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Considerations for Solar Energy Technologies to Make Progress Towards Grid Price Parity

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CEMAC Clean Energy Manufacturing Analysis Center
Operated by the Joint Institute for Strategic Energy Analysis

King Abdullah University of Science and Technology (KAUST) Solar Symposium 2015. Thuwal, Saudi Arabia.

November 10, 2015

Alfred Hicks and Kendra Palmer
Graphics and Communications

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Overview of Presentation

I. Value Proposition and Needs for Increased Solar Deployment:

- Lower greenhouse gas emissions and predictable (zero) fuel price
- The sensitivity of levelized cost of energy (LCOE) to capital costs, operation and maintenance (O&M), and fuel prices for the traditional and other renewable energy options in power generation
- The LCOE of PV and relationship to total system costs
- The current ranges of LCOE for photovoltaics (PV) across the United States

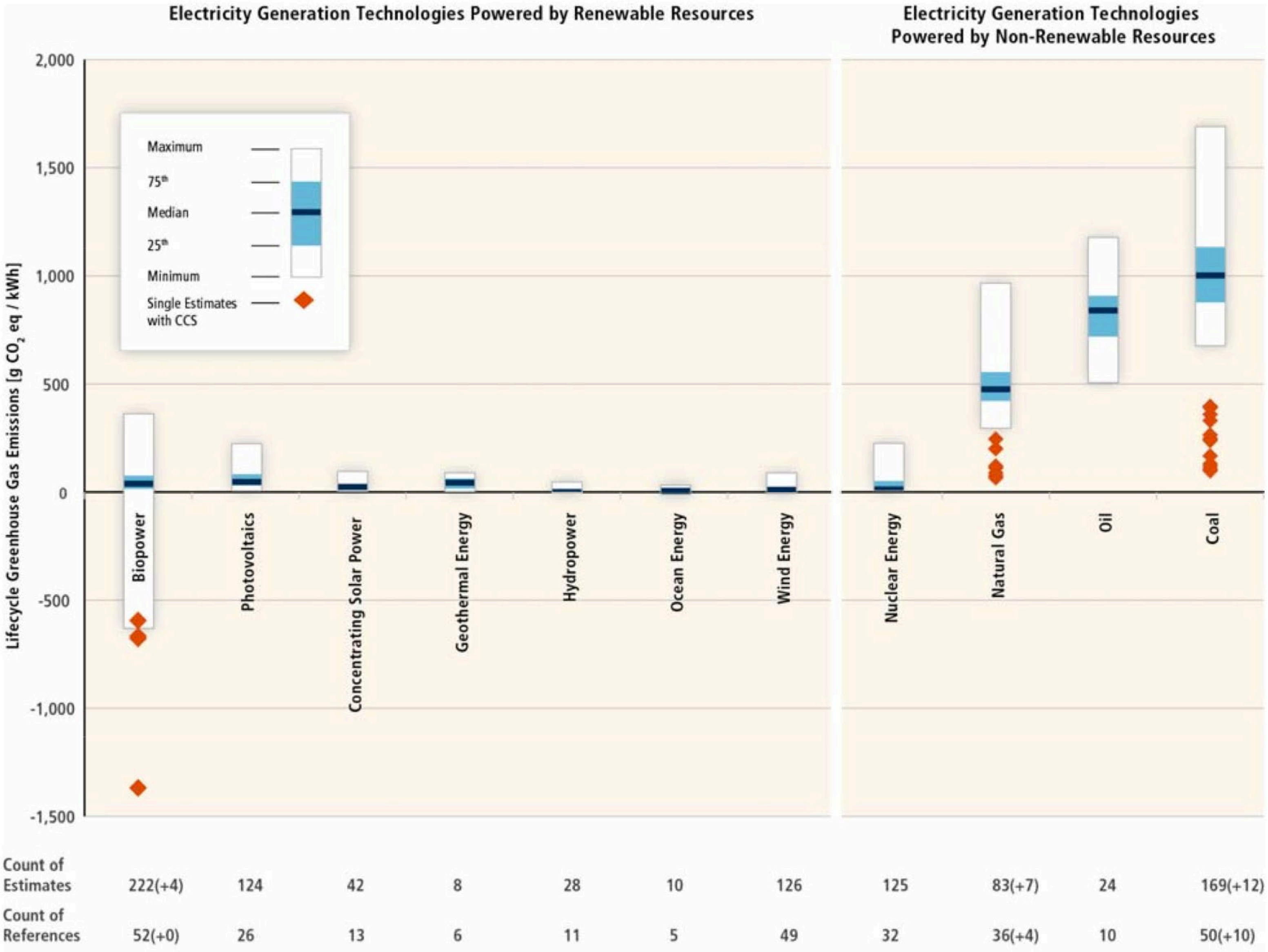
II. Benchmarking Photovoltaics Component Costs:

- Overview of NREL's bottom-up cost modeling methods and results for crystalline silicon and thin-film module technologies

III. The Path Forward:

- Technology development opportunities that impact LCOE
- A changing energy mix: Regional Energy Deployment Systems (ReEDS) model results for expansion in power generation capacity.

Greenhouse Gas Emission Characteristics of Several Energy Choices



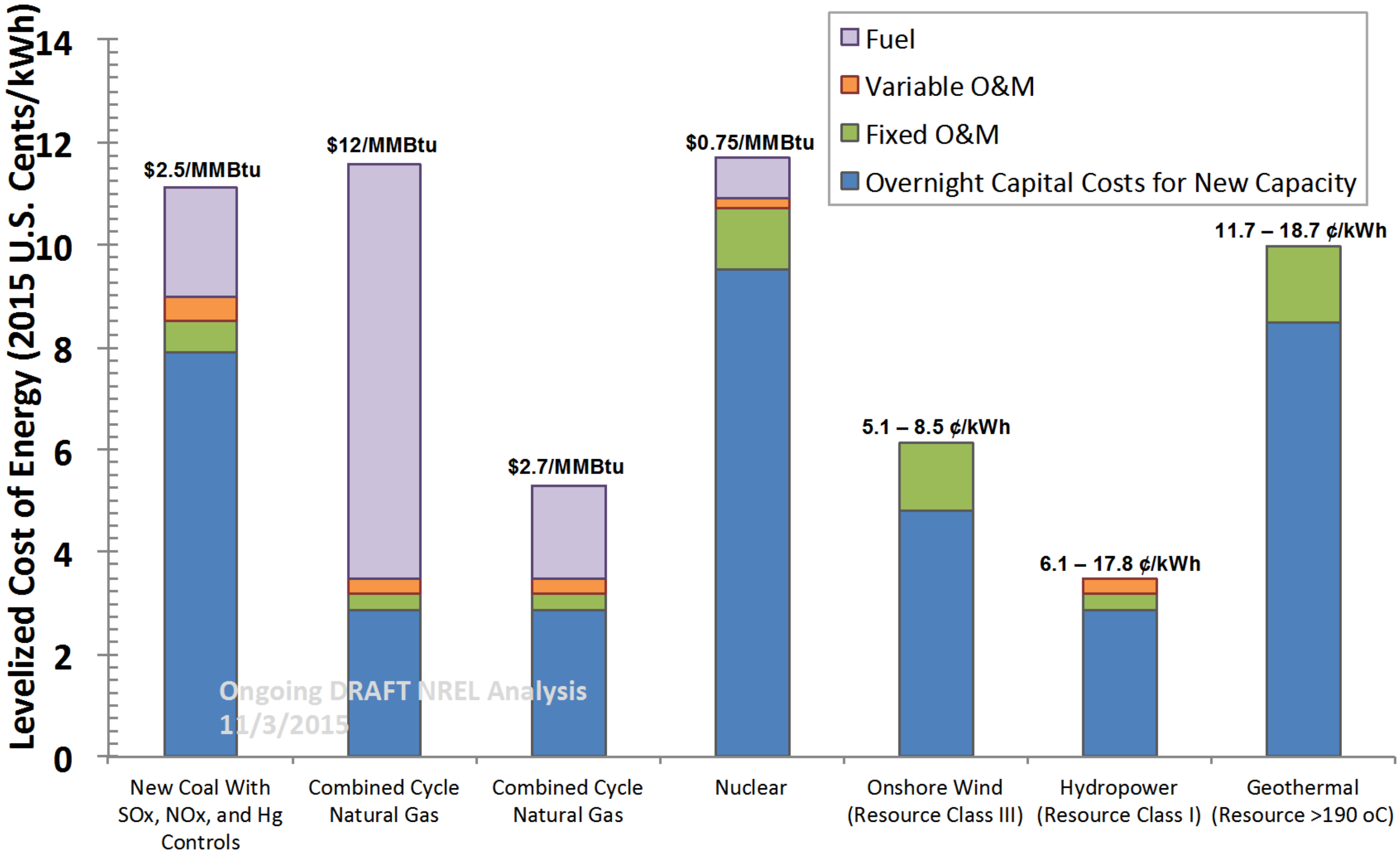
Source of GHG ranges: Intergovernmental Panel on Climate Change (IPCC). 2011. Figure 8 in Executive Summary of the 33rd Session (Abu Dhabi, May 2011). Accessed May 2015, http://www.ipcc.ch/meetings/session33/doc20_p33_SPM_SRREN.pdf.

Benchmark LCOE for Various Energy Options

Estimates of Electricity Production Costs From New Capacity

November 3, 2015

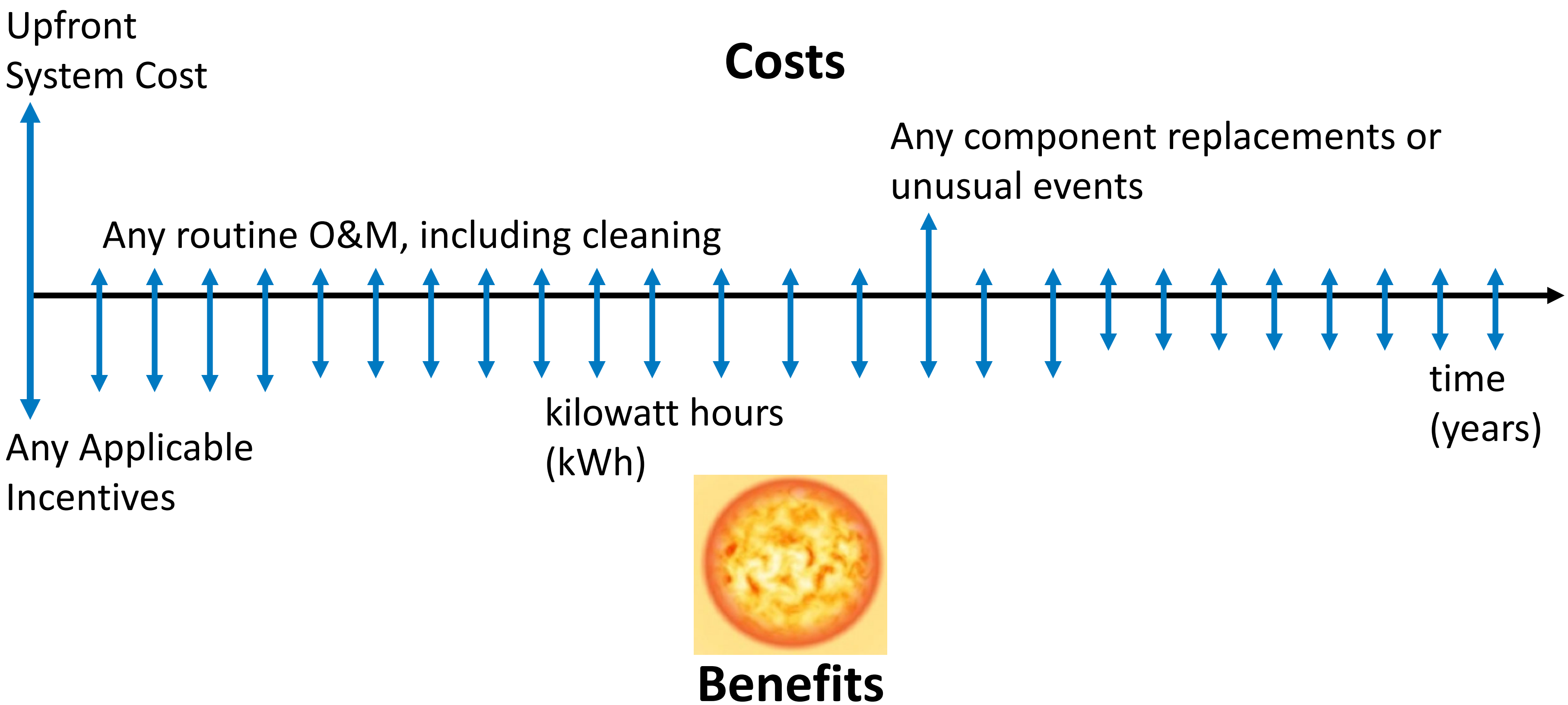
Representative fuel-based capital and O&M costs are without carbon capture and sequestration (CCS). Renewable resource classes selected on the basis of largest available U.S. capacity in 2015 (ranges reflect other resource classes within the U.S.).



Source: "Transparent Cost Database: LCOE Spreadsheet." 2015. Golden, CO: NREL. Accessed October 2015. Available online: http://www.nrel.gov/analysis/data_tech_baseline.html

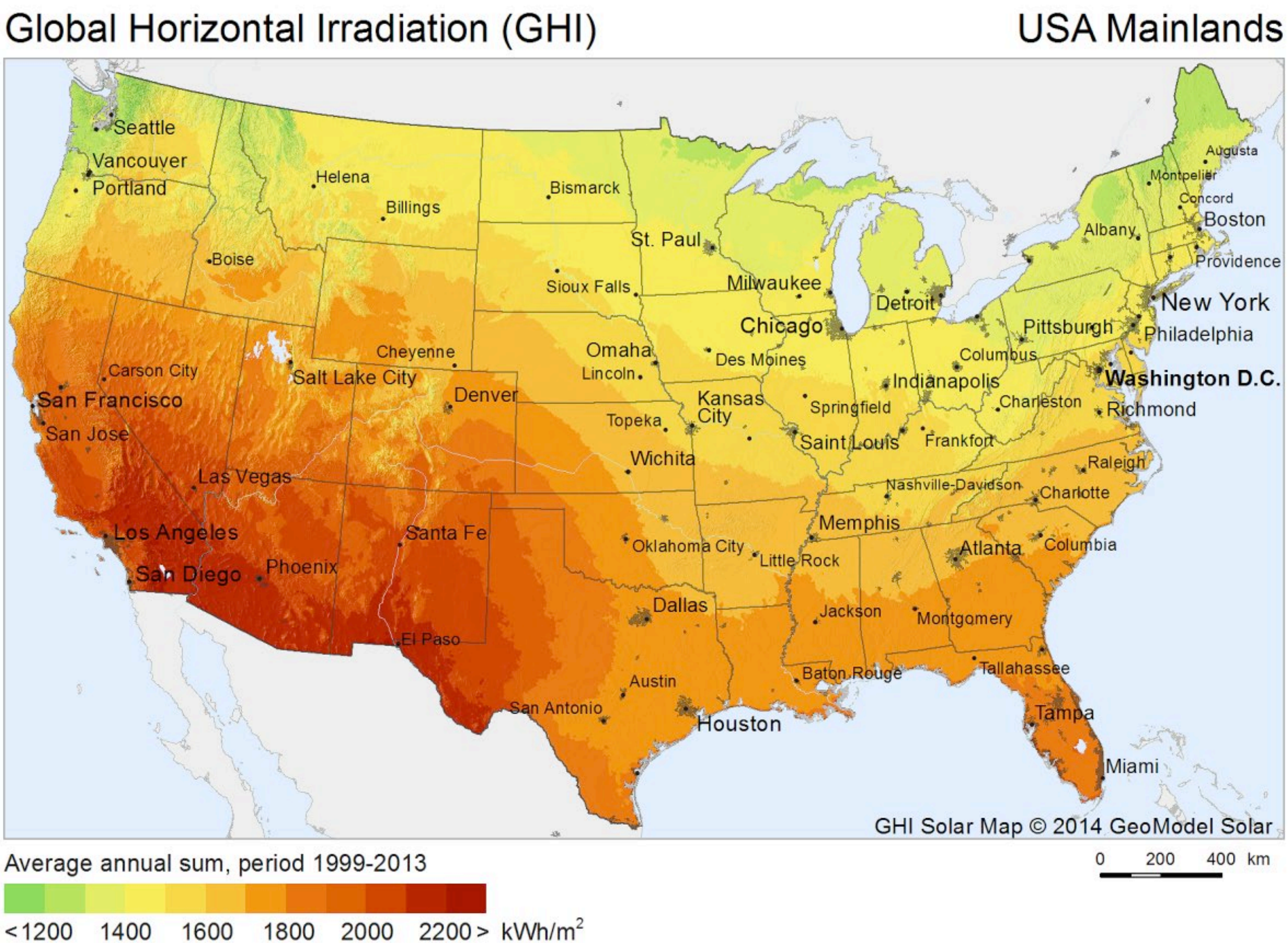
Calculating the LCOE of PV

$$\text{LCOE (\$/kWh)} = \frac{\text{Total Life Cycle Cost (\$)}}{\text{Total Lifetime Energy Production (kWh)}}$$



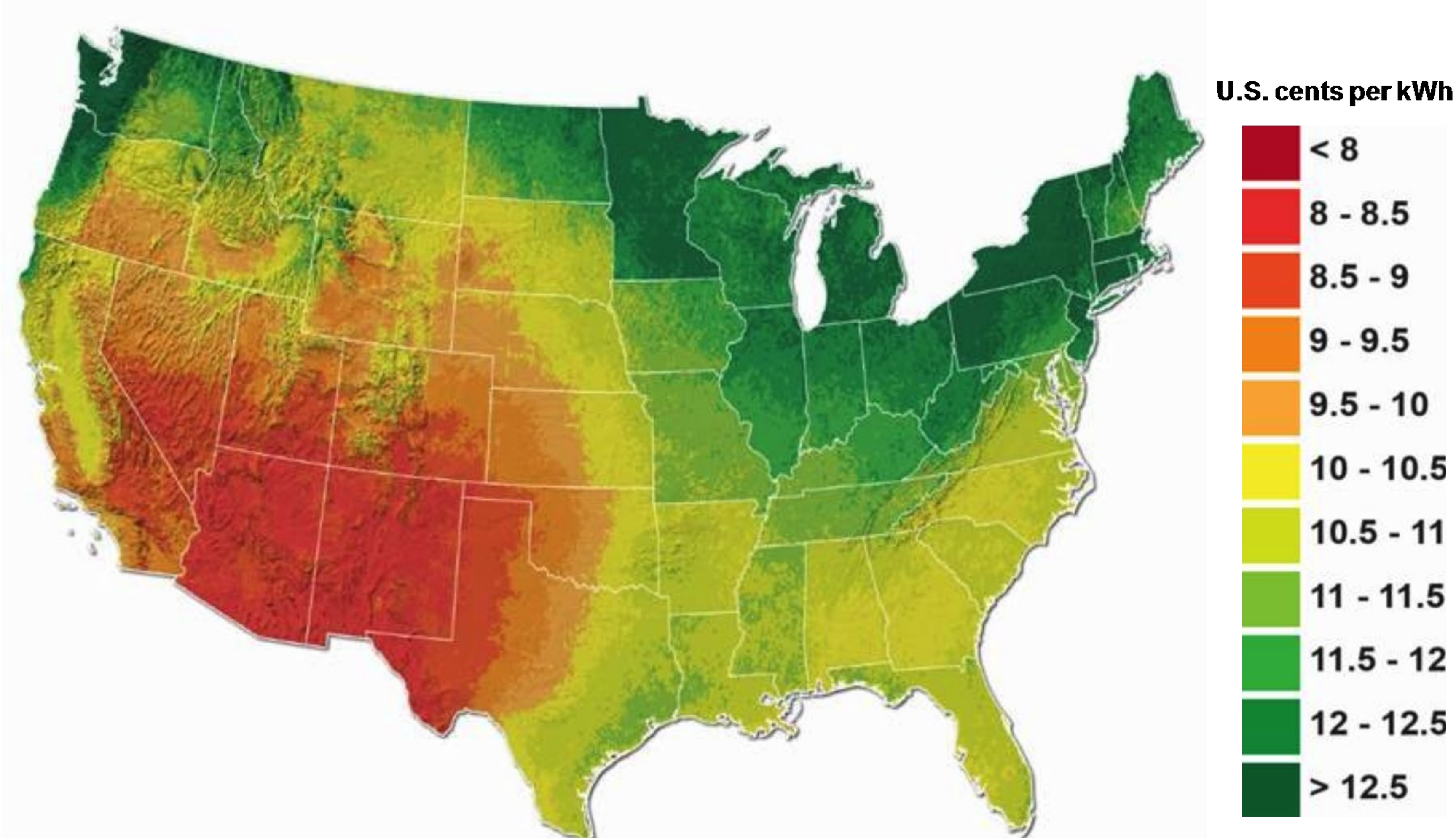
For an overview of the NREL System Advisor Model (SAM) approach to calculating LCOE, please see: Short, W., D.J. Packey, and T. Holt. 1995. *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies*. NREL/TP-462-5173. Golden, CO: NREL. Accessed May 2015, http://www.nrel.gov/docs/legosti/old/5173.pdf.

Calculating the LCOE of Solar: Location Matters



Source of figure: http://solargis.info/doc/free-solar-radiation-maps-GHI. Accessed November 2015.

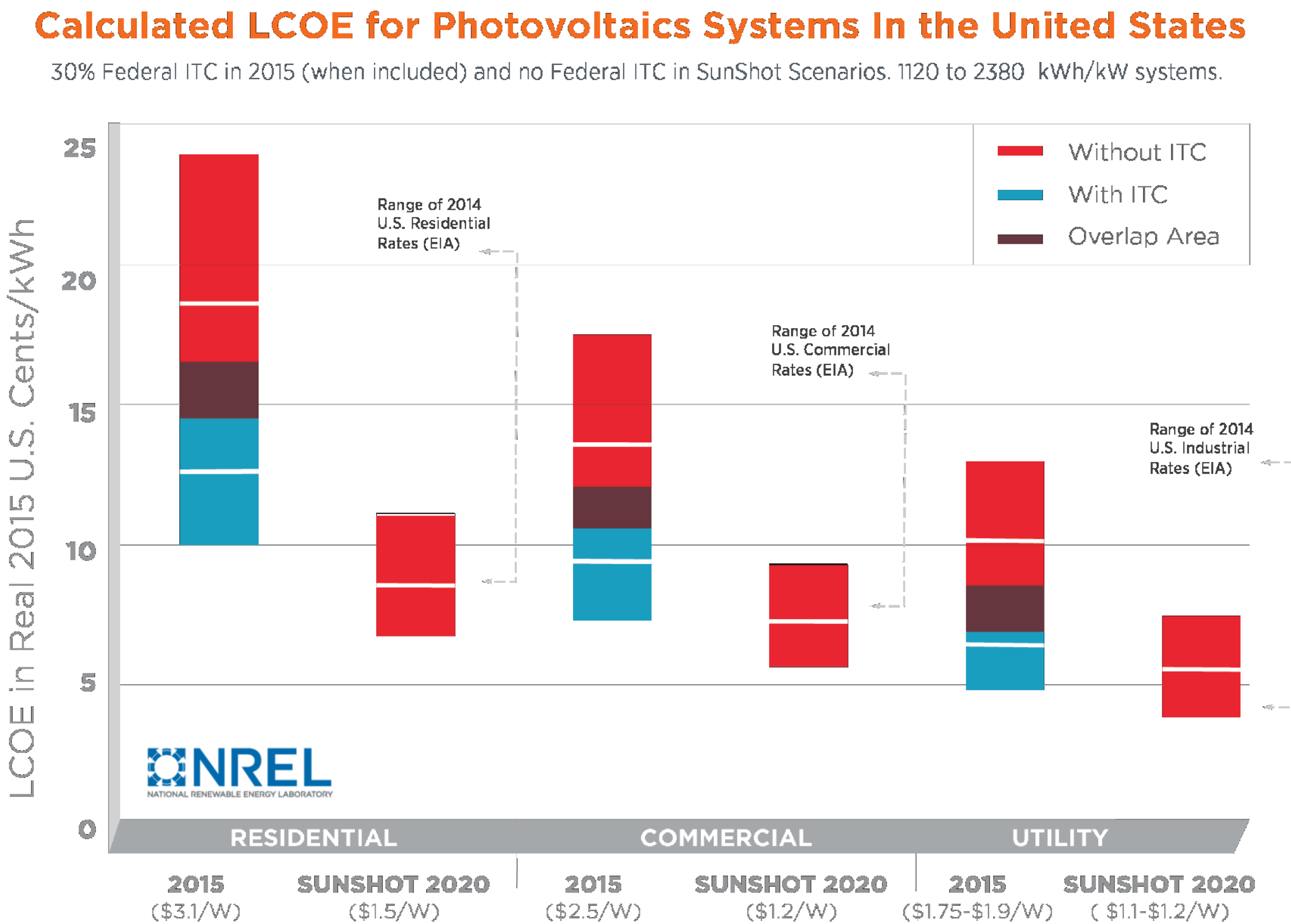
Calculated Fixed-Tilt, Utility-Scale LCOE for PV Across the Contiguous United States



50-MW PV system (including 25-year system life, 10% IRR target, 10.9% nominal discount rate, 50% debt fraction at 7% interest for 20 years, 30% federal ITC, and 5-year federal and state MACRS depreciation). Regional considerations for wind and snow loads, labor rates, permitting costs, and sales taxes are also included.

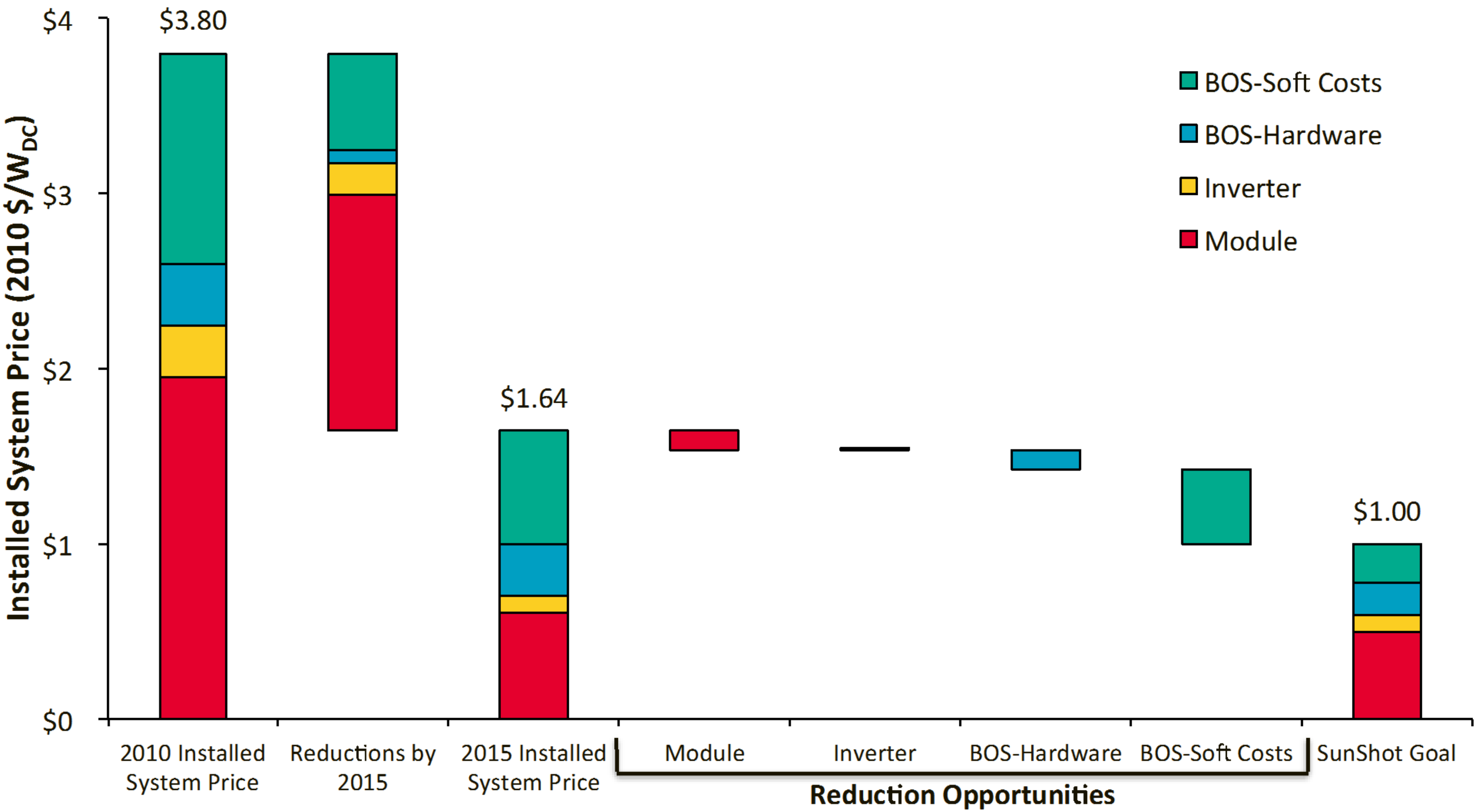
Source of figure: Fu, R., T. James, D. Chung, D. Gagne, A. Lopez, and A. Dobos. 2015. "Economic Competitiveness of U.S. Utility-Scale Photovoltaics Systems—Regional Cost Modeling of Installed Price and LCOE." *IEEE Journal of Photovoltaics*, Accepted, 2015.

Benchmark and SunShot 2020 Target LCOEs for Solar PV



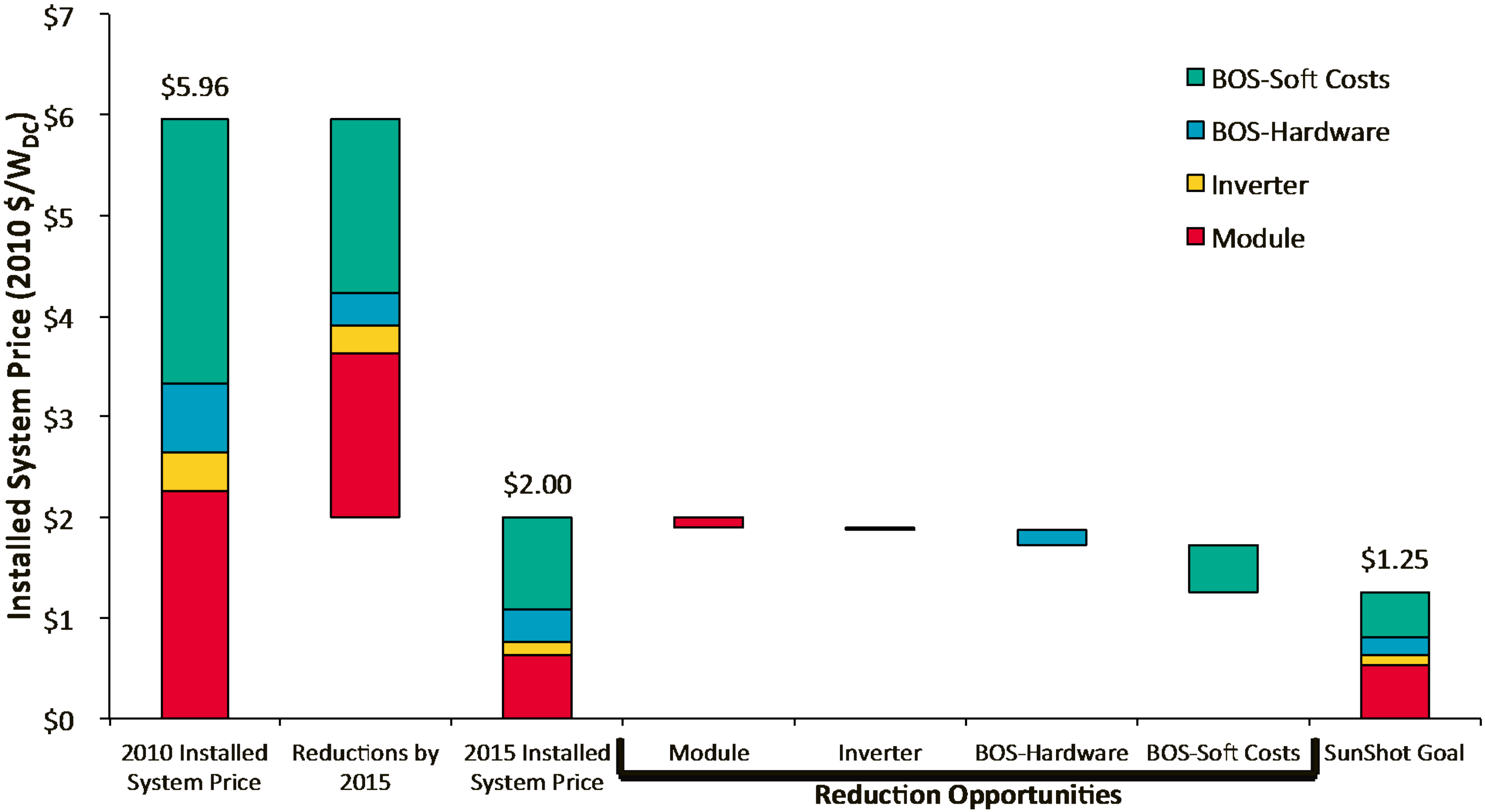
Source: Jones-Albertus, R., D. Feldman, R. Fu, K. Horowitz, and M. Woodhouse. 2015. *Technology Advances Needed for Photovoltaics to Achieve Widespread Grid Price Parity*. Washington, D.C.: Department of Energy (DOE). Accessed September 2015, http://energy.gov/eere/sunshot/downloads/technology-advances-needed-photovoltaics-achieve-widespread-grid-price-parity.

Past, Present, and SunShot 2020 Systems Costs (Utility)



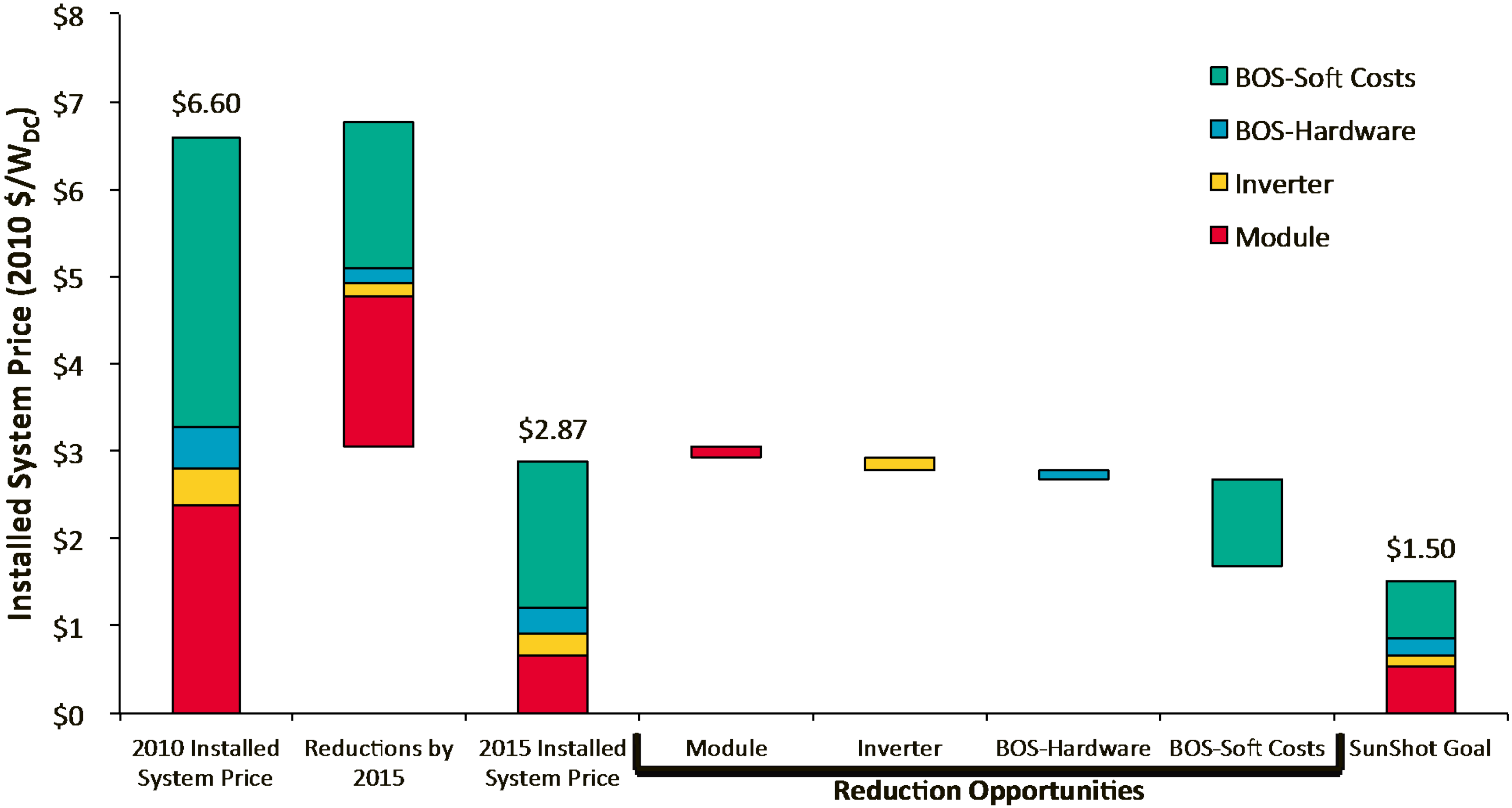
Sources: **2010**: Feldman et al. 2014. "Photovoltaic System Pricing Trends: Historical, Recent, and Near-Term Projections –2014 Edition." NREL/PR-6A20-62558. Golden, CO: NREL. **2015**: Chung et al. 2015. *U.S. Photovoltaic Prices and Cost Breakdowns: Q1 2015 Benchmarks for Residential, Commercial, and Utility-Scale Systems*. NREL/TP-6A20-64746. Golden, CO: NREL. **SunShot Goal**: DOE. (2012). *SunShot Vision Study*. DOE/GO-102012-3037. Washington, D.C.: DOE.

Past, Present, and SunShot 2020 Systems Costs (Commercial)



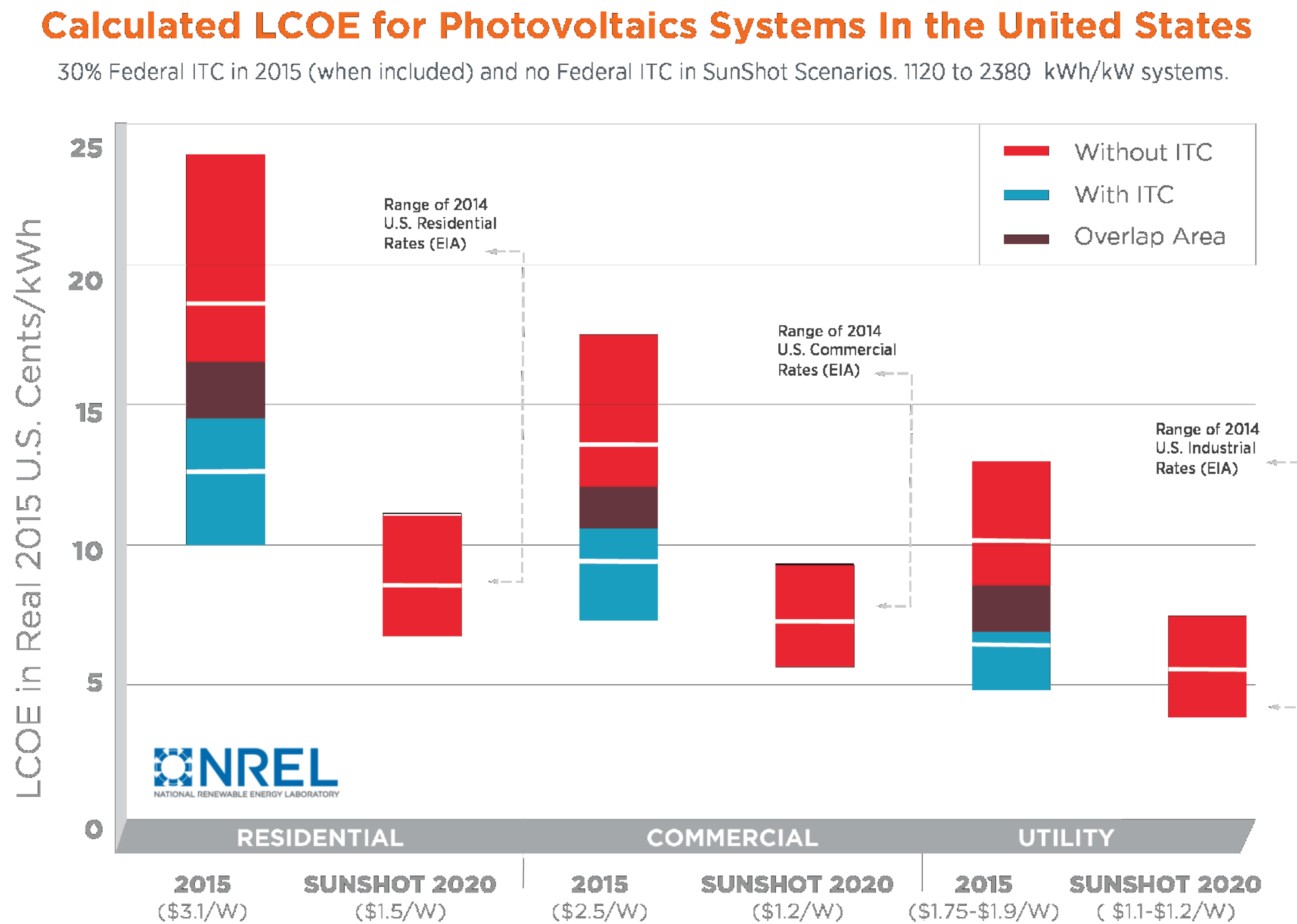
Sources: **2010**: Feldman et al. 2014. "Photovoltaic System Pricing Trends: Historical, Recent, and Near-Term Projections –2014 Edition." NREL/PR-6A20-62558. Golden, CO: NREL. **2015**: Chung et al. 2015. *U.S. Photovoltaic Prices and Cost Breakdowns: Q1 2015 Benchmarks for Residential, Commercial, and Utility-Scale Systems*. NREL/TP-6A20-64746. Golden, CO: NREL. **SunShot Goal**: DOE. (2012). *SunShot Vision Study*. DOE/GO-102012-3037. Washington, D.C.: DOE.

Past, Present, and SunShot Systems Costs (Residential)



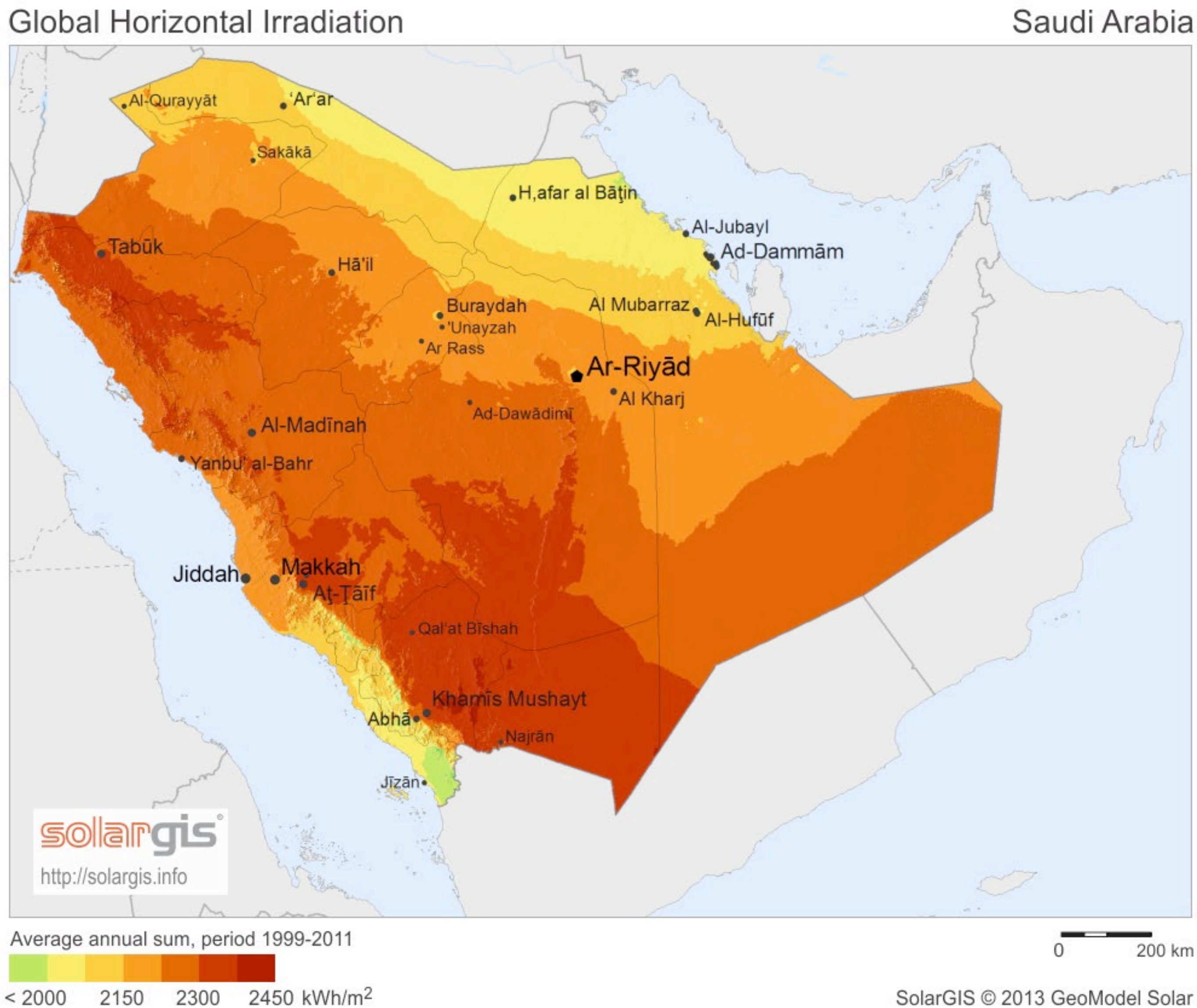
Sources: **2010**: Feldman et al. 2014. "Photovoltaic System Pricing Trends: Historical, Recent, and Near-Term Projections –2014 Edition." NREL/PR-6A20-62558. Golden, CO: NREL. **2015**: Chung et al. 2015. *U.S. Photovoltaic Prices and Cost Breakdowns: Q1 2015 Benchmarks for Residential, Commercial, and Utility-Scale Systems*. NREL/TP-6A20-64746. Golden, CO: NREL. **SunShot Goal**: DOE. (2012). *SunShot Vision Study*. DOE/GO-102012-3037. Washington, D.C.: DOE.

Benchmark and SunShot 2020 Target LCOEs for Solar PV



Source: Jones-Albertus, R., D. Feldman, R. Fu, K. Horowitz, and M. Woodhouse. 2015. *Technology Advances Needed for Photovoltaics to Achieve Widespread Grid Price Parity*. Washington, D.C.: Department of Energy (DOE). Accessed September 2015, http://energy.gov/eere/sunshot/downloads/technology-advances-needed-photovoltaics-achieve-widespread-grid-price-parity.

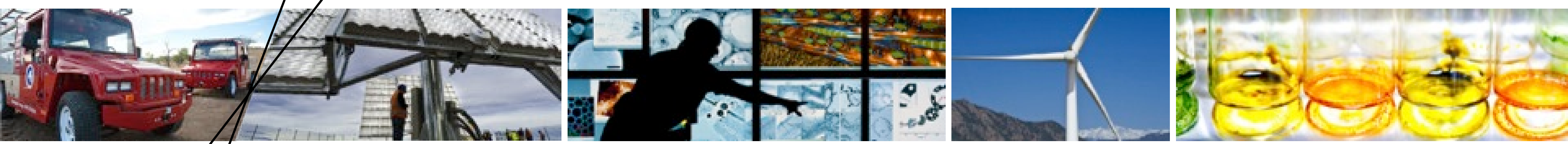
Opportunities for Future Work:
Applying the NREL LCOE Method to the Kingdom of Saudi Arabia



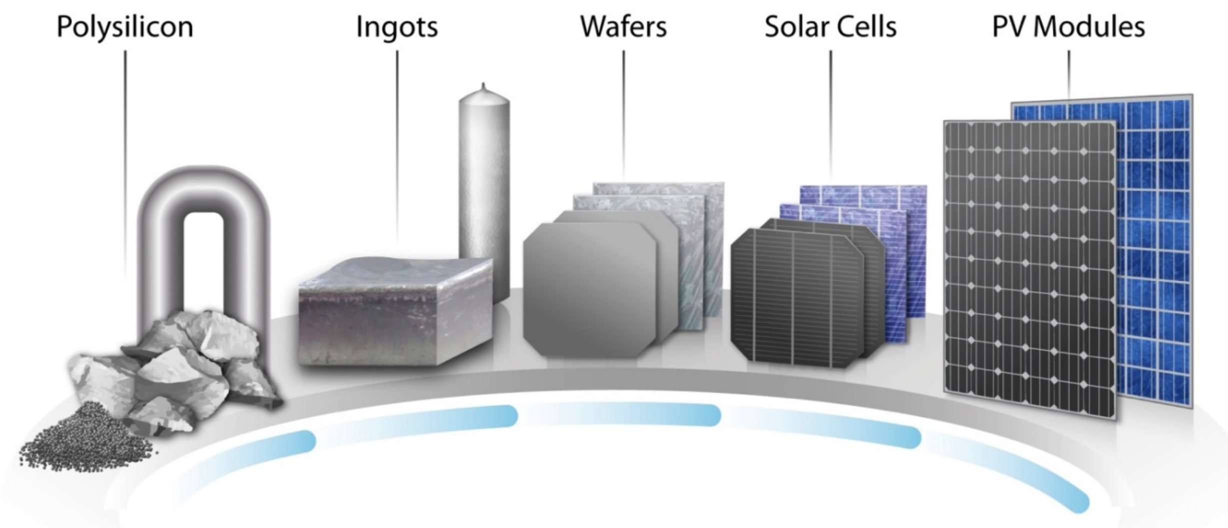
Source of figure: Saudi Arabia Solar Industry Association. Accessed November 2015. Available online: *http://saudi-sia.com/solargis-data/*

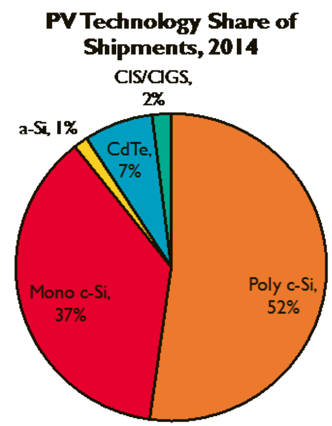
Part II:

Overview of NREL's Bottom-Up Cost Modeling Methods and Recent Results



Part IIa: The Crystalline Silicon (c-Si) Supply Chain





Source of figures: NREL.

The Global Nature of the Photovoltaics Industry

Facility Locations and Manufacturing Capacities for the Top 500 Companies

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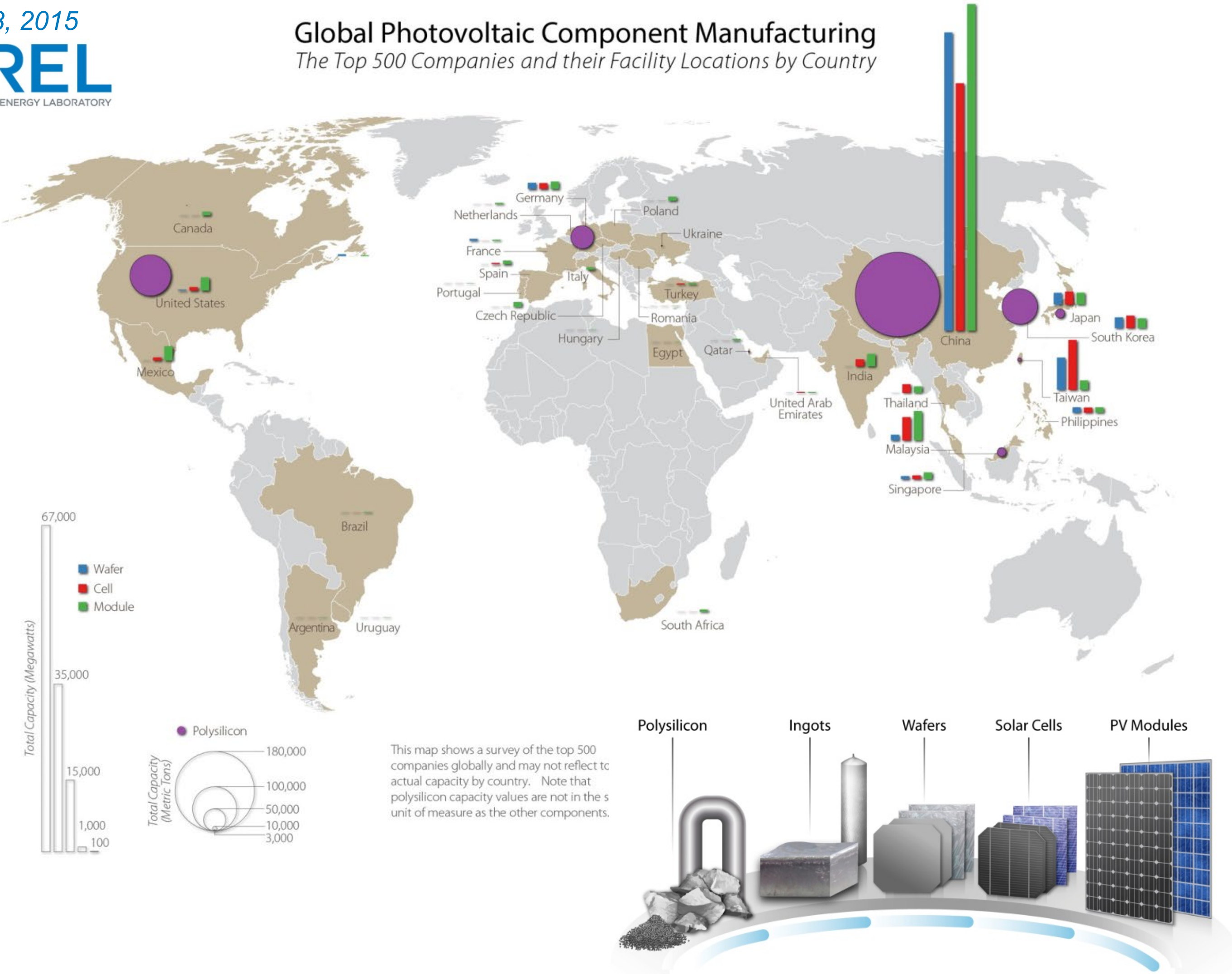
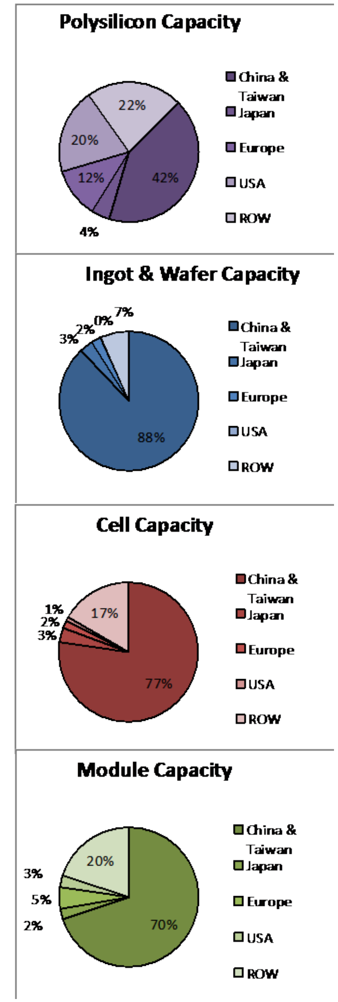
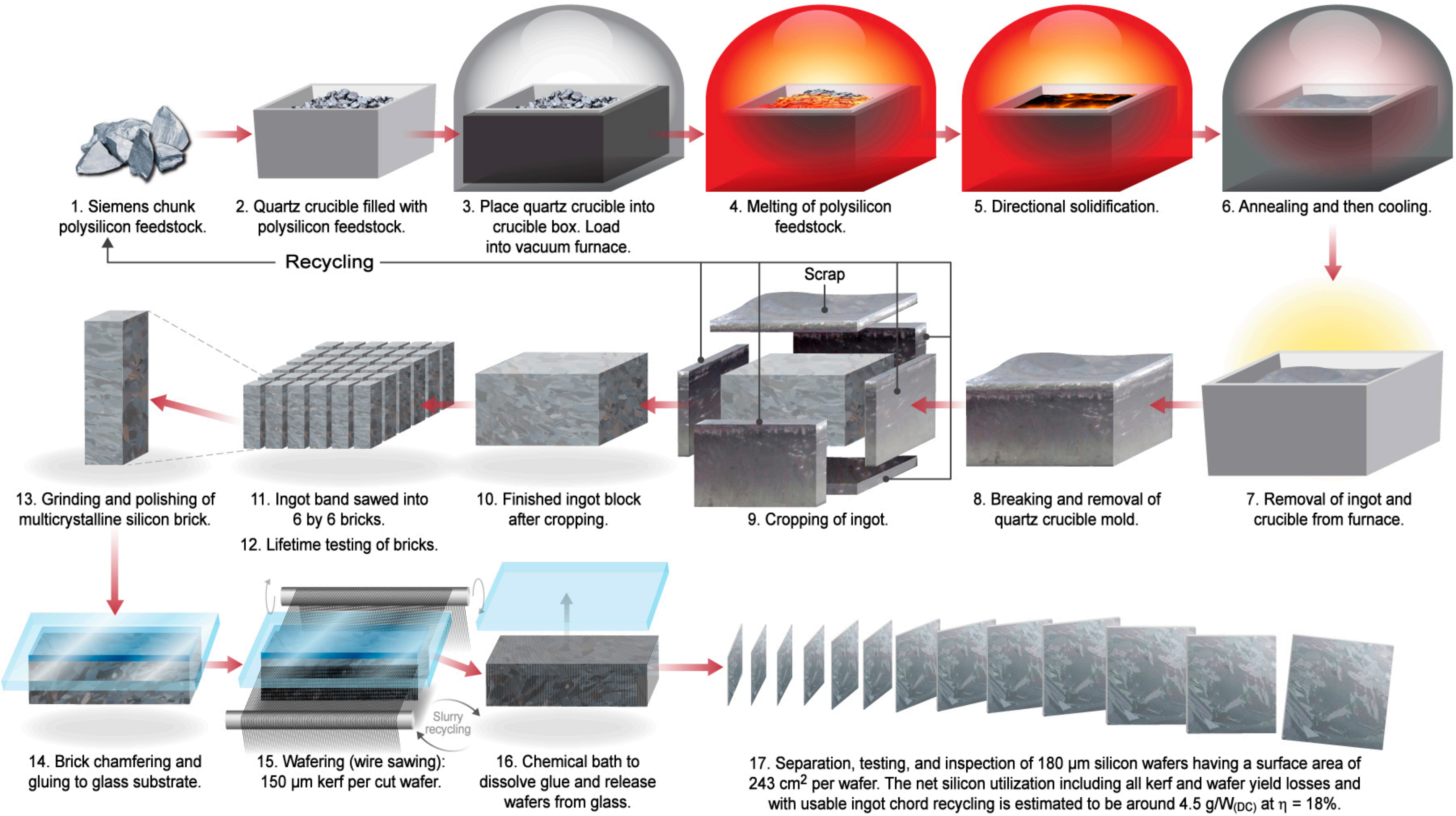


Market Share



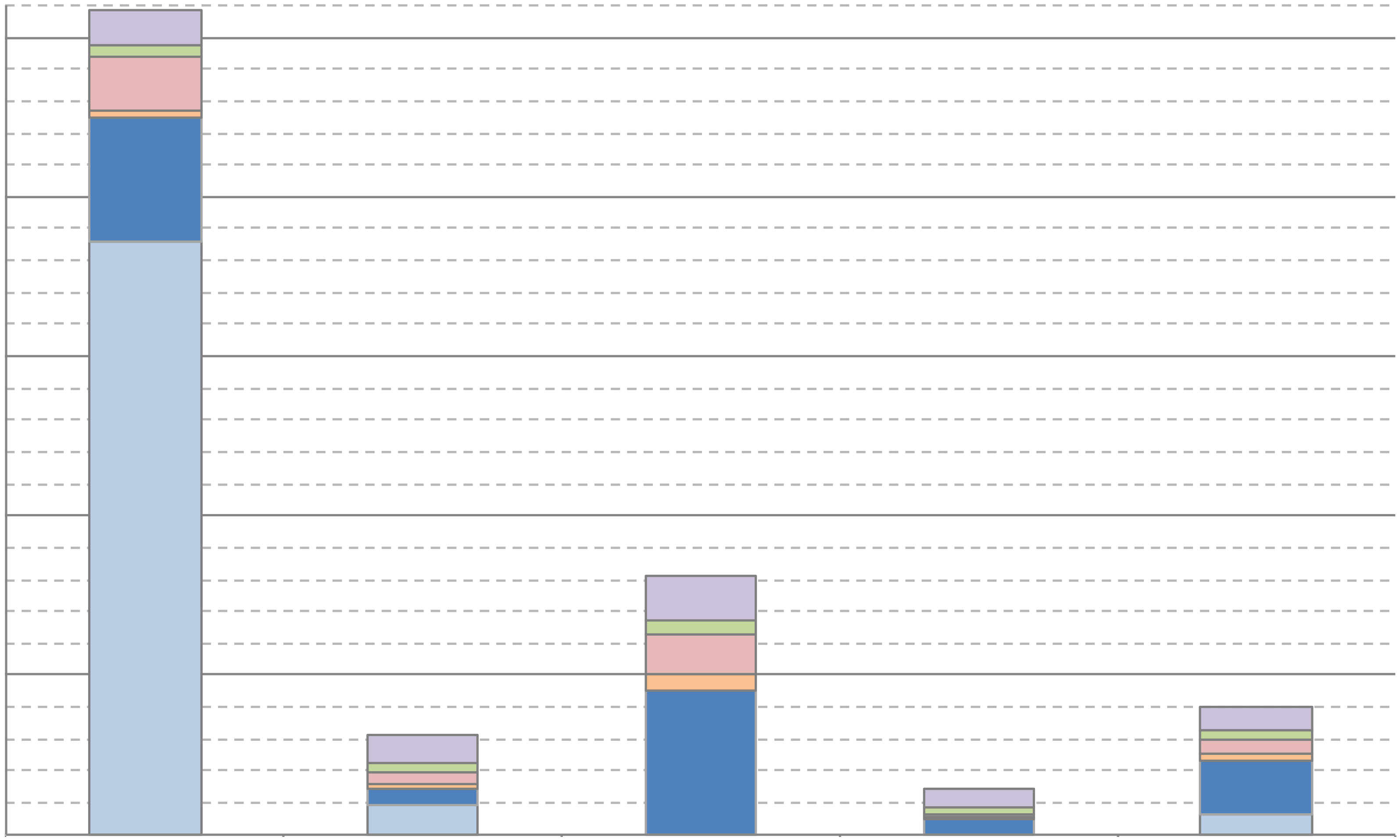
Countries observed to currently have wafer, cell, and module manufacturing production:
United States, China, Taiwan, South Korea, Japan, Philippines, Malaysia, Singapore, and Germany.

The Processes of Multicrystalline Ingot Formation with the Bridgman Directional Solidification Method and Wafering with Wire Sawing

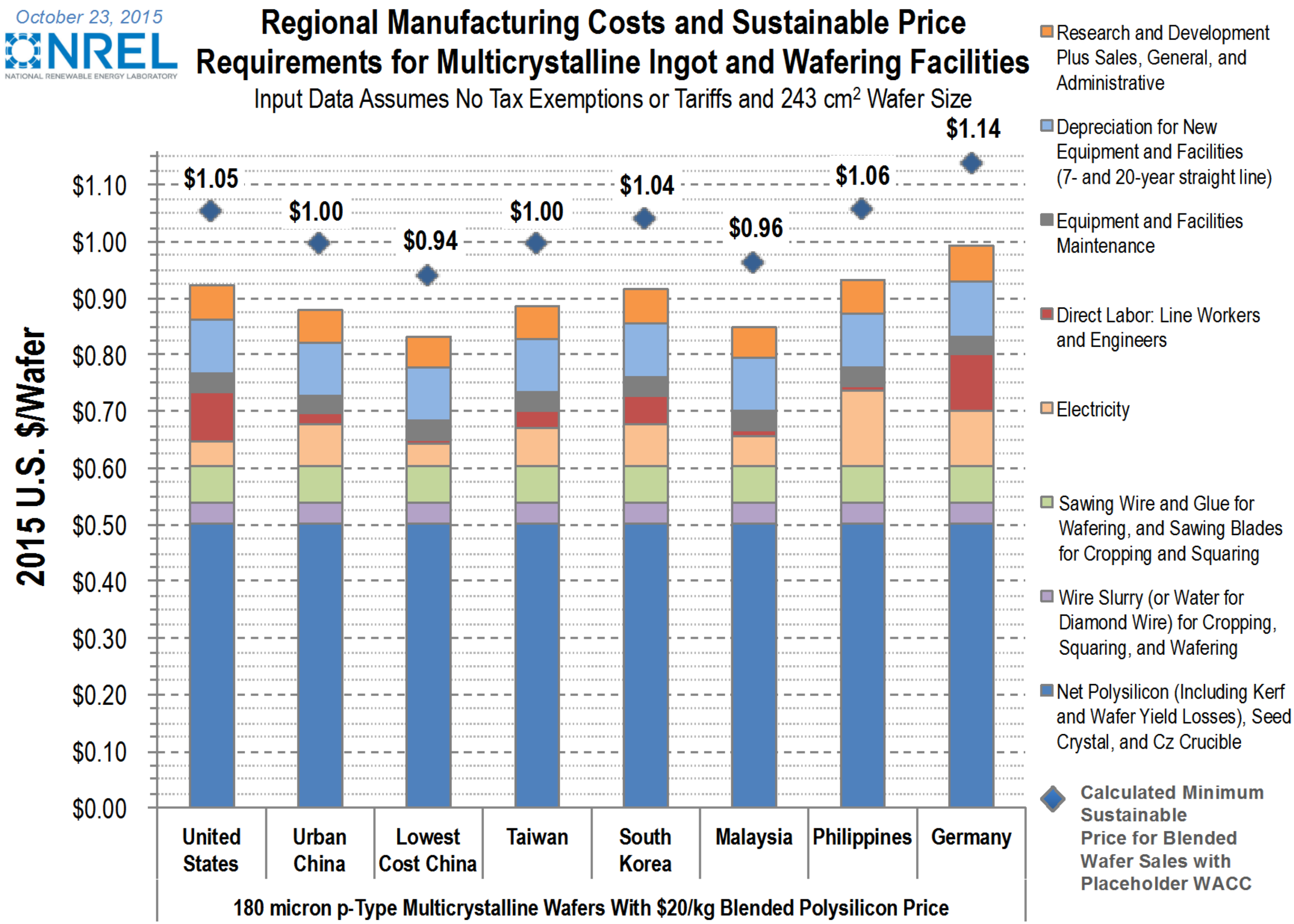


Source of figure: M Woodhouse, R Fu, T Remo, K Horowitz, D Feldman, D Chung, B Gallagher, and R Margolis "Economic Factors of Production Affecting Crystalline Silicon Photovoltaics Manufacturing Costs", *In Preparation.*

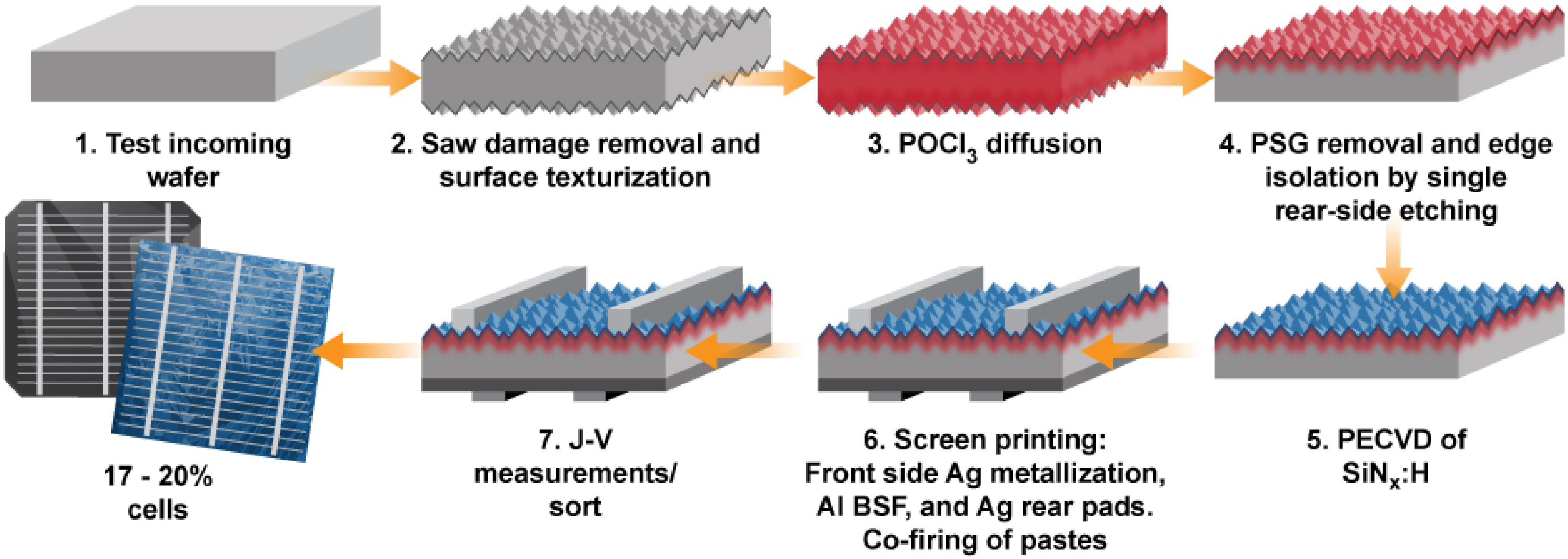
Aggregated Step Costs for Multicrystalline Ingot Growth and Wire Sawing of Wafers



Calculated Manufacturing Costs for the Directional Solidification Process Carried Out Across the Globe: The Case of the *p*-type Wafer Made with Solar Grade Polysilicon

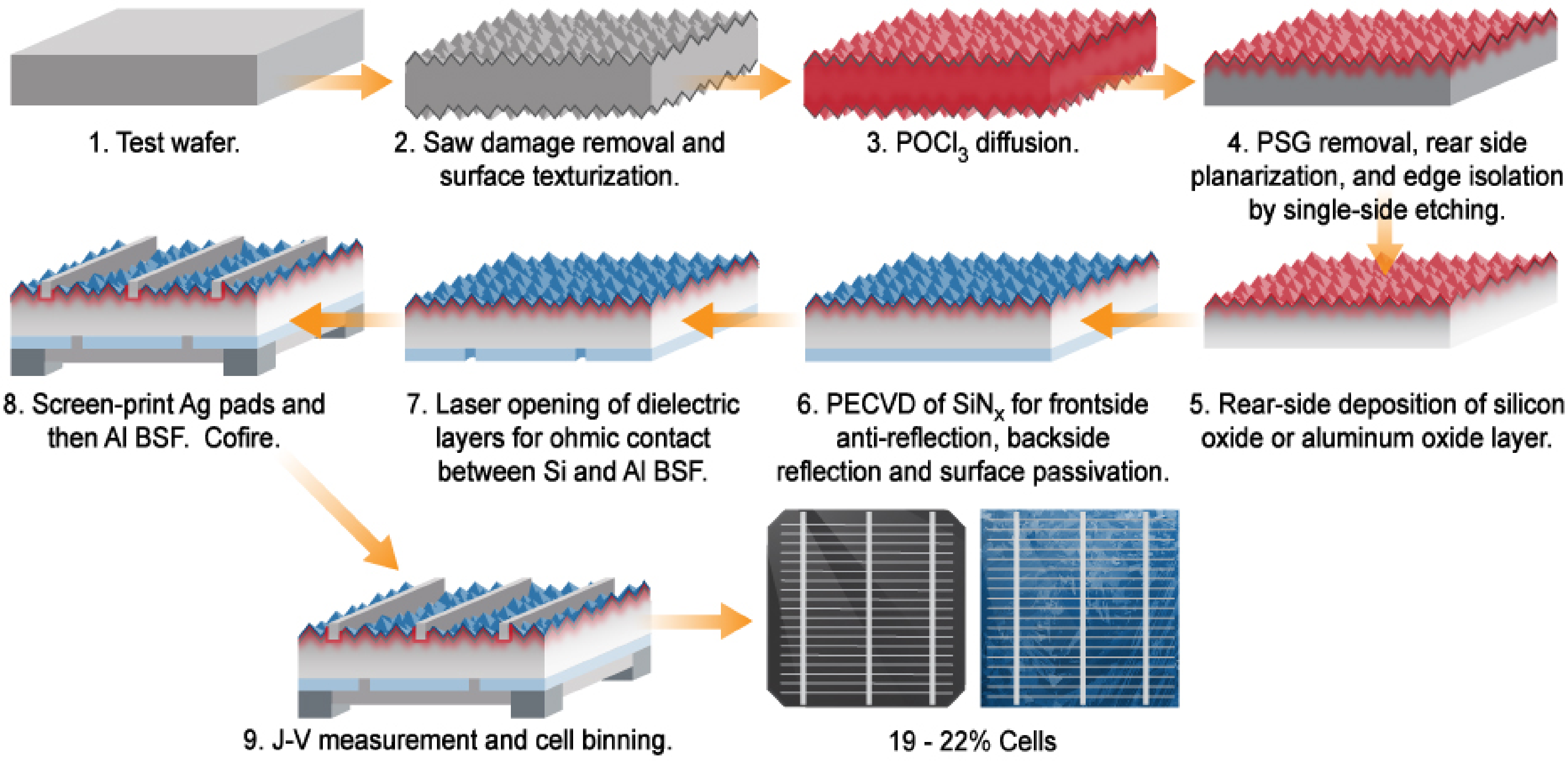


The Standard c-Si Solar Cell



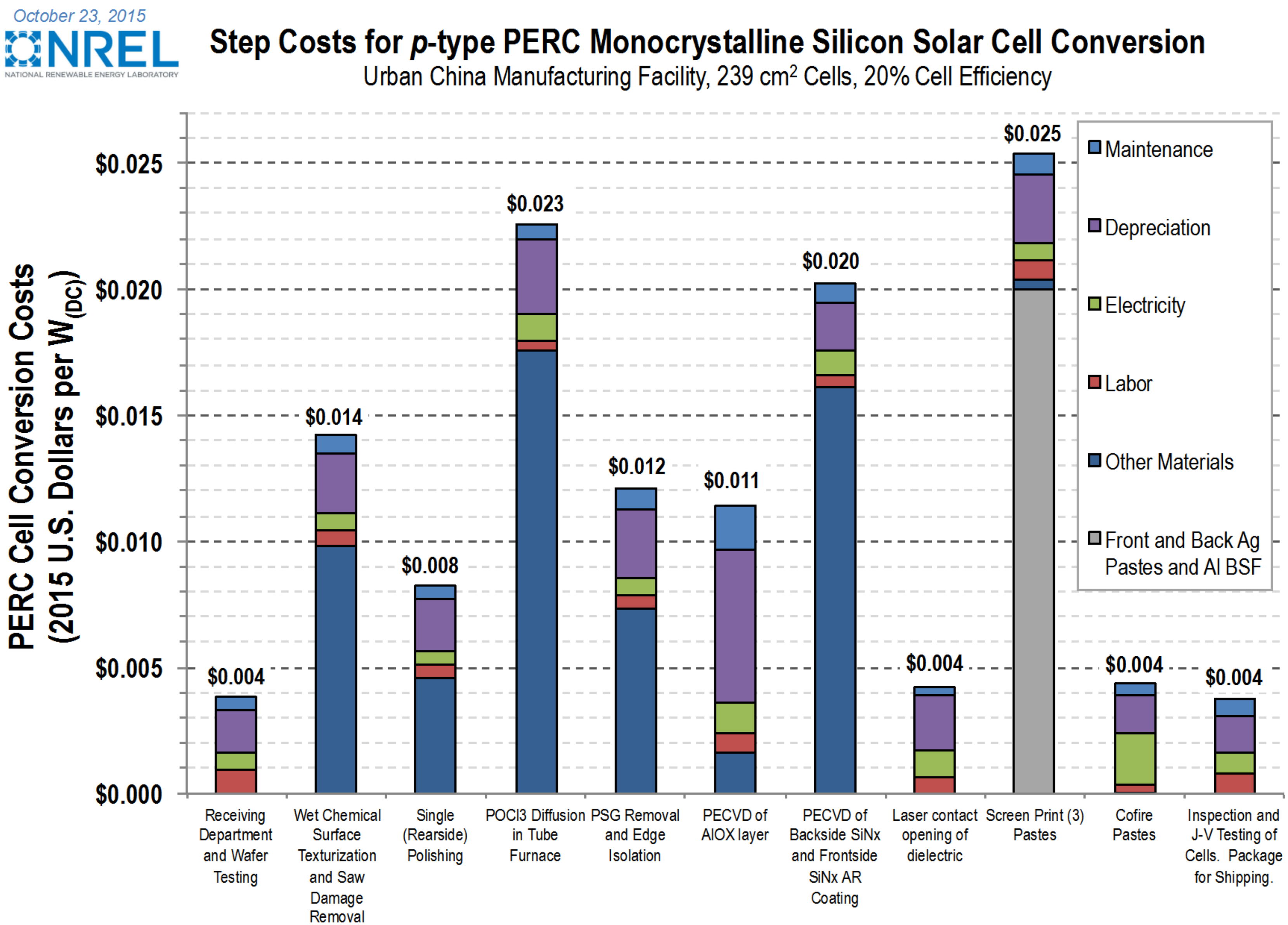
Source of figure: NREL.

Passivated Emitter and Rear Cells (PERC)

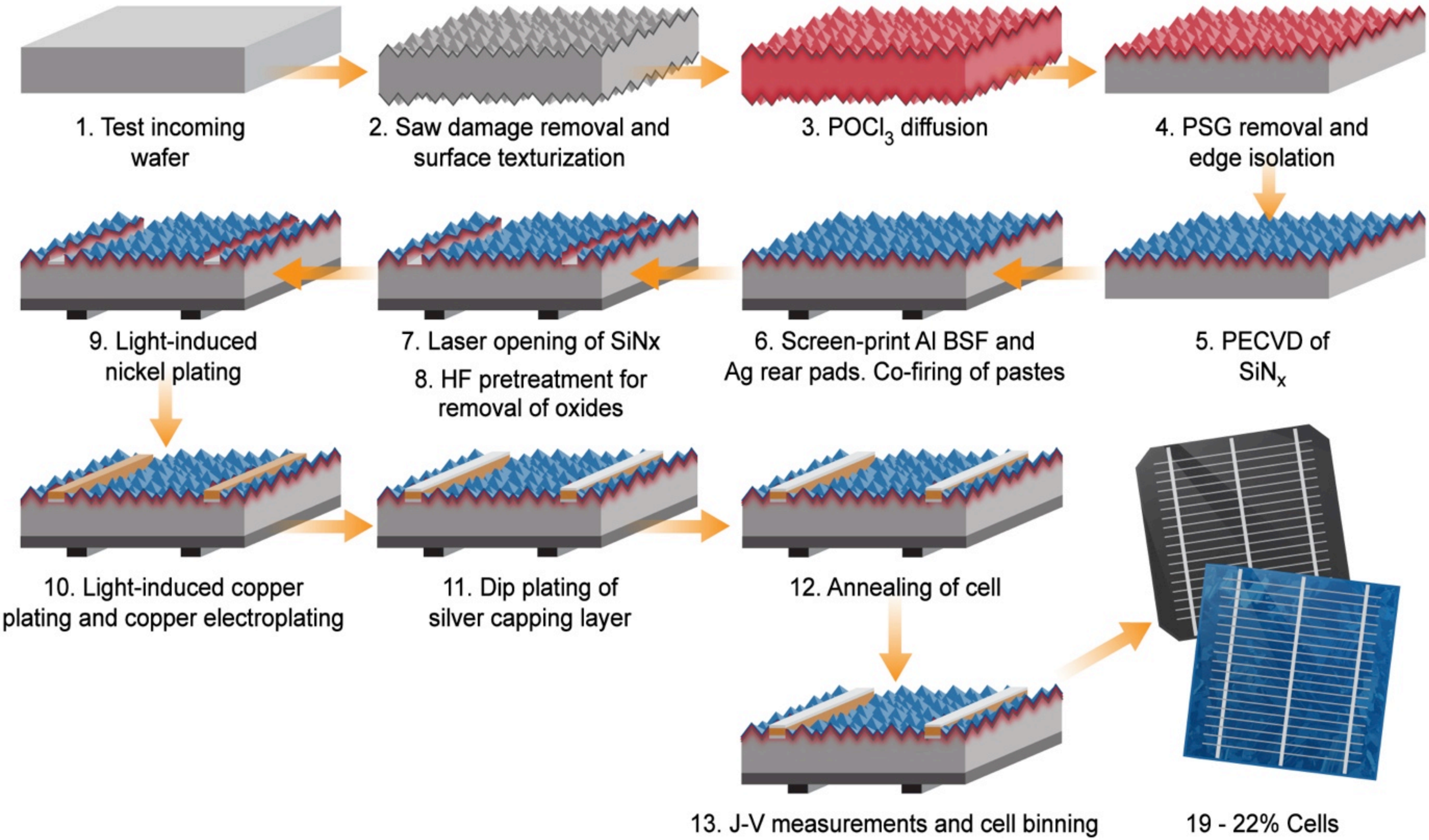


Source of figure: NREL.

Aggregated Step Costs for PERC Cell Conversion

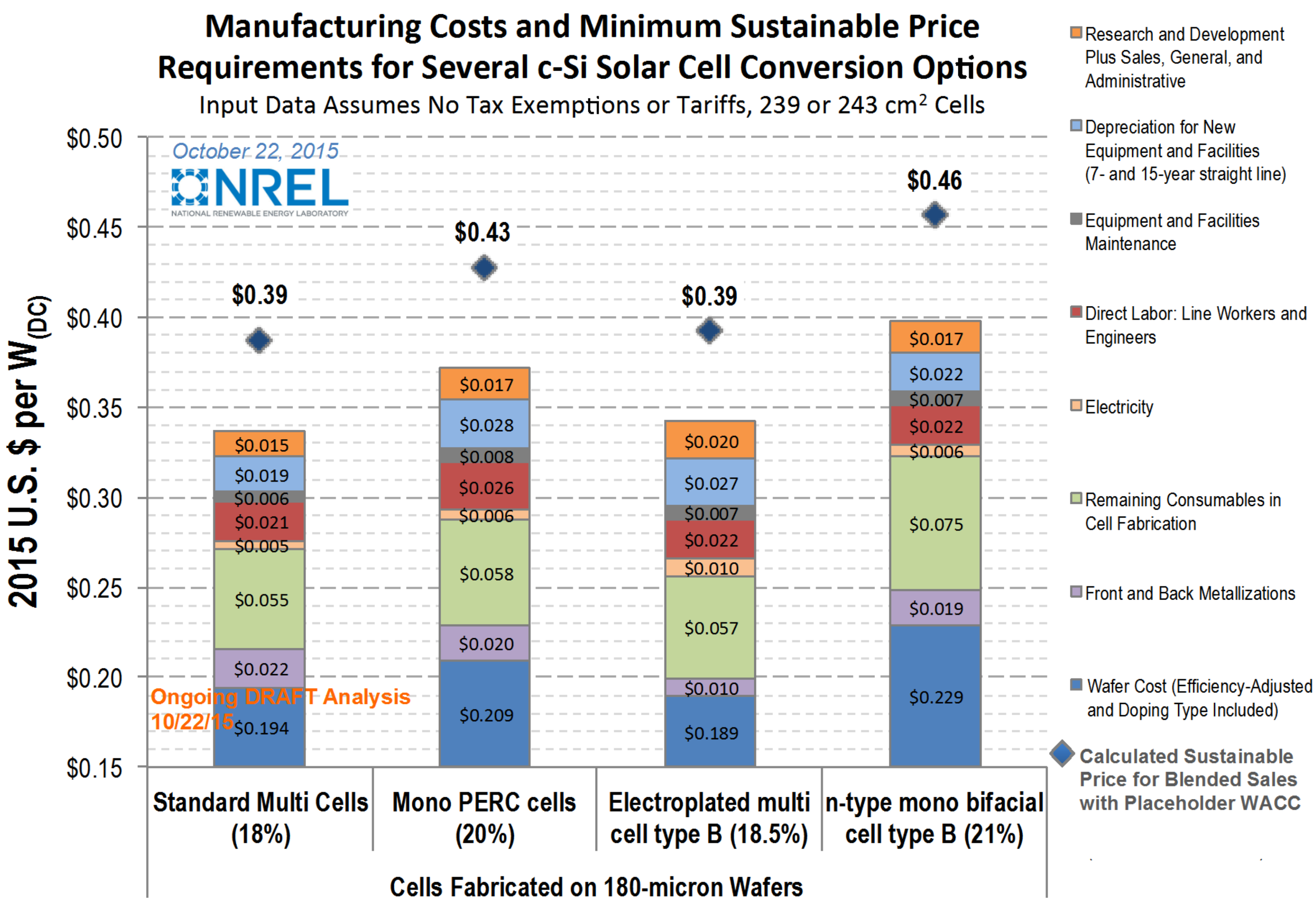


Electroplated Cells

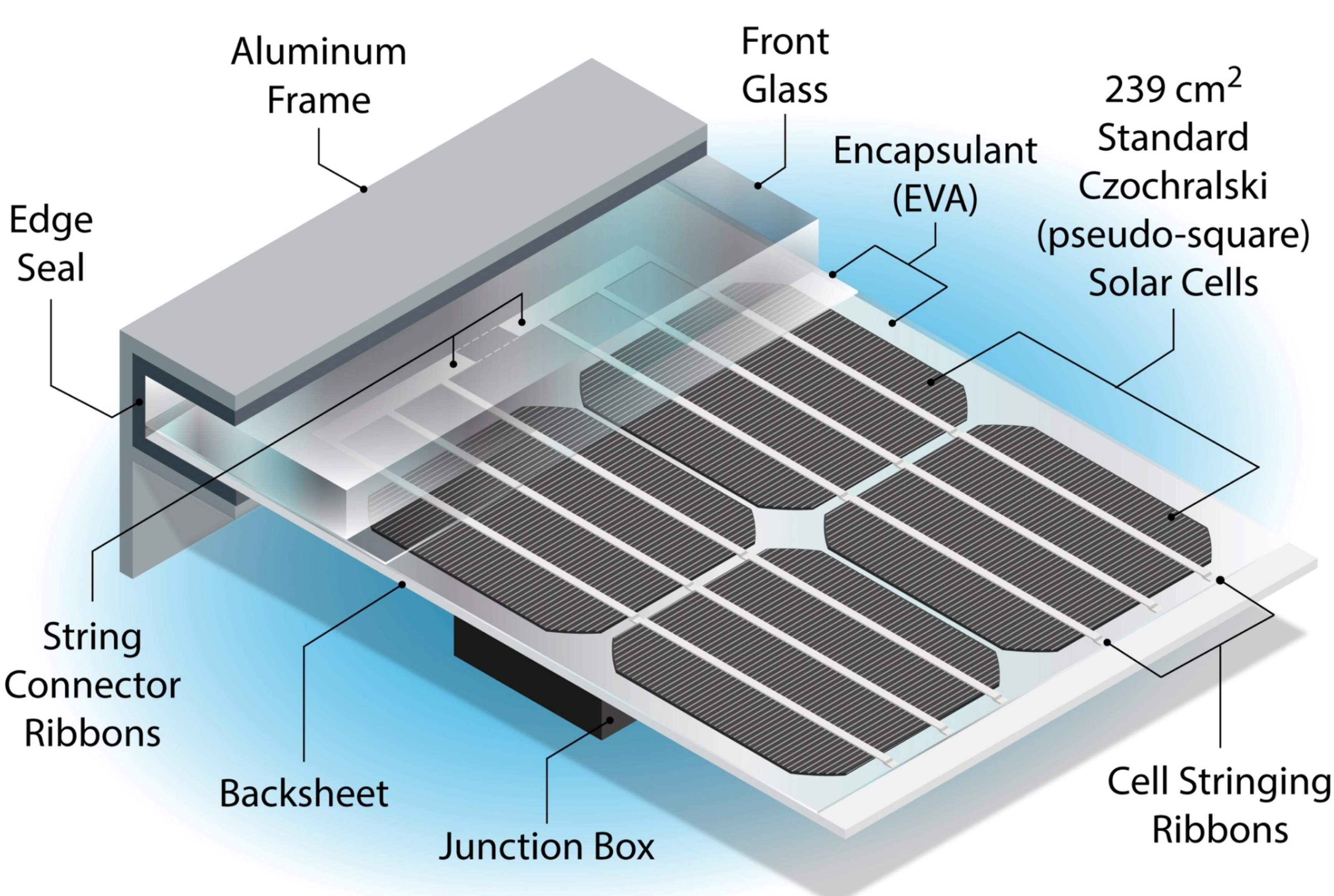


Source of figure: NREL.

Bottom-Up Cost Model Results for Several Cell Conversion Options

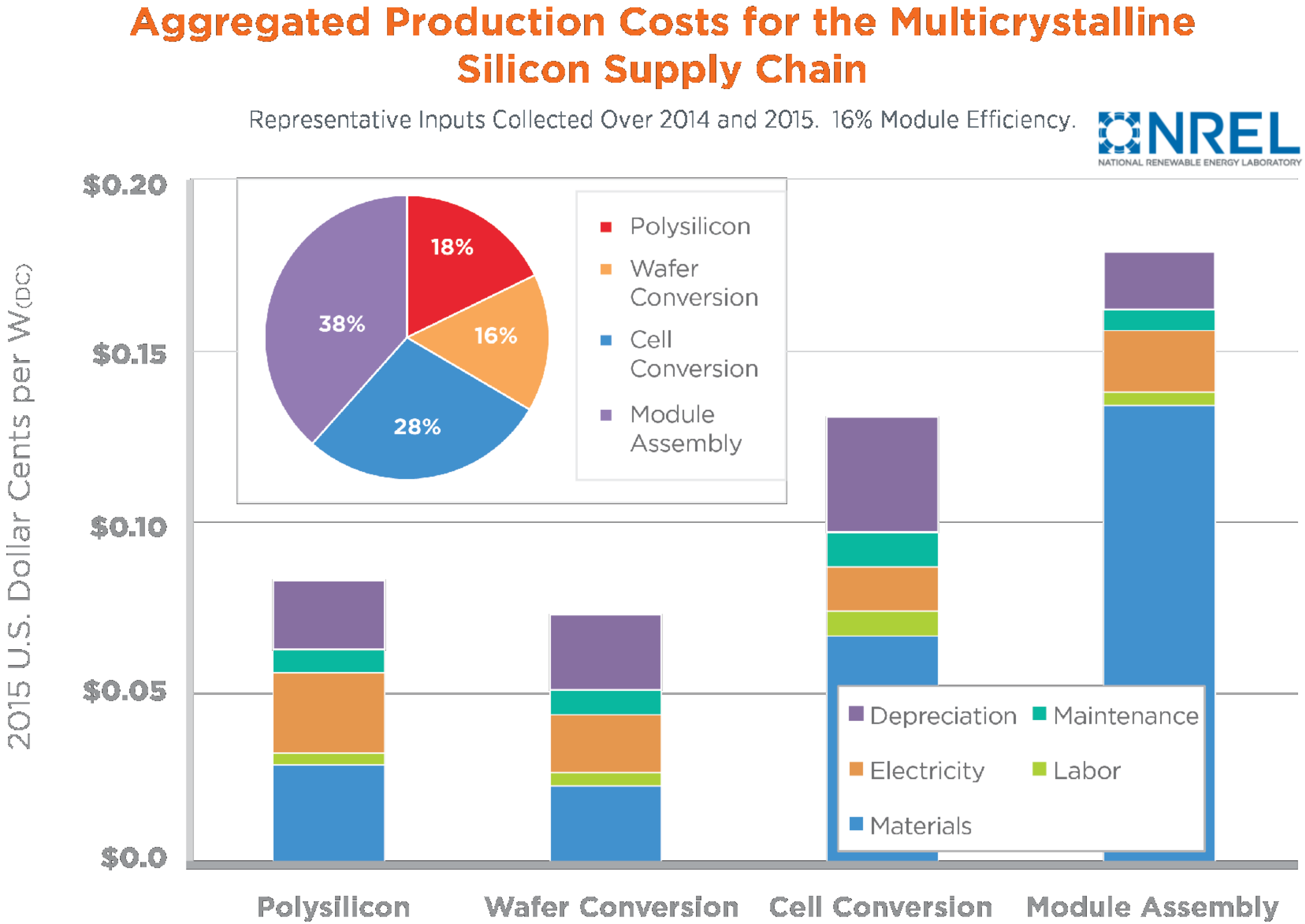


Total Module Components



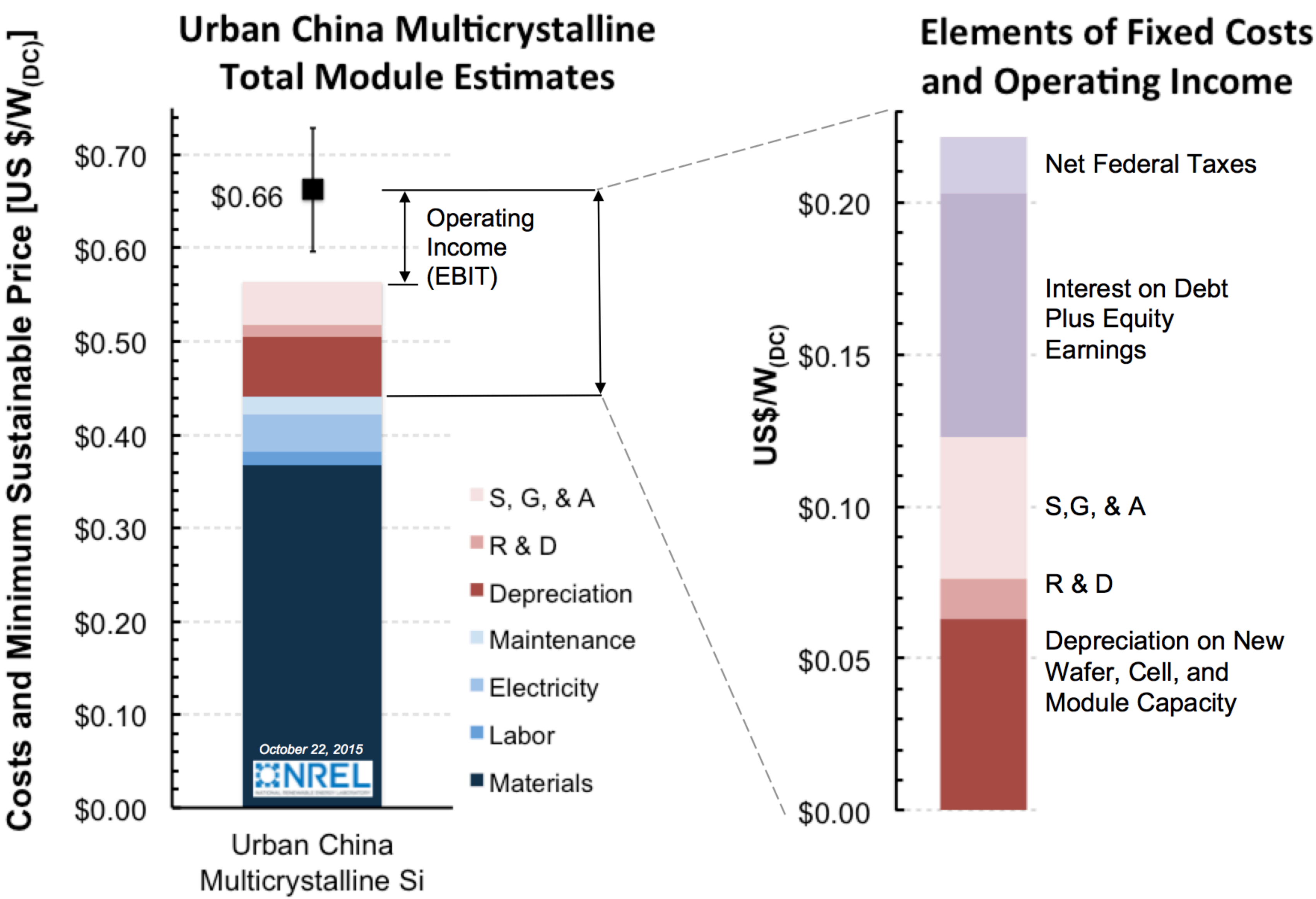
Source of Figure: NREL

Review: Cost Elements Within the Crystalline Silicon Supply Chain



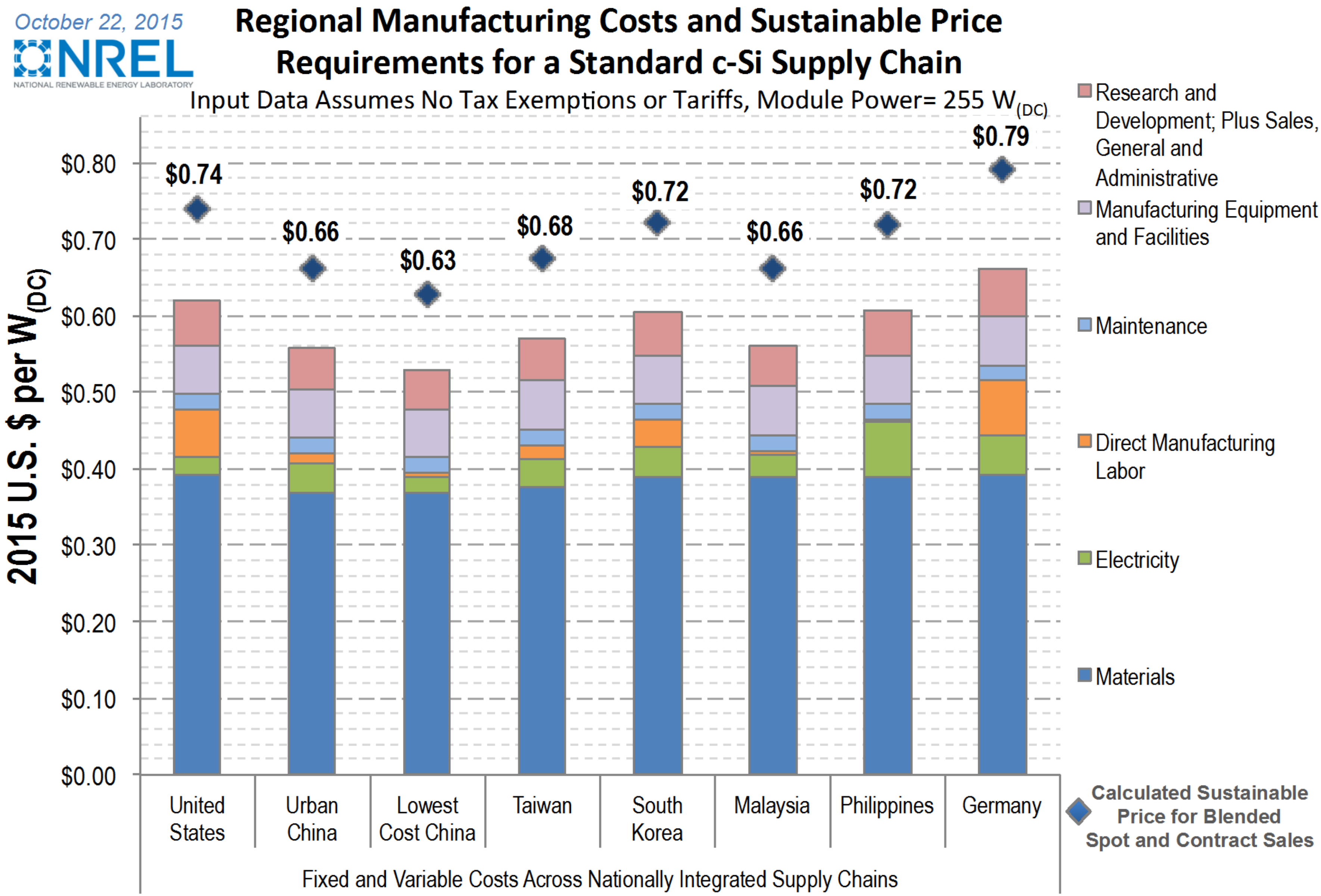
Source: Jones-Albertus, R., D. Feldman, R. Fu, K. Horowitz, and M. Woodhouse. 2015. *Technology Advances Needed for Photovoltaics to Achieve Widespread Grid Price Parity*. Washington, D.C.: Department of Energy (DOE). Accessed September 2015, http://energy.gov/eere/sunshot/downloads/technology-advances-needed-photovoltaics-achieve-widespread-grid-price-parity.

Elements in Multi-Module Costs and Calculated Minimum Sustainable Margins (Nationally Integrated)

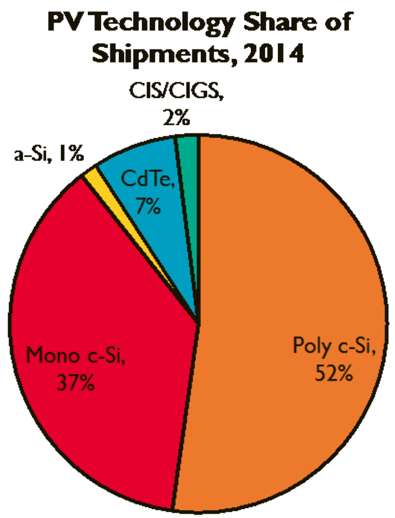


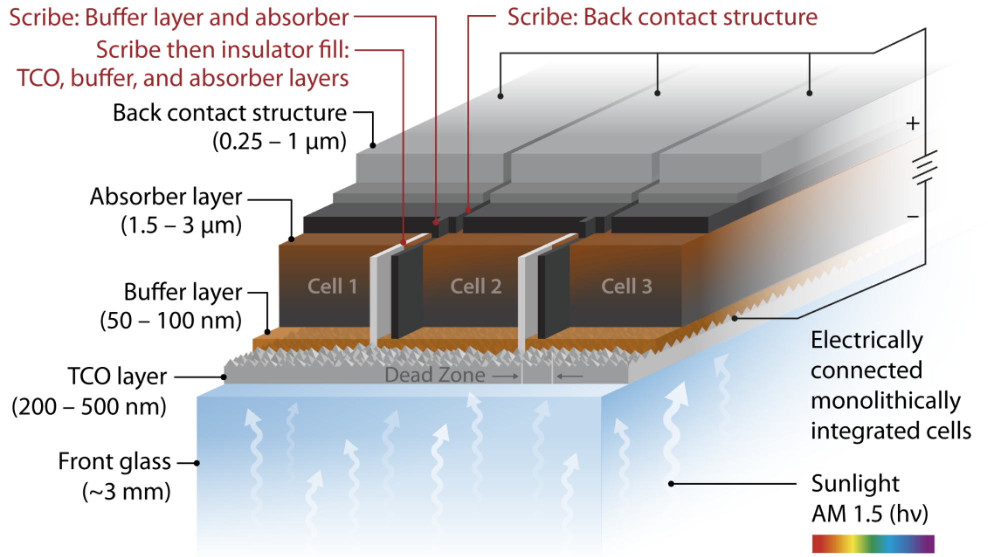
Source of figure: NREL and MIT. Please also see: D M Powell, R Fu, K Horowitz, P A Basore, M Woodhouse, and T Buonassisi "The Capital Intensity of Photovoltaics Manufacturing: Barrier to Scale and Opportunity for Innovation", *Energy and Environmental Science*, Accepted 2015.

Standard Multicrystalline Silicon Module Assembly With Nationally Integrated Minimum Sustainable Cell Prices

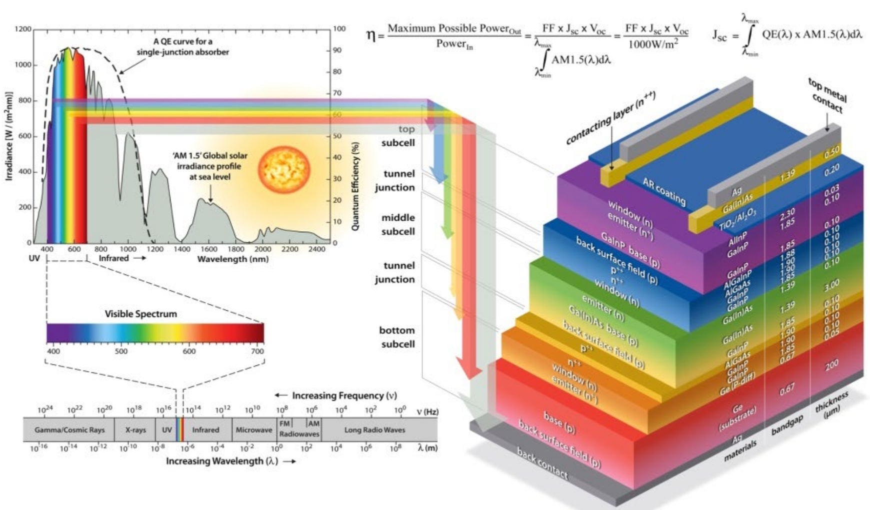


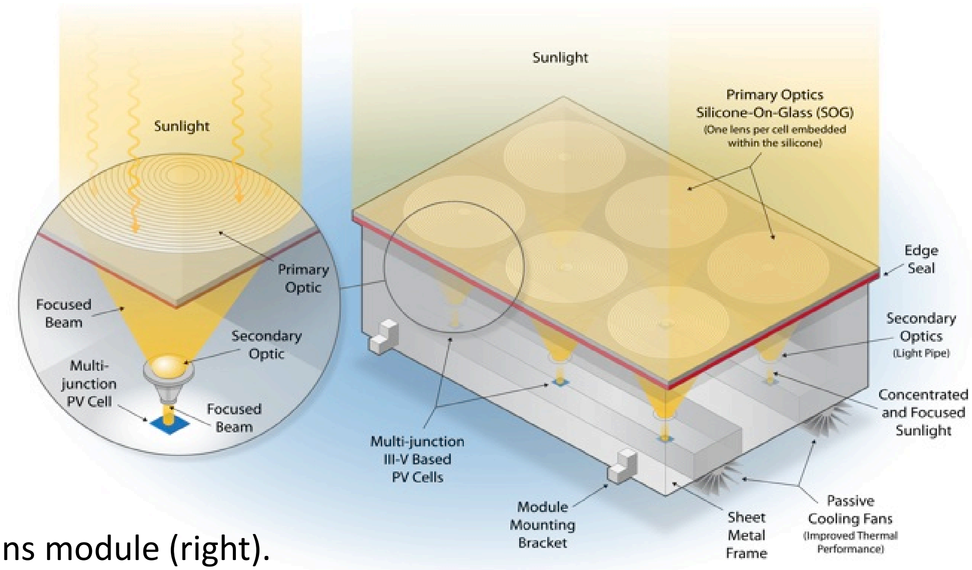
Part IIb: Thin-Film PV Module Technologies





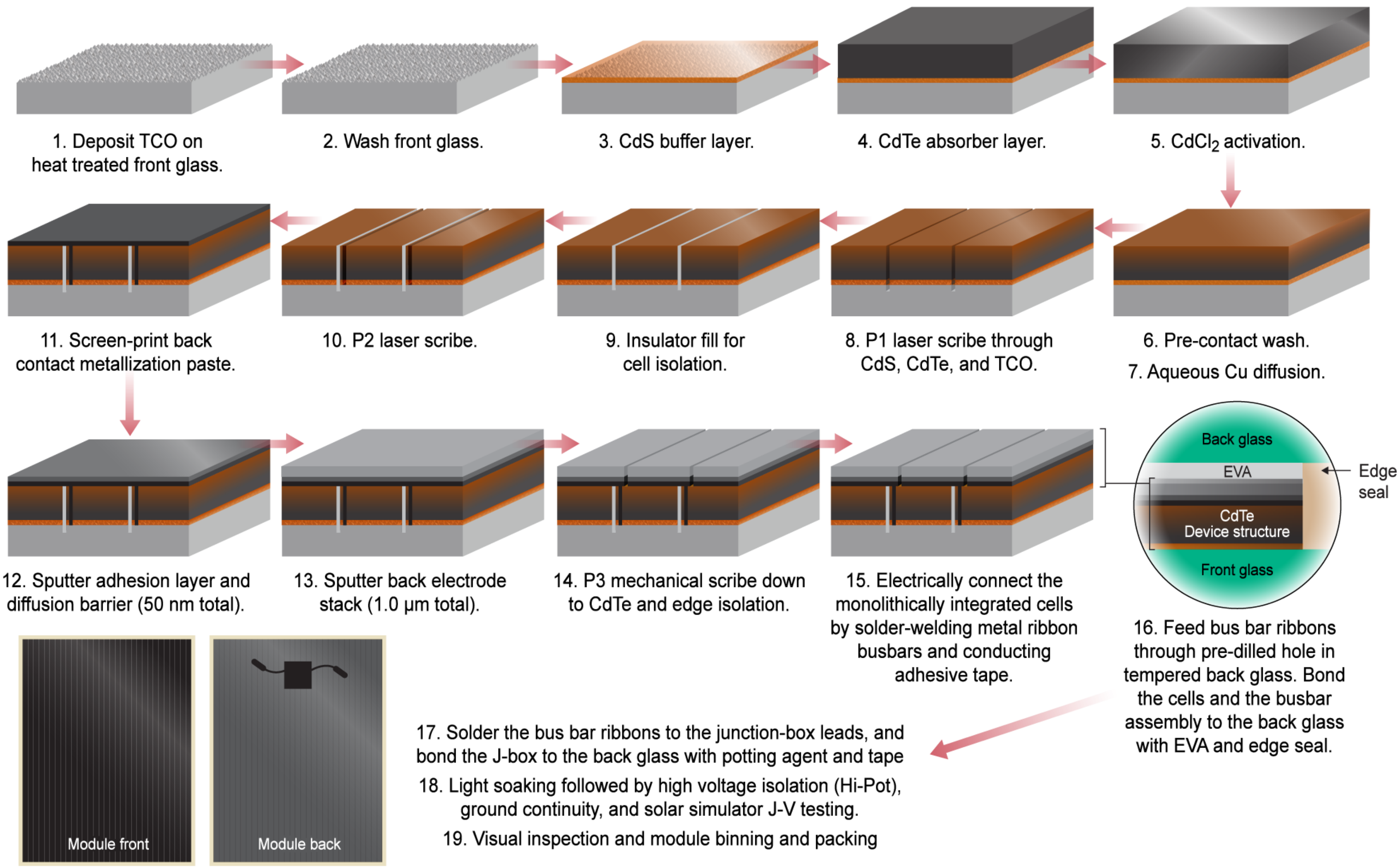
Typical thin-film module by monolithic integration. Source of Figure: NREL





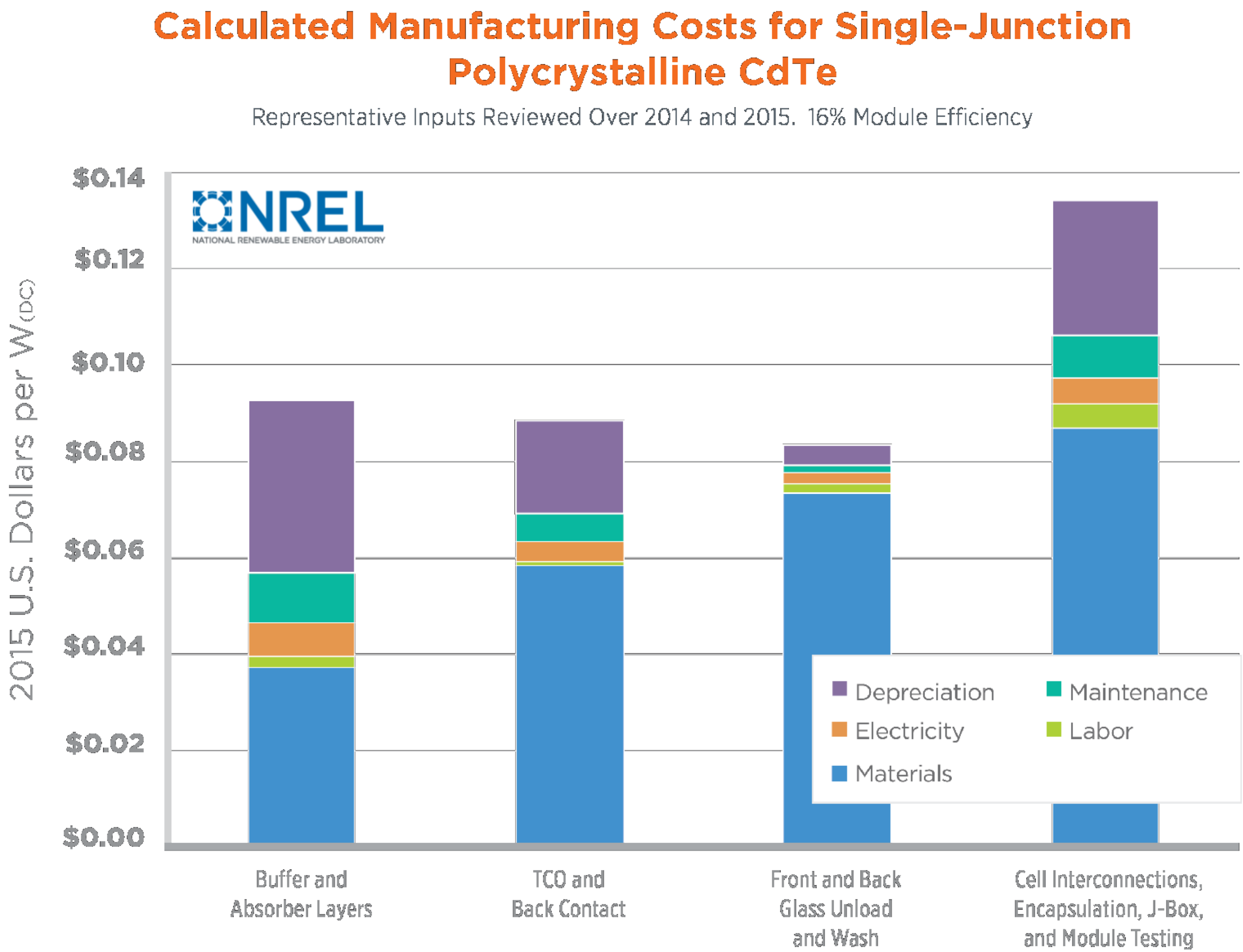
Multi-junction solar cells (left) and concentrating fresnel lens module (right).
Source of Figure: NREL

The Process Flow Used in the NREL CdTe Cost Model



Source of Figure: NREL

Cost Elements for CdTe Manufacturing



Source: Jones-Albertus, R., D. Feldman, R. Fu, K. Horowitz, and M. Woodhouse. 2015. *Technology Advances Needed for Photovoltaics to Achieve Widespread Grid Price Parity*. Washington, D.C.: Department of Energy (DOE). Accessed September 2015, http://energy.gov/eere/sunshot/downloads/technology-advances-needed-photovoltaics-achieve-widespread-grid-price-parity.

Summary of Findings: Technologies

Summary of Findings: Technologies (Single Country)

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Part III:

Specific Technology Pathways to Lower the LCOE of PV

Costs-Benefits Analysis: Cells

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module and $0.080/W for systems costs.

laser opening); thus, slightly higher CapEx: Calculated cost penalty of $0.011/W (2) Higher maintenance, electricity, and materials costs: Calculated cost penalty of $0.015/W (3) Mono wafer needed for 2% efficiency gain: $0.015/W cost.

PERC: Passivated Emitter and Rear Cells
($0.058/W net cost reduction potential)

igher efficiency cell benefit (0.5%) of $0.005/W for balance-of-
odule and $0.030/W for systems costs.

(1) Additional manufacturing steps (laser SiN_x opening, and electroplati processes over screen-printing); thus, slightly higher CapEx: Calculated cost penalty of $0.008/W. (2) Higher maintenance, electricity, and wastewater costs: Calculated Cost Penalty of $0.007/W.

Electroplated Cells ($0.020/W)

Higher efficiency cell benefit (3%) of $0.027/W for balance-of-
nodule and $0.110/W for systems costs.
May also improve capacity factor (kWh/kW) of installed power
production over the system's lifetime.

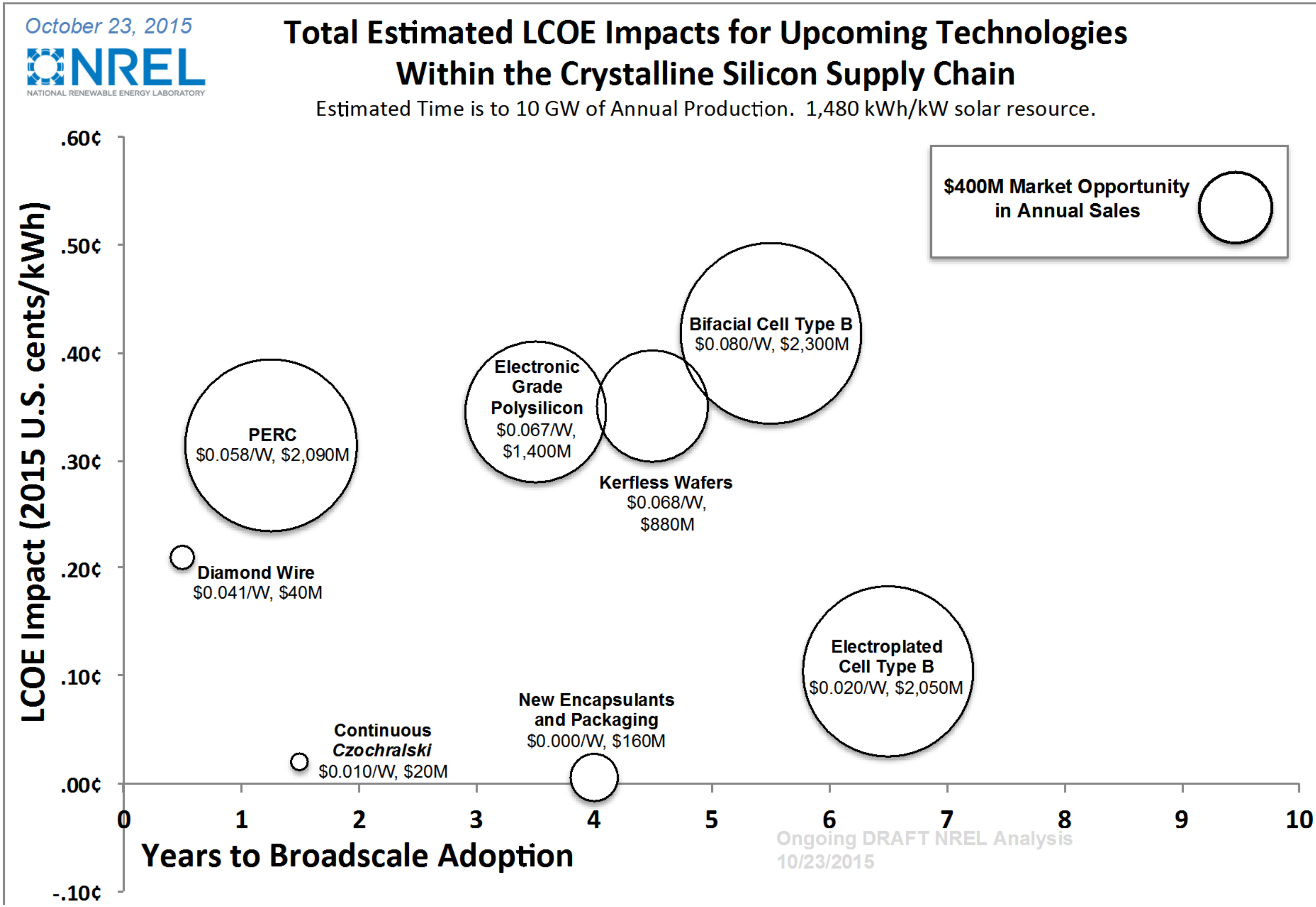
(1) Additional manufacturing steps; thus, slightly higher CapEx: Calculated cost penalty of $0.005/W. (2) 15% price premium for *n*-type wafers: Calculated cost penalty of $0.035/W. (3) Additional materials costs for cell fabrication: Calculated cost penalty of $0.017/W

***n*-type Bifacial Cell B**
($0.080/W net cost reduction potential)

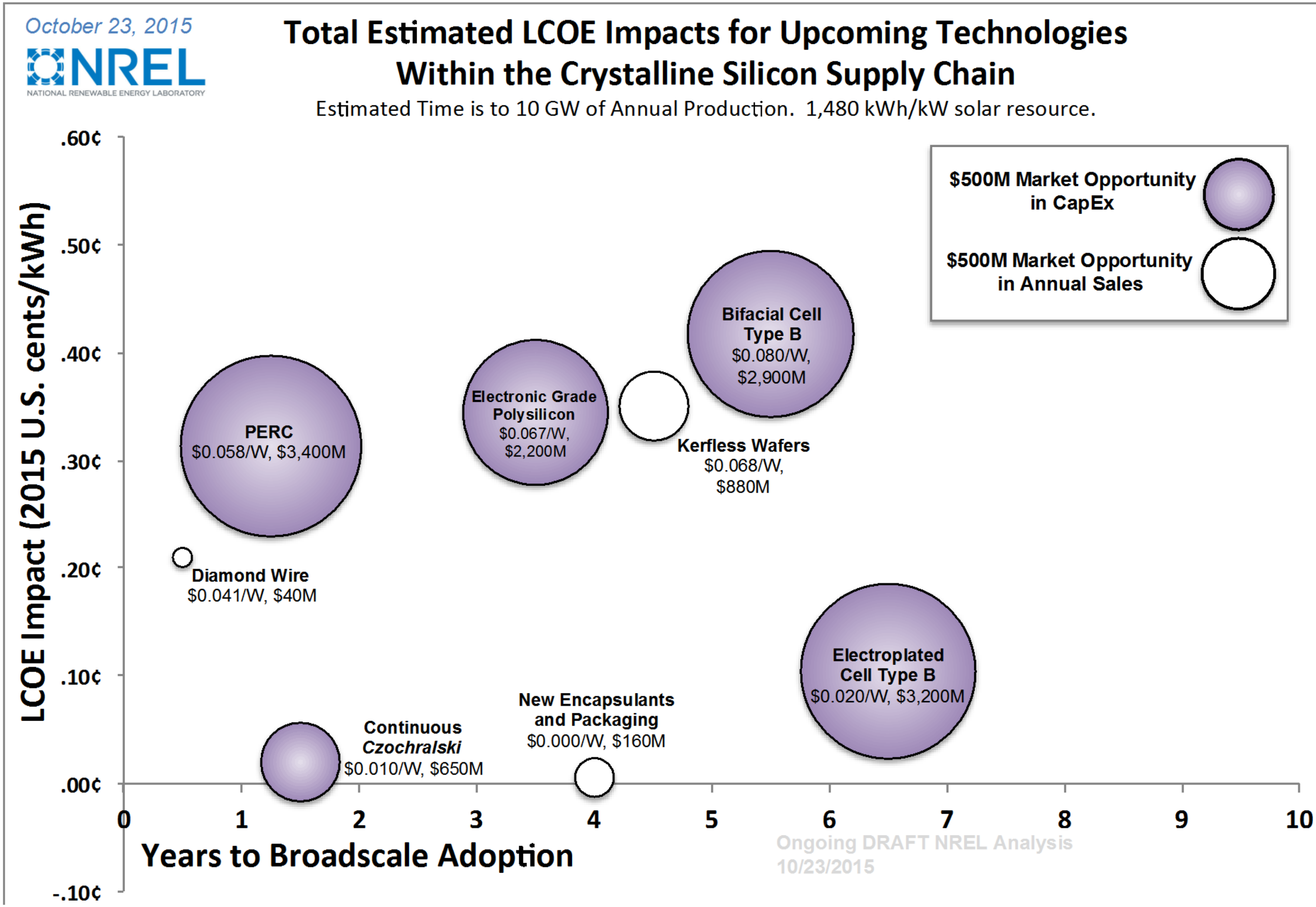
Ongoing DRAFT NREL Analysis. 10/23/2015.

015 $/W$_{(DC)}$)

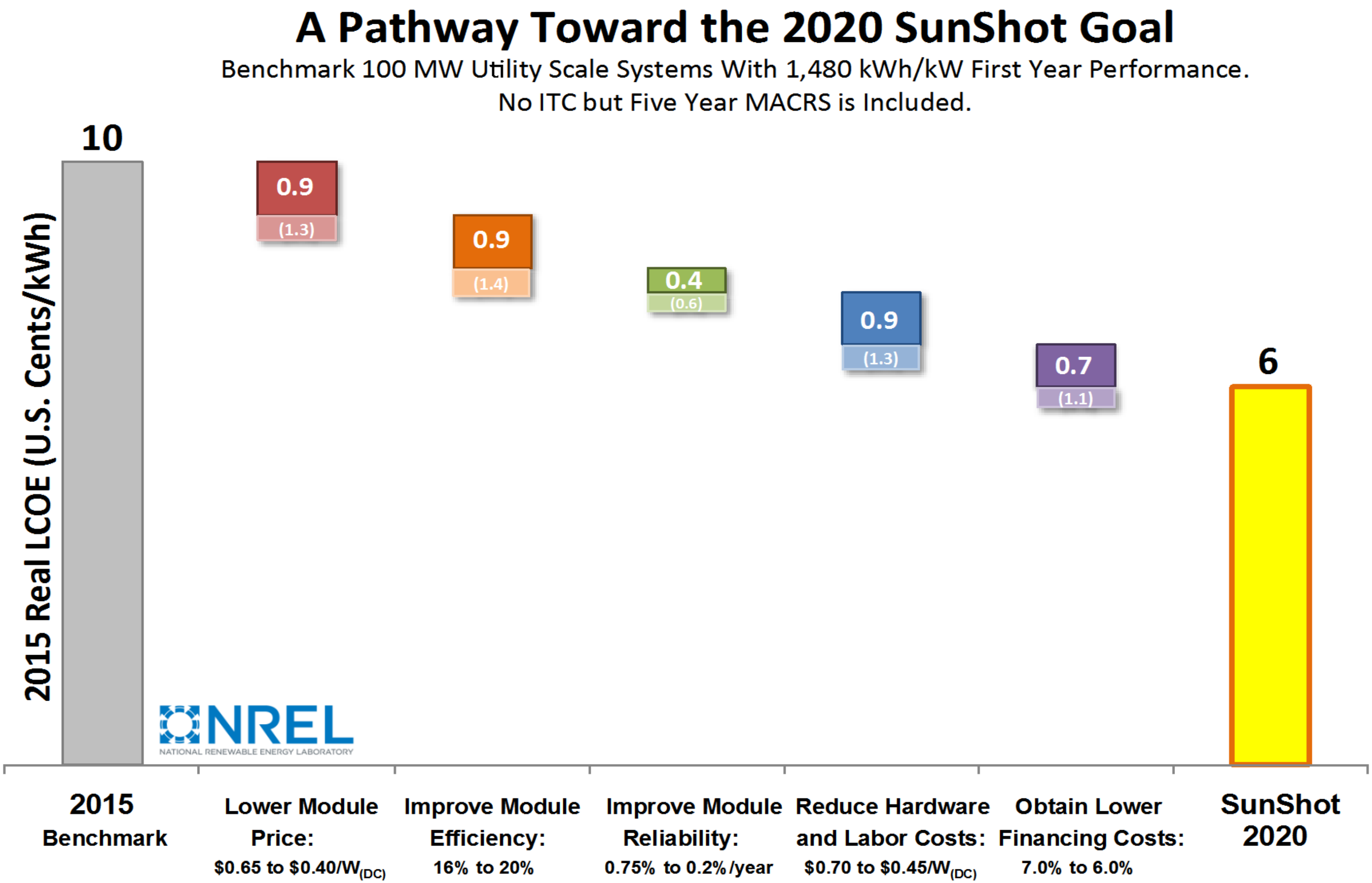
Incorporation into LCOE and Other Projections



Incorporation into LCOE and Other Projections

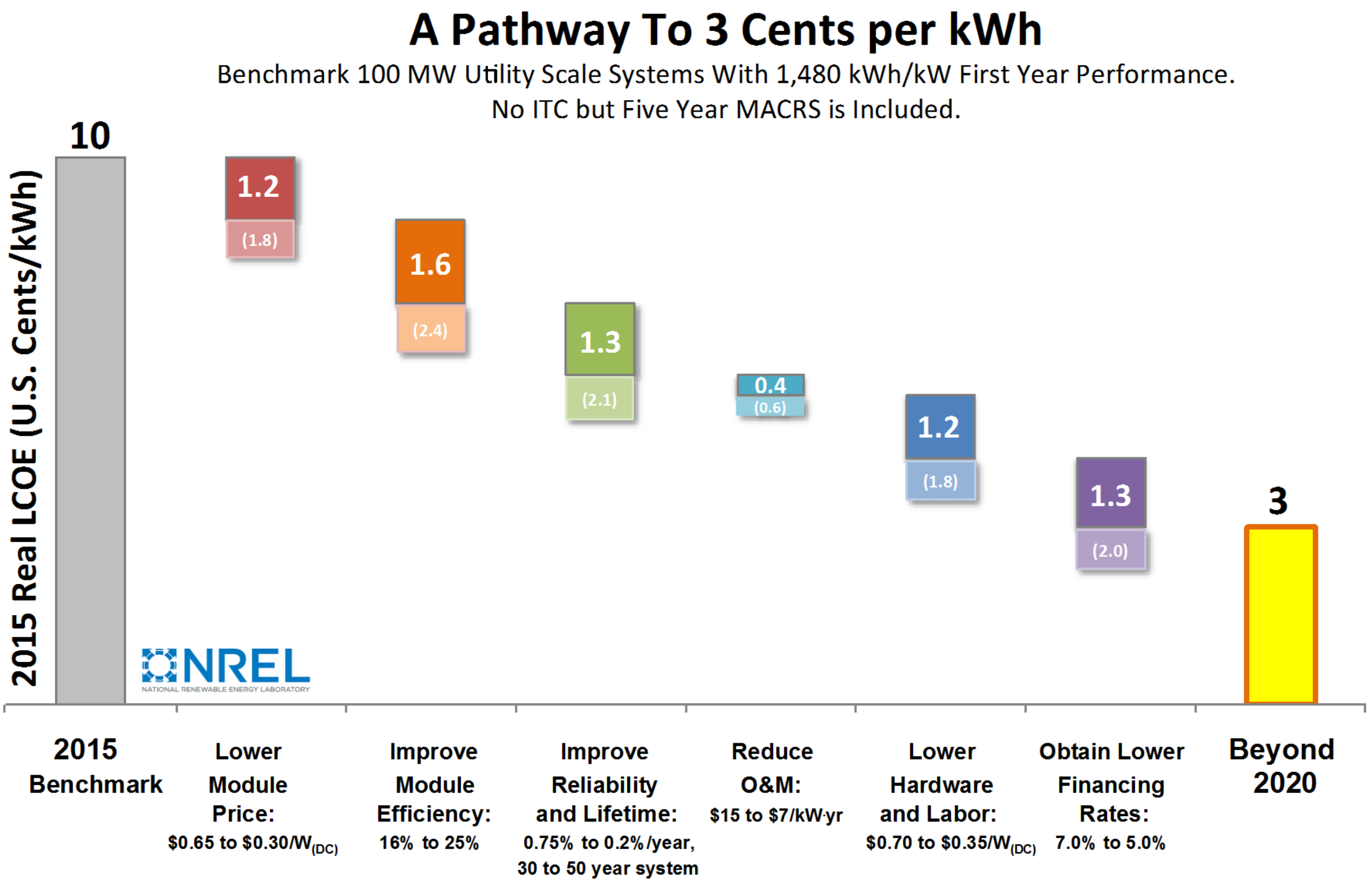


Technology Pathways to Lower LCOE: Efficiency, Reliability, and Costs



Source: Jones-Albertus, R., D. Feldman, R. Fu, K. Horowitz, and M. Woodhouse. 2015. *Technology Advances Needed for Photovoltaics to Achieve Widespread Grid Price Parity*. Washington, D.C.: Department of Energy (DOE). Accessed September 2015, http://energy.gov/eere/sunshot/downloads/technology-advances-needed-photovoltaics-achieve-widespread-grid-price-parity.

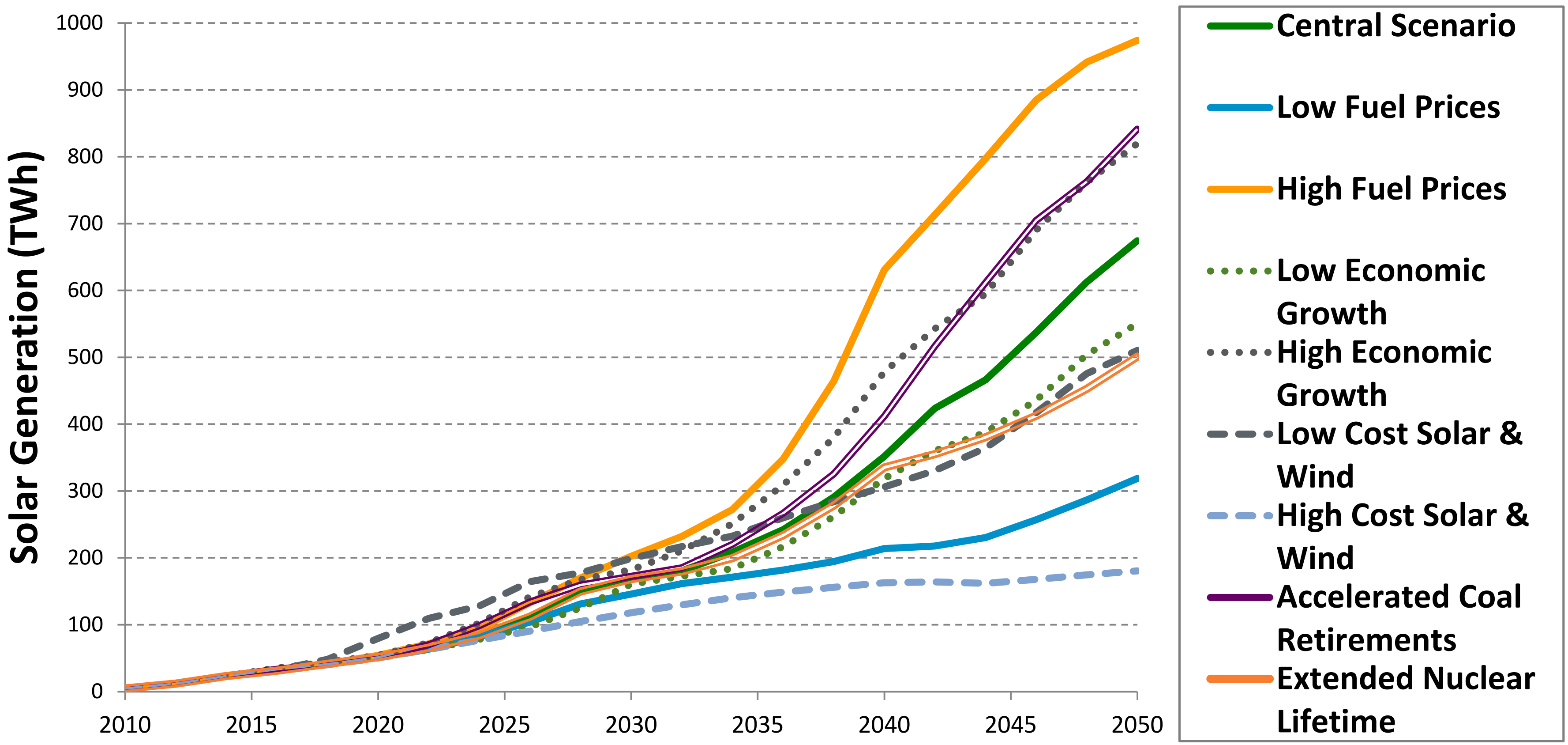
Technology Pathways to Lower LCOE: Efficiency, Reliability, and Costs



Source: Jones-Albertus, R., D. Feldman, R. Fu, K. Horowitz, and M. Woodhouse. 2015. *Technology Advances Needed for Photovoltaics to Achieve Widespread Grid Price Parity*. Washington, D.C.: Department of Energy (DOE). Accessed September 2015, http://energy.gov/eere/sunshot/downloads/technology-advances-needed-photovoltaics-achieve-widespread-grid-price-parity.

Impacts to Energy Mix

Model Scenarios for Electricity Capacity Expansion

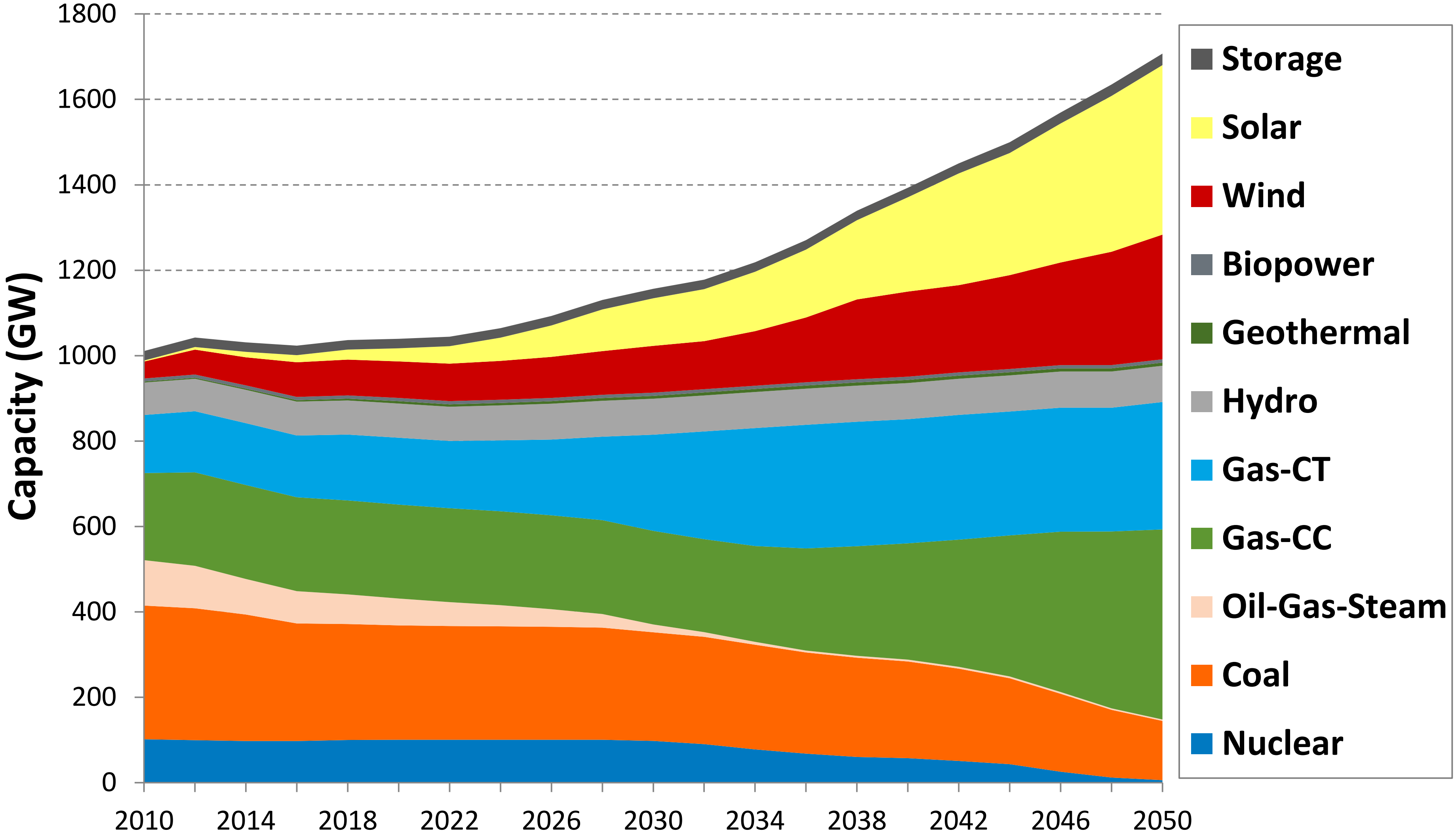


Results from NREL's Regional Energy Deployment Systems (ReEDS) model:

- Capacity expansion model to meet projected U.S. electricity requirements
- Based upon system-wide, least-cost optimization, including storage resource development and applicable state renewable portfolio standards
- Fuel price projections based upon 2014 EIA *Annual Energy Outlook*

Source of figure: Sullivan, P., W. Cole, N. Blair, E. Lantz, V. Krishnan, T. Mai, D. Mulcahy, and G. Porro. 2015. *2015 Standard Scenarios Annual Report: ReEDS Model Description and Scenario Exploration.* NREL/TP-6A20-64072. Golden, CO: NREL. Accessed September 2015, http://www.nrel.gov/docs/fy15osti/64072.pdf.

ReEDS Model Scenarios for Electricity Capacity Expansion by Technology: The Central Scenario of Fuel Prices



Results shown are for the 'Central Scenario'. Source of figure: Sullivan, P., W. Cole, N. Blair, E. Lantz, V. Krishnan, T. Mai, D. Mulcahy, and G. Porro. 2015. *2015 Standard Scenarios Annual Report: ReEDS Model Description and Scenario Exploration.* NREL/TP-6A20-64072. Golden, CO: NREL. Accessed September 2015, http://www.nrel.gov/docs/fy15osti/64072.pdf.

Conclusions

1. The broader adoption of solar energy technologies is most significantly influenced by policy, economic growth, the continuation of module and total systems cost reductions, and future fuel prices for the traditional sources.
2. In terms of approaching LCOE parity with the traditional energy generation options, model results suggest that improvements to PV module and system reliability may contribute as much as improvements to PV module efficiency. Reliability is also believed to influence financing rates, which has a significant impact upon LCOE.
3. BUT, improvements in both efficiency and reliability are useful in lowering the LCOE of solar.
4. For further reductions in LCOE, innovations that could lead to lower hardware, installation labor, and financing costs could present larger opportunities than continued reductions in module prices.
5. Grid integration and reliability and developing compatible utility business models are also critical factors for the future adoption of solar.

Conclusions: Part II

1. Thank you to the organizers of KAUST Solar Symposium 2015!

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3. Interested in working with NREL's Clean Energy Manufacturing Analysis Center (CEMAC) and Strategic Energy Analysis Center (SEAC)?
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CEMAC Clean Energy Manufacturing Analysis Center

Operated by the Joint Institute for Strategic Energy Analysis