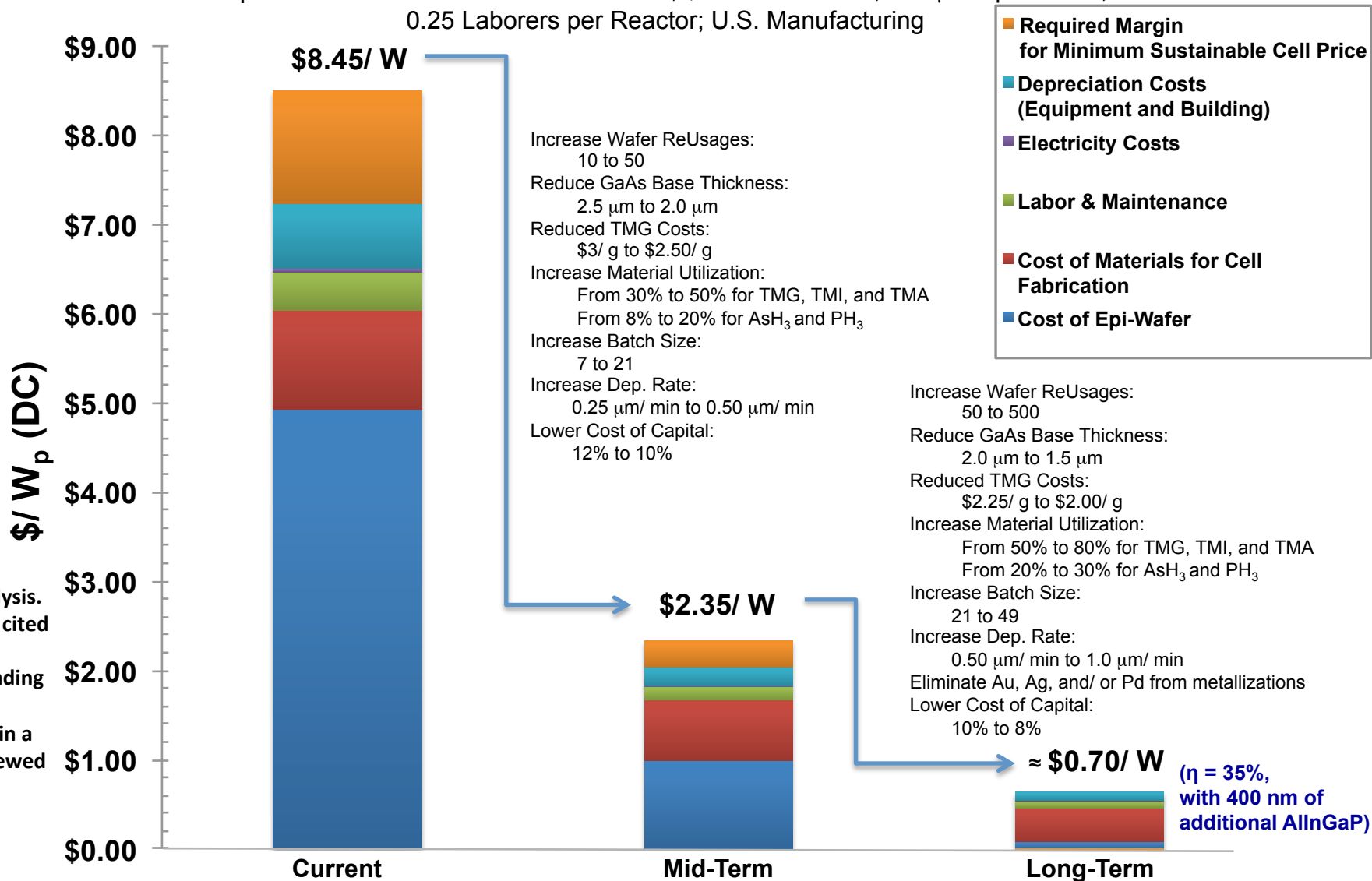
Draft analysis.  
Not to be cited  
until the  
corresponding  
paper is accepted  
in a peer-  
reviewed journal.

# Considering the Tandem Cell

Assuming an efficiency boost from 28% to 35% by depositing 400 nm of additional AlInGaP-based layers.

## Cost Model Results for MOCVD of Single and Two-Junction III-V Solar Cells

$\eta = 28\%$  for current and mid-term cases; \$180 for 133 cm<sup>2</sup>, 600  $\mu\text{m}$  Epi-Wafers;  
0.25 Laborers per Reactor; U.S. Manufacturing

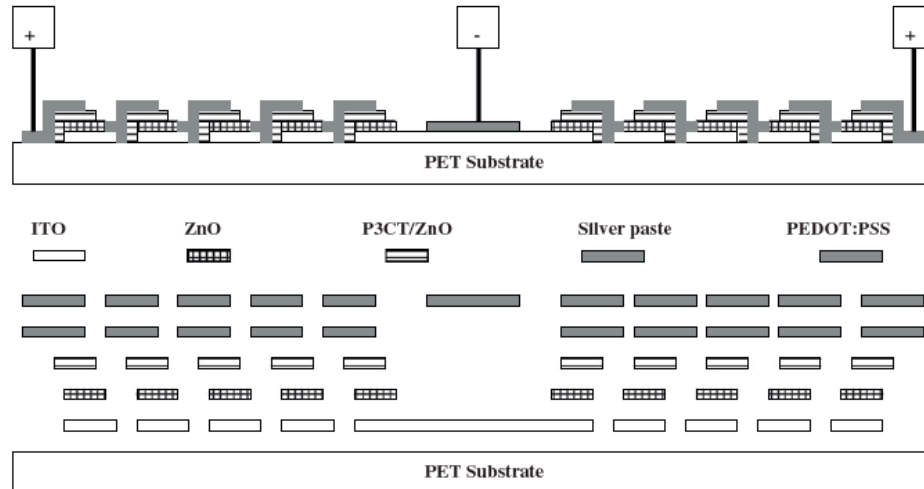
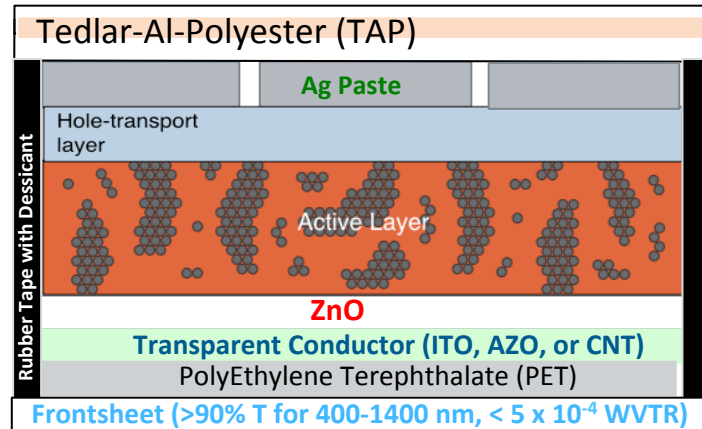
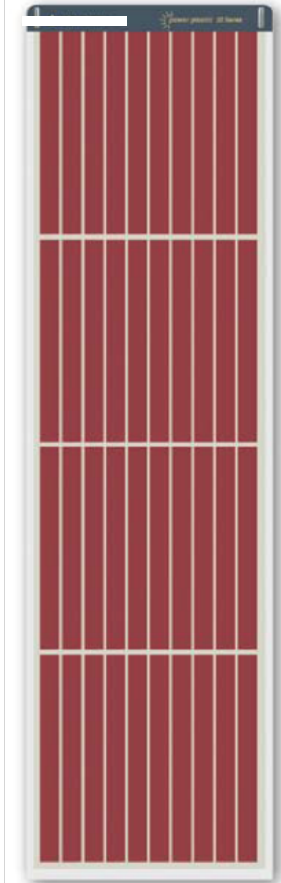


Draft analysis.  
Not to be cited  
until the  
corresponding  
paper is  
accepted in a  
peer-reviewed  
journal.

# Some Solution-Processed PV Stuff

# Hypothetical Single-Junction OPV Module

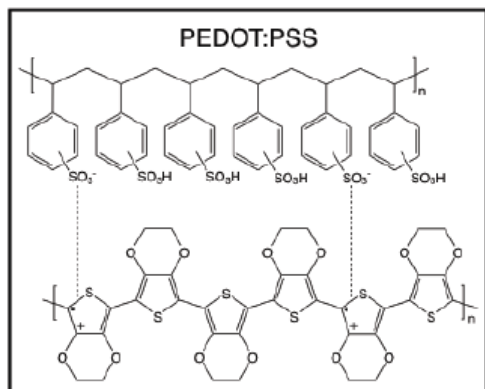
OPV Module



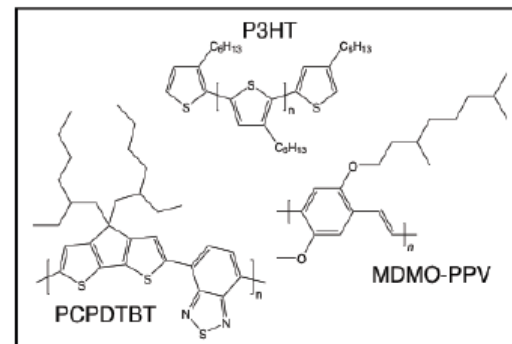
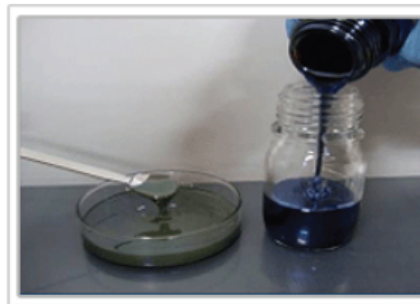
Krebs, et al.; *Sol Energy Mater Sol Cells*, 93 (2009), 422

Krebs, et al.; *J Mater Chem*, 19 (2009), 5442

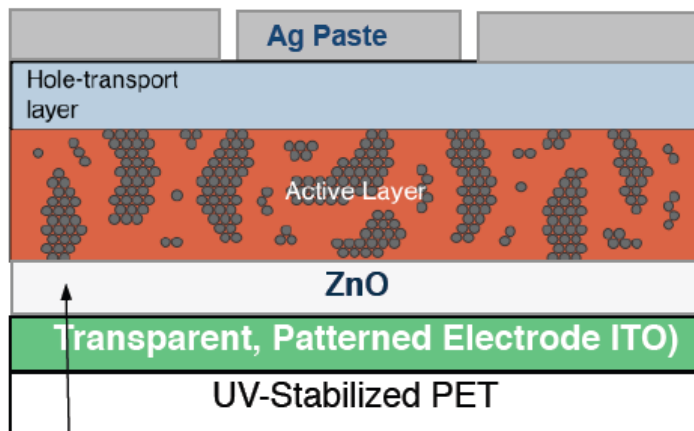
# Highlights of OPV Ink Prices



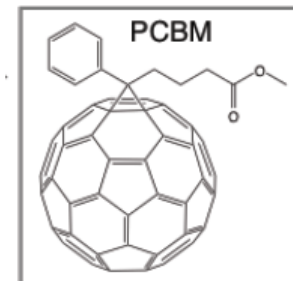
*Ag Paste*  
 \$0.80/ g.  
 Need 1  $\mu\text{m}$  thick, but depends upon final current density.  
 Assumed to cover 80% of module area.



*PEDOT:PSS*  
 $\approx$ \$500/ L  
 Need 50 nm dried thickness:  
 2.5 mL/  $\text{m}^2$



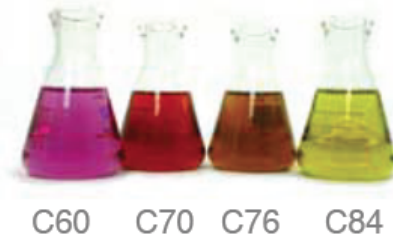
*Active Layer Inks*  
 $\approx$ \$1000/ L  
 (estimated cost for bulk production of 5 step polymer synthesis)  
 Need 200 nm:  
 10 mL/  $\text{m}^2$



*10% ZnO NP's in  $\text{C}_6\text{H}_5\text{Cl}$ / MeOH/ MEA*  
 Need 30 nm from Ink:  
 ZnO NP's: \$1.16/ g  
 $\text{C}_6\text{H}_5\text{Cl}$ : \$39/ L  
 MeOH: \$13/ L  
 MEA: \$245/ L  
 Bulk Price Estimates (Sigma Aldrich)  
 ZnO NPs prepared from  $\text{Zn}(\text{OAc})_2$

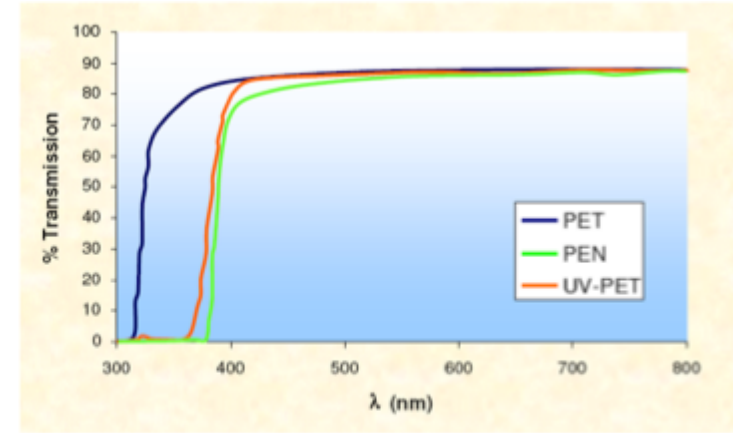
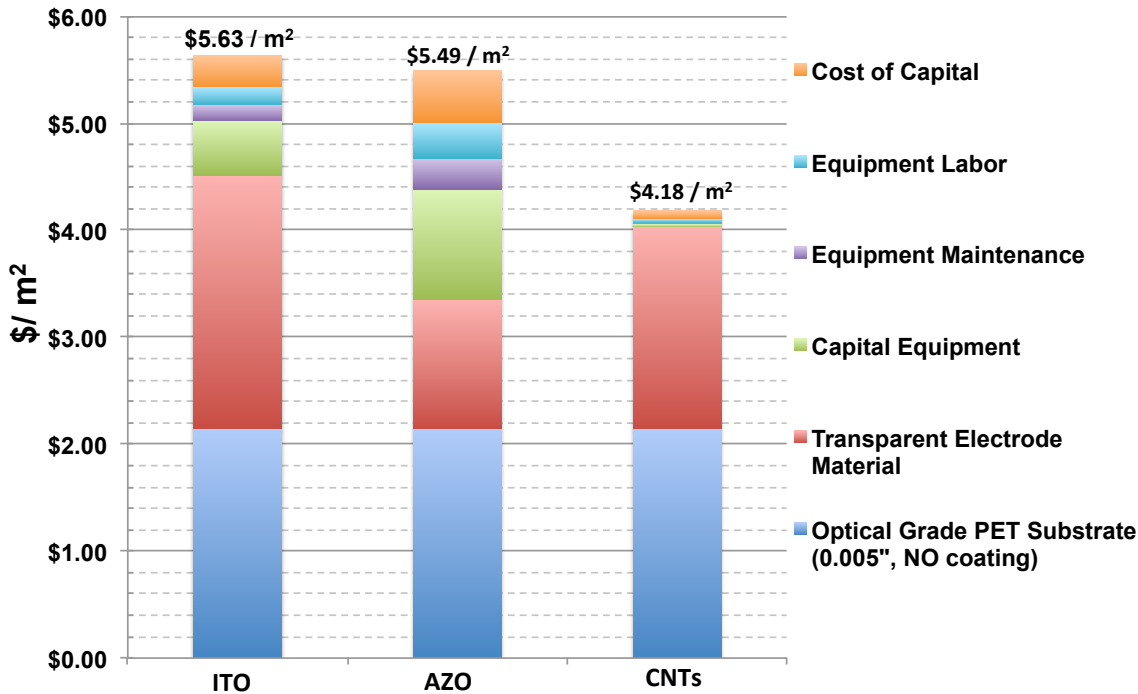


**Draft Analysis.**  
 Not to be cited until the corresponding paper is accepted in a peer-reviewed journal.



# Web-Based Transparent Electrodes at 2011 Material Prices

Calculated Costs for Three Different Transparent Electrode Options



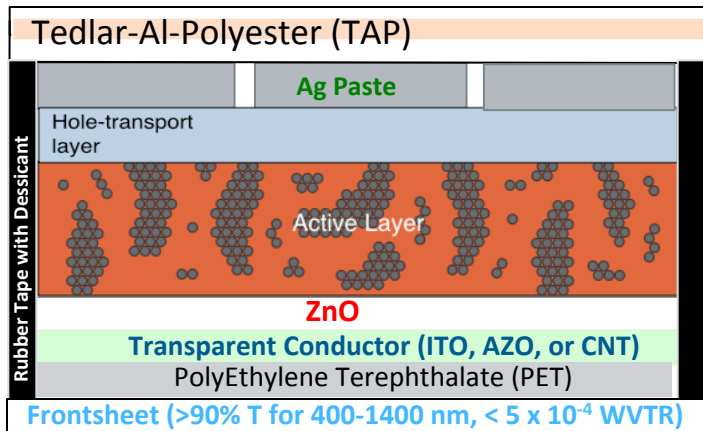
Notable material price trends:

- Indium ↑
- CNTs ↓

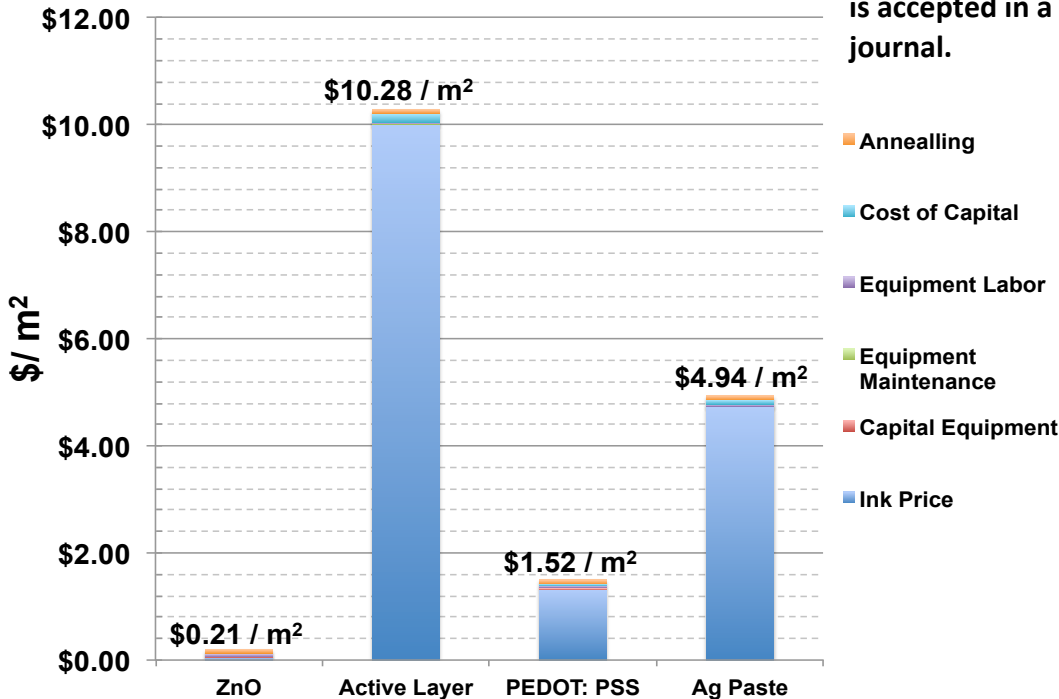
Draft analysis.  
Not to be cited until the corresponding paper is accepted in a peer-reviewed journal.

- **100 nm ITO sputtered from Planar Targets.**  $\approx 30 \Omega/\square$  expected
  - Price: \$990/ kg, 30% target utilization, 10% Discount Rate, U.S. Labor Rates
  - *Best material deposited at 200-300 °C, which may actually require the use of PEN (\$5 – 10 more/ m<sup>2</sup>)*
- **400 nm AZO sputtered from Planar Targets.**  $\approx 30 \Omega/\square$  expected
  - Price: \$170/ kg, 30% target utilization, 10% Discount Rate, U.S. Labor Rates
  - *AZO can be sputtered at about a 2X faster deposition rate than ITO.*
  - *As a disadvantage, AZO does have a higher reflectivity*
- **45 nm CNT (with 30% porosity) printed** at 45 m/ min.  $\approx 60 \Omega/\square$  expected. Price: \$50,000/ kg.

# Web-Based Device Layers at 2011 Material Prices



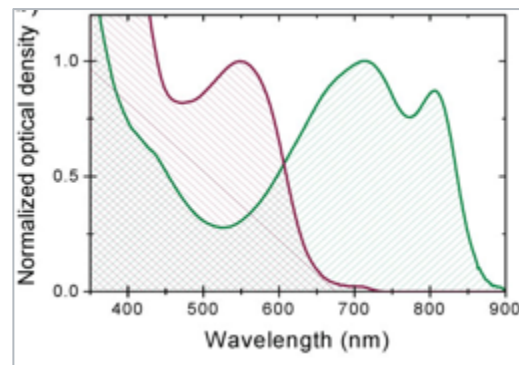
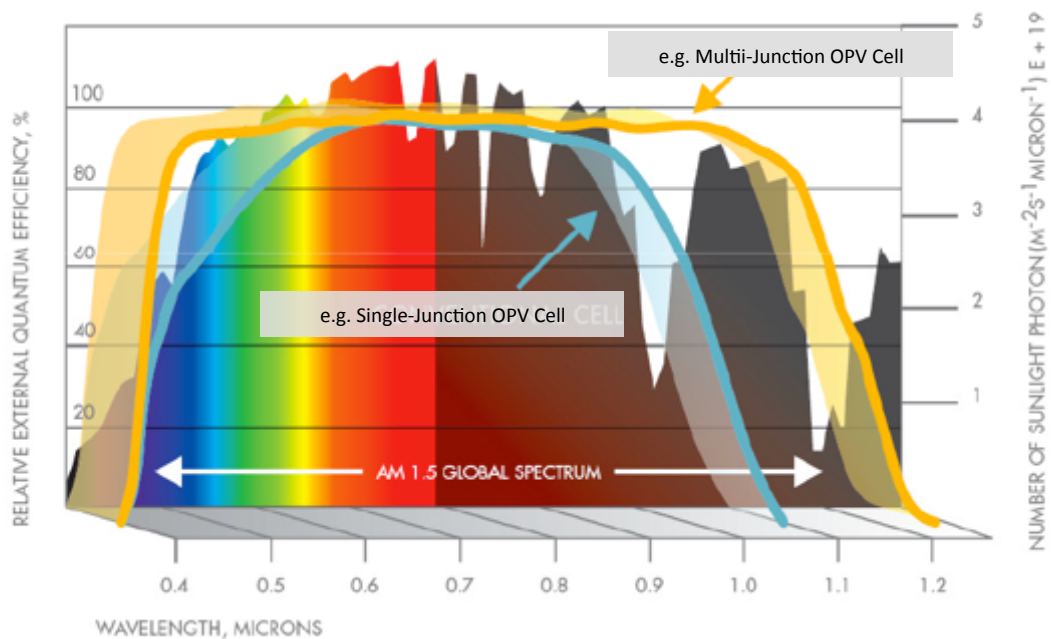
Draft analysis. Not to be cited until the corresponding paper is accepted in a peer-reviewed journal.



Estimated 'CapEx' for a new c-Si plant:  
**\$1.40 - \$1.60/ W.** See for example:  
[http://www.pv-tech.org/news/gcl\\_poly\\_energy\\_foxconn\\_technology\\_partner\\_for\\_solar\\_plant\\_in\\_shanxi\\_provin](http://www.pv-tech.org/news/gcl_poly_energy_foxconn_technology_partner_for_solar_plant_in_shanxi_provin)

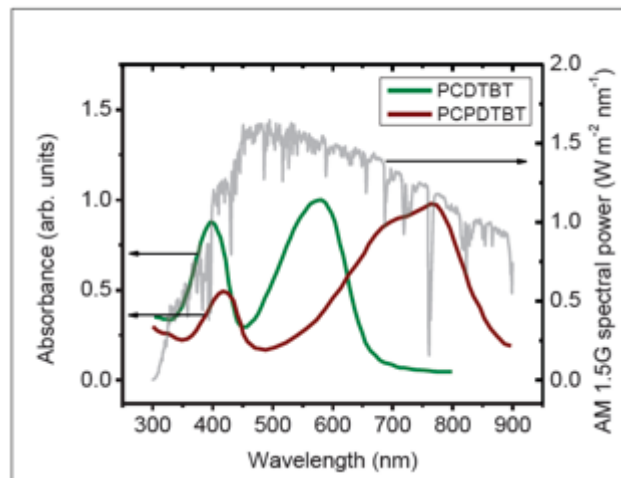
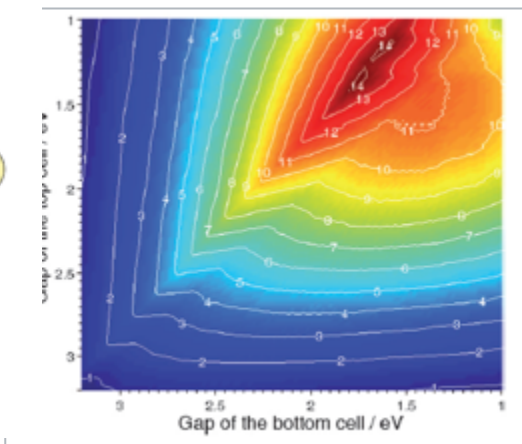
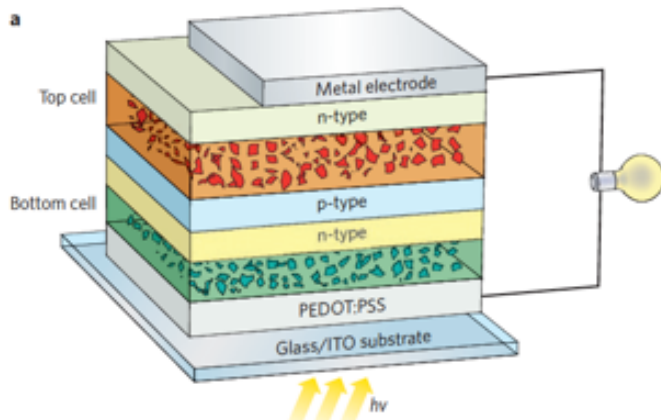
A R2R system setup to make 15% devices at 45 m/ min : **\$0.056/ W.**

# One Long-Term Pathway to >10% Efficiencies at UltraLow Cost: Multi-Junction OPV



Absorption profiles for typical OPV molecules shown above and below. Multi-junction architectures are likely needed in order to increase efficiencies to a level comparable to inorganics.

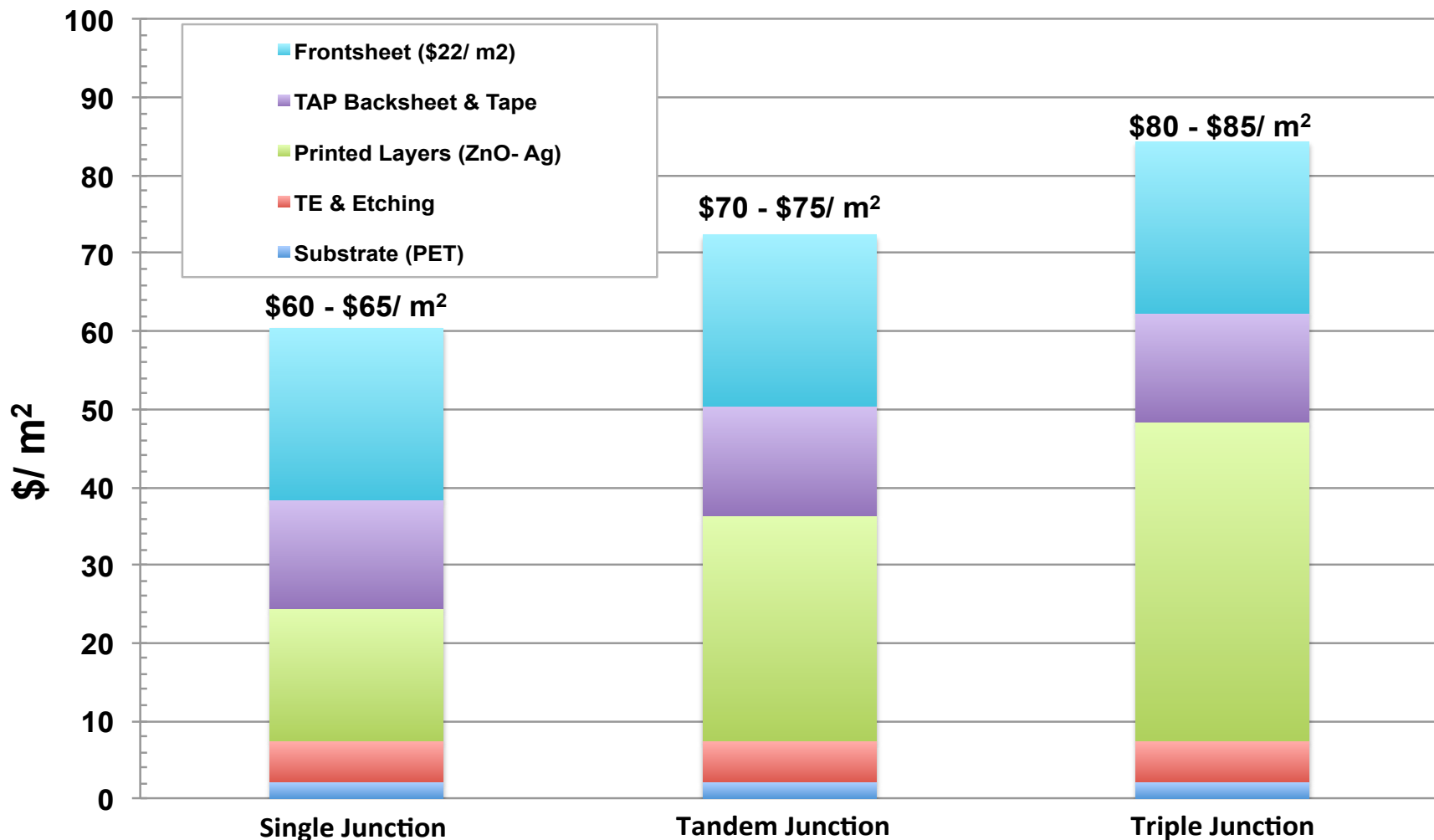
$$J_{sc} = \int_{\lambda_{min}}^{\lambda_{max}} QE(\lambda) \times AM1.5(\lambda) d\lambda$$



Li, G.; Zhu, R.; Yang, Y.  
*Nature Photonics*, (6): pp. 153-159.  
 Tandem Junction 8.6% efficient OPV cell

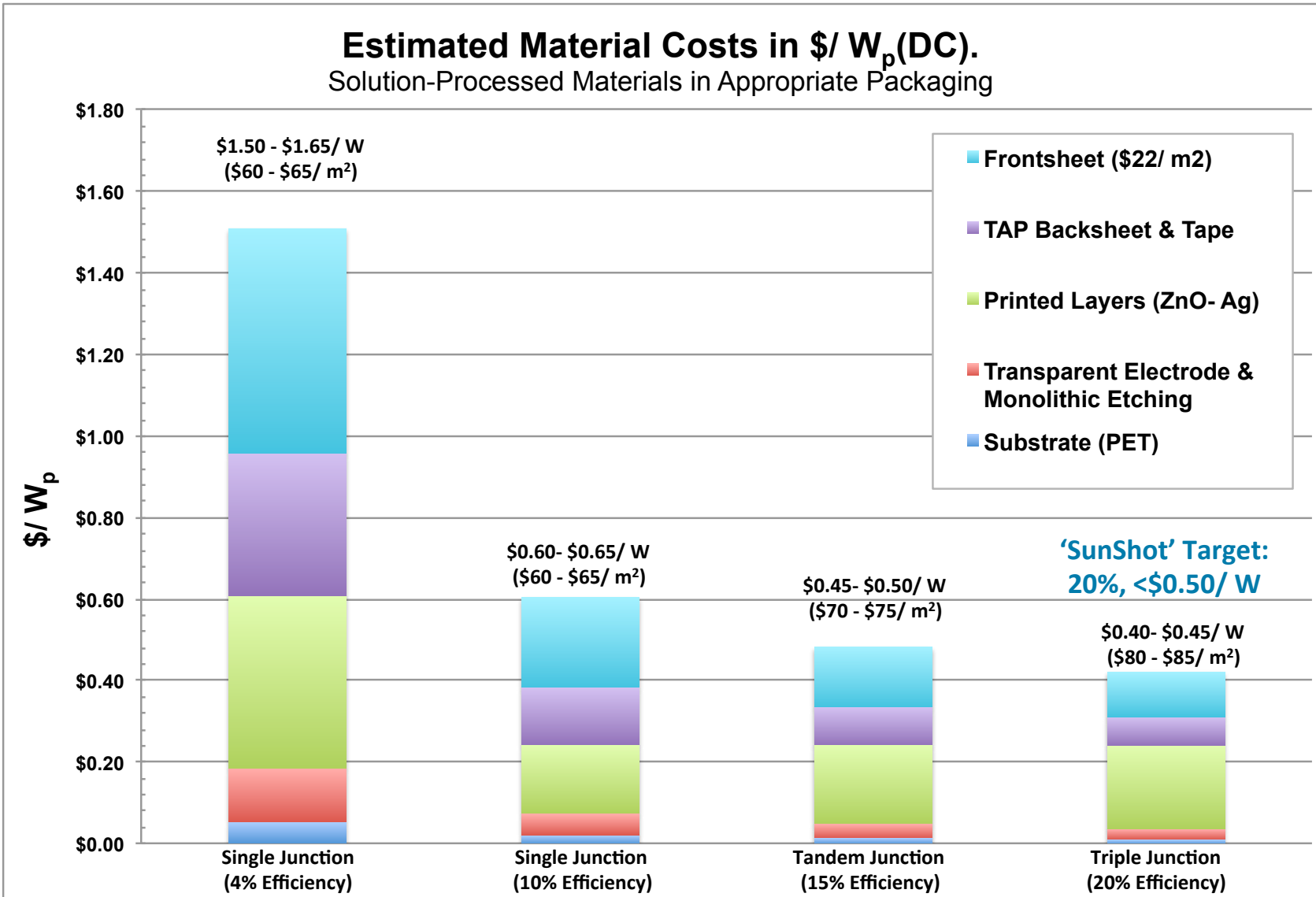
# Calculated Costs for Module Made via Solution Processing

**Estimated Material Costs in \$/ m<sup>2</sup>**  
Solution-Processed Materials in Appropriate Packaging



Draft analysis. Not to be cited until the corresponding paper is accepted in a peer-reviewed journal.

# Calculated Costs for Module Made via Solution Processing

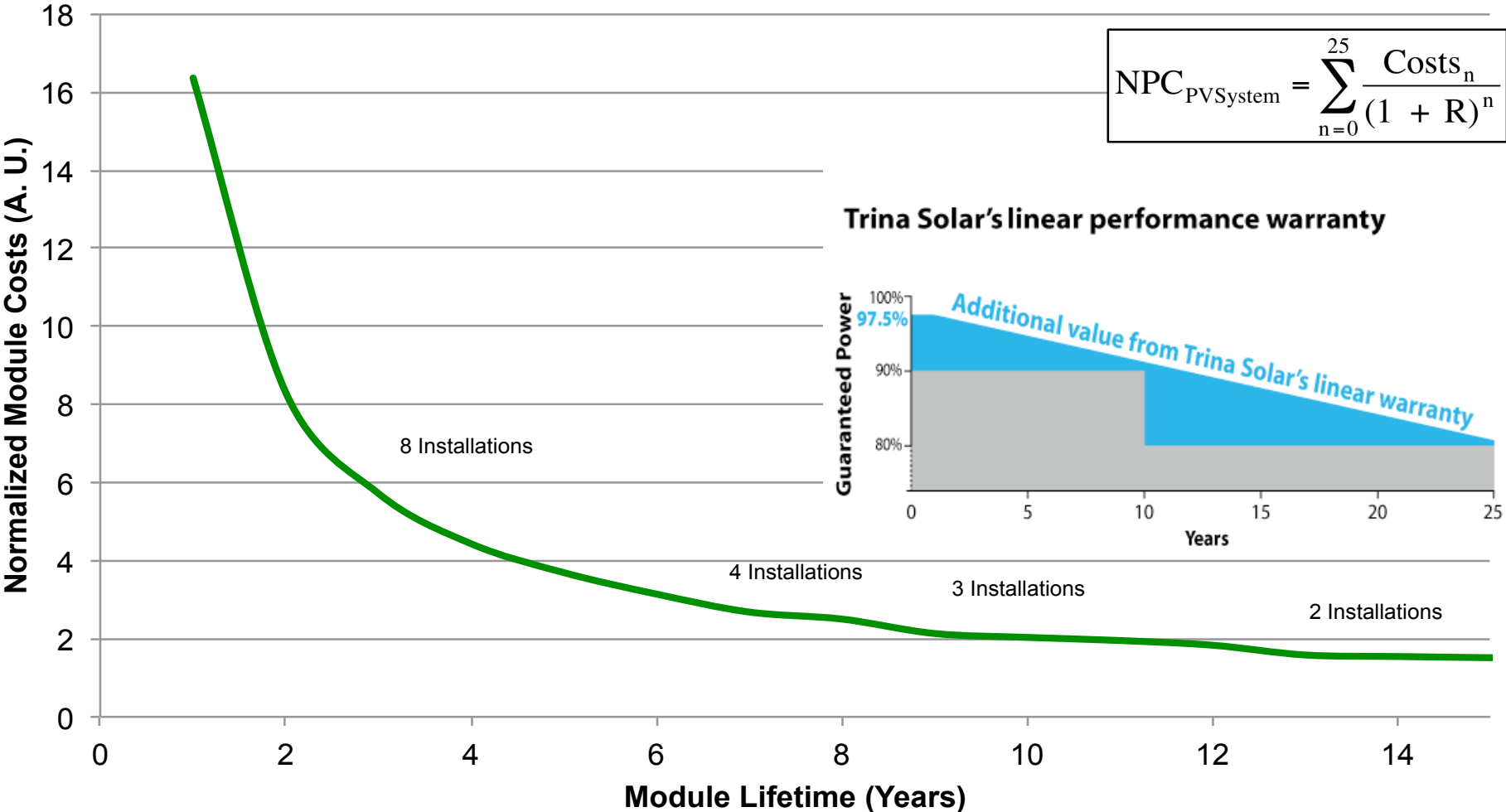


Draft analysis. Not to be cited until the corresponding paper is accepted in a peer-reviewed journal.

# That product will also need to come with a warranty

## Normalized Total Net Present Module Costs as a Function of Module Lifetime

(7% Discount Rate (R), 25% Installer Margin on Module, Includes Replacement Labor)



$$NPC_{PVSystem} = \sum_{n=0}^{25} \frac{Costs_n}{(1 + R)^n}$$

<http://www.trinasolar.com/eu/products/product-resources/product-warranty>

# Storage is also critical

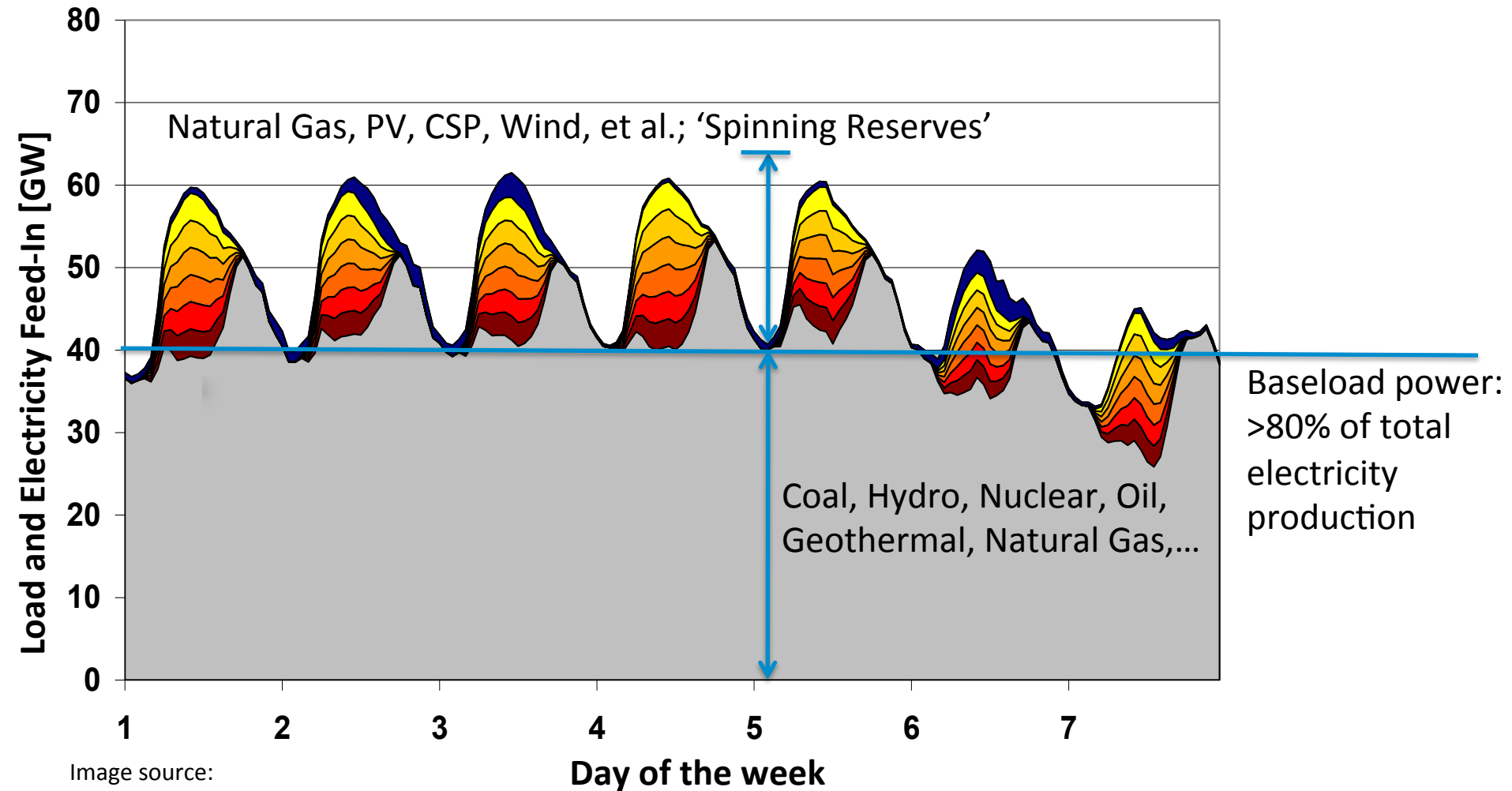


Image source:  
European Photovoltaics Industry Association

Energy storage solutions are needed for penetration >10-20%.

Please see: Denholm, P. and Margolis, R. (2007). *Energy Policy*, 35: pp. 2852-2861.

# Questions? Comments?

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[david.feldman@nrel.gov](mailto:david.feldman@nrel.gov)  
[alan.goodrich@nrel.gov](mailto:alan.goodrich@nrel.gov)

call: 303-384-7623 (mike's number)

Thank You!