NATIONAL RENEWABLE ENERGY LABORATORY

The International Supply Chain and Manufacturing Costs for Photovoltaic Modules, and Project Economics of Systems Including Storage

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Strategic Energy Analysis Center

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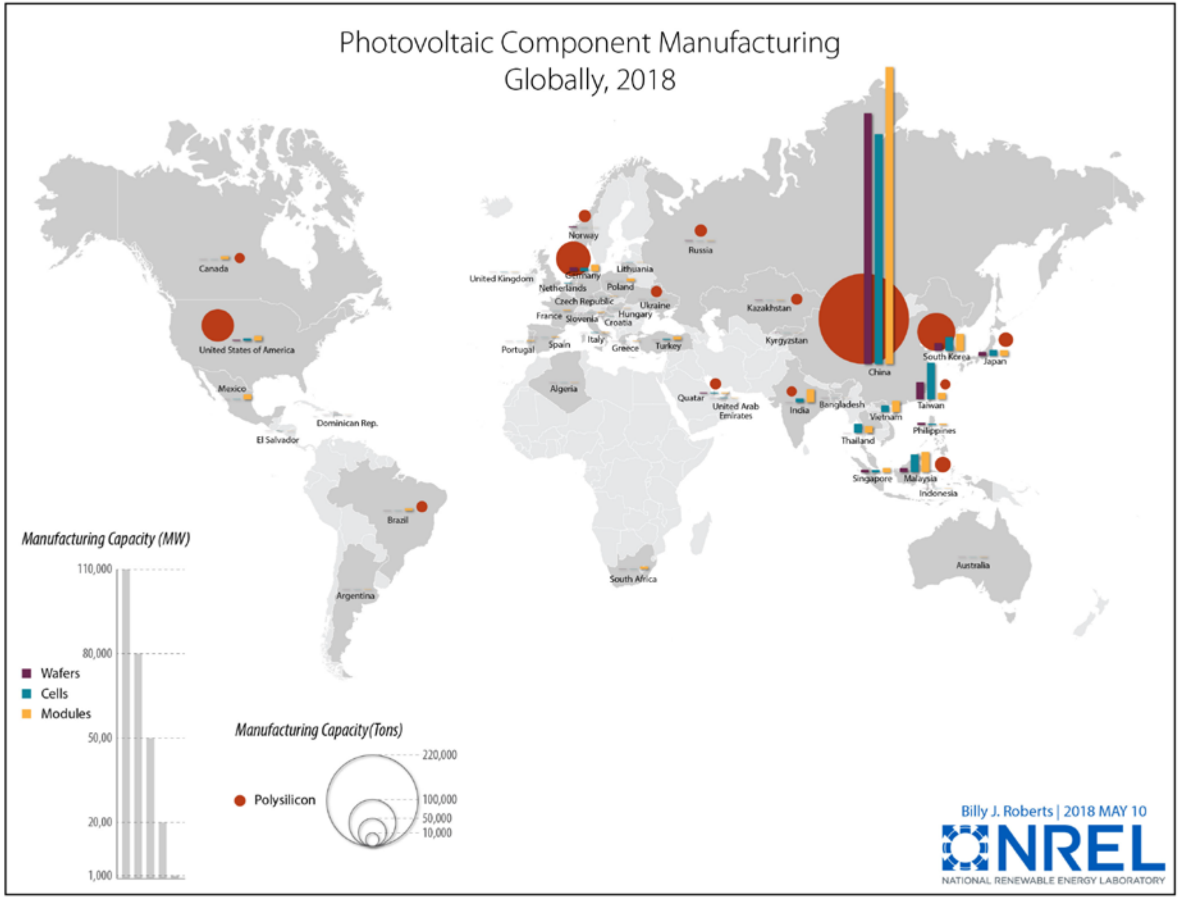
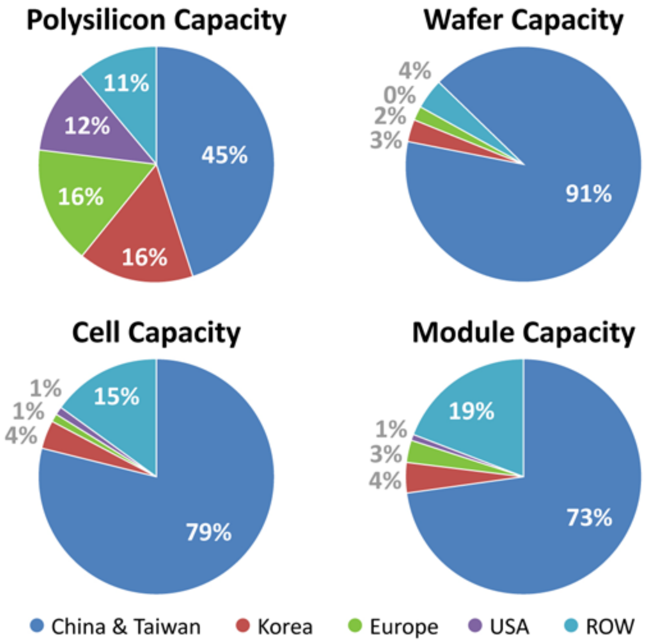
Presentation Outline

The Global Nature of the Photovoltaic Industry

Facility Locations and Manufacturing Capacities for the Top 500 Companies





Input data sources for map and pie chart: IHS and BNEF.

The Global Nature of the Photovoltaic Industry

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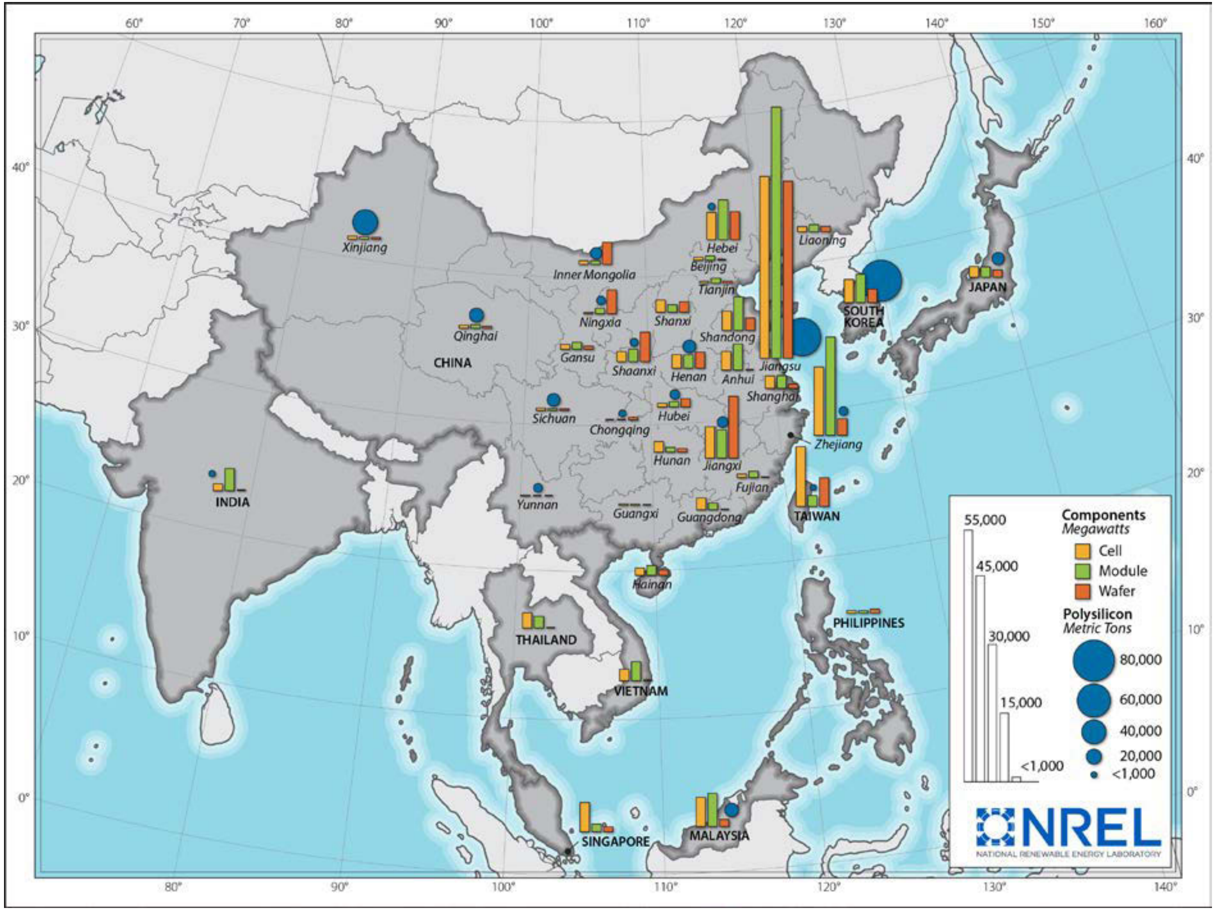
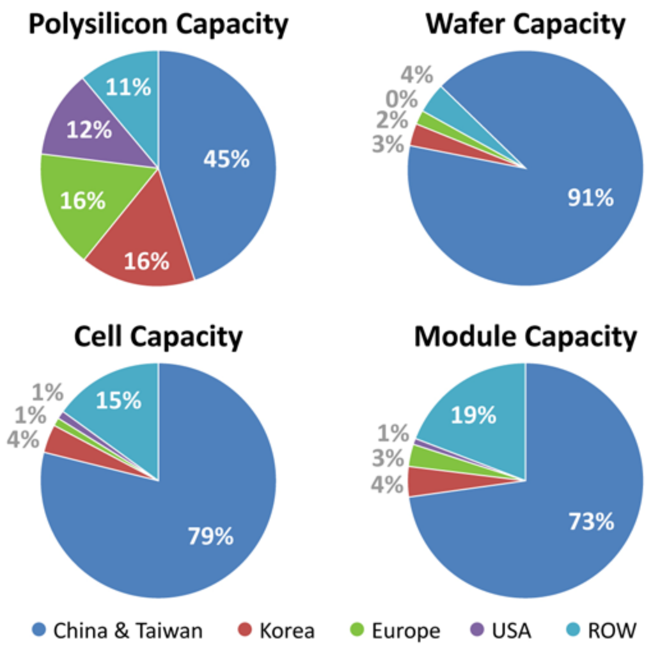


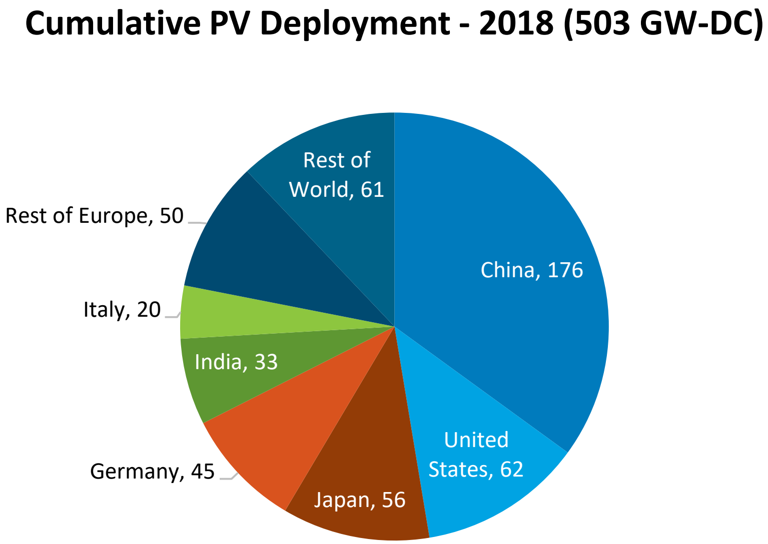


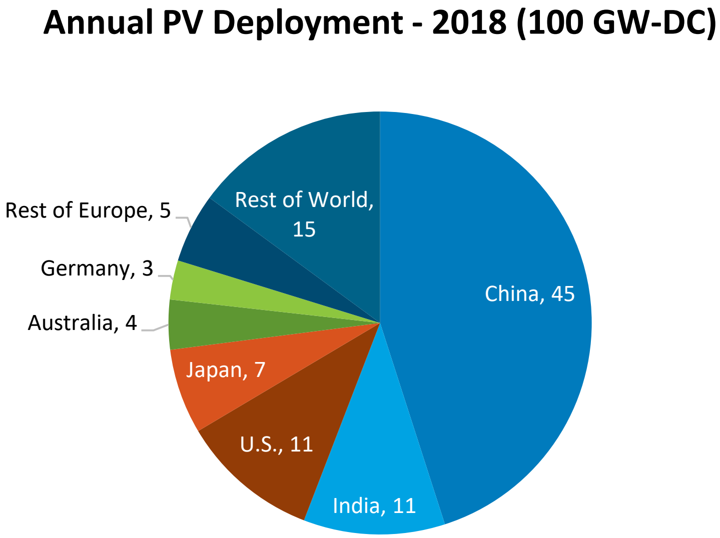
Input data sources for map and pie chart: IHS and BNEF.

Top PV Markets

- At the end of 2018, global PV installations reached 503 GW-DC, an annual increase of 100 GW-DC from 2017.
- The leading five markets, in cumulative and annual PV installations at the end of 2018, were China, India, the United States, Japan, and Europe.

- By the end of 2018 China had over 175 GW of cumulative PV installations, an annual increase of 45 GW. That is less than the 53 GW China installed in 2017; however it is still more than the other top 9 markets combined.
- At the end of 2018 the United States PV market was the second-largest cumulatively, and a close third for 2018 installations behind China and India. 2018 annual PV additions in India grew by 19% to 11 GW.





Source: IEA "PVPS Snapshot 2019."

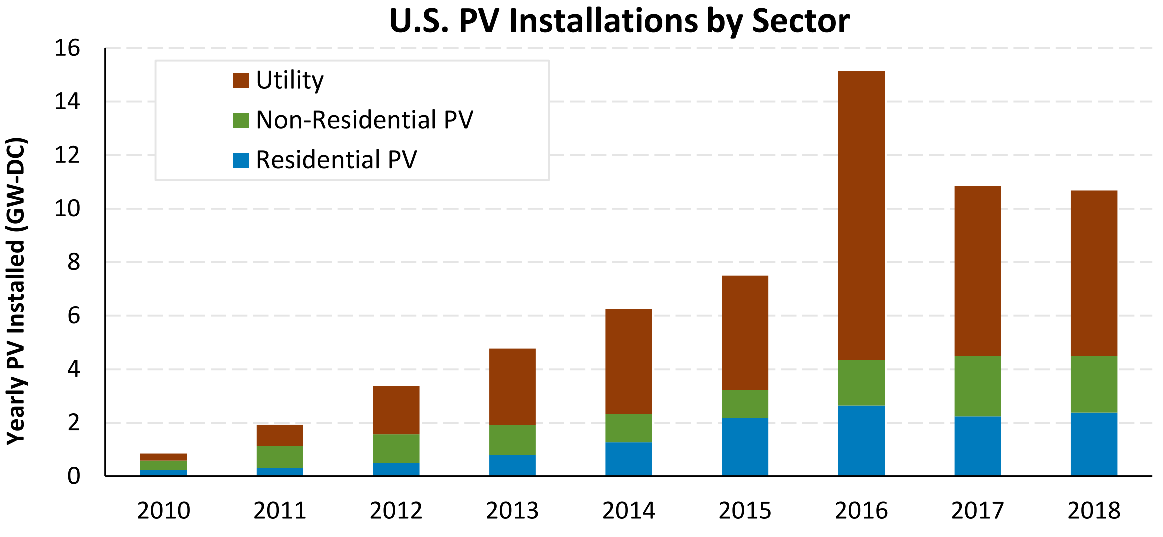
Presentation Outline

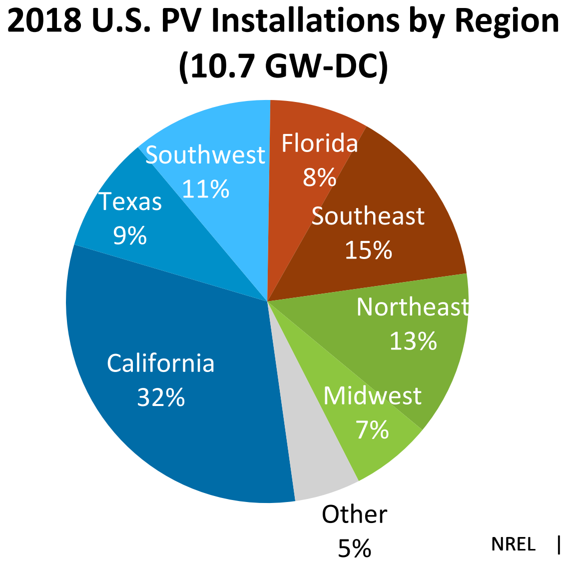
U.S. Installation Breakdown

- The United States installed 10.7 GW-DC of PV in 2018. 4.2 GW-DC was installed in Q4 alone. Cumulative installed capacity across all sectors reached 62.5 GW.
- 2018 U.S. PV installations were down 2%, y/y, with the residential market growing 7%, but the non-residential and utility-scale markets contracting 7% and 2%, respectively.

- New PV installations had a fair geographic mix across the United States in 2018.
- Renewable energy targets within each state can affect demand growth. Example:

  --Effective January 1, 2020, California will require solar systems to be included on all new residential buildings



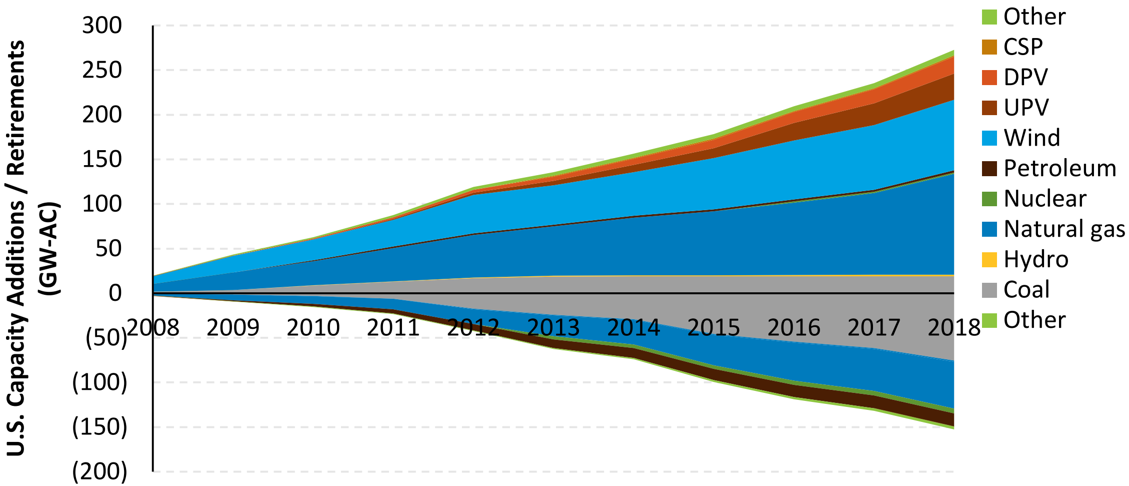


Sources: Wood Mackenzie/SEIA: U.S. Solar Market Insight 2018 Year-in-Review.

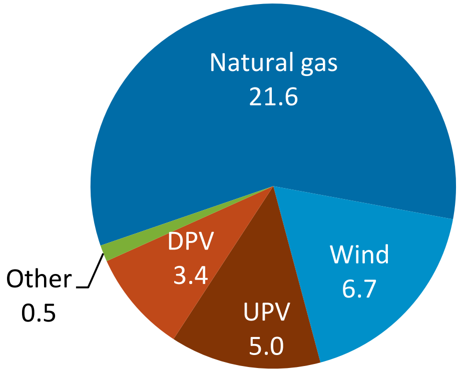
U.S. Electric Generation Capacity Additions by Source

- From 2008 to 2018 solar grew to the third highest electricity generation capacity in the U.S. (50 GW-AC). Natural gas (113 GW-AC) and wind (79 GW-AC) represented the top two.
  - Wind led net capacity additions during that time, as 52 GW-AC of natural gas facilities were also retired (netting 61 GW-AC).
  - Coal capacity reduced the most over that time, retiring 75 GW-AC while adding 19 GW-AC.
- 37 GW-AC of new U.S. electricity generating capacity came online in 2018. This was a 44% increase from the 25.6 GW-AC of electricity capacity additions in 2017.
  - The growth is attributed to a 105% increase in natural gas deployment, reaching 21.6 GW – its highest level since 2003.
  - From 2008 to 2018, average annual U.S. electric capacity additions was 23 GW.
  - Total solar installations (DPV and UPV) represented 23% of all new U.S. electric generation capacity in 2018—second to natural gas (58%).
- 2018 was the first year since 2013 that solar and wind did not represent more than 50% of new U.S. electric generation capacity.

Cumulative U.S. Generation Capacity Additions (2008-2018)



2018 U.S. Generation Capacity Additions (Total 37.2 GW-AC)



Sources: EIA "Preliminary Monthly Electric Generator Inventory" (December 2018). EIA, "Electric Power Monthly" Table 6.1; 2018. PV data prior to 2015 from GTM Research / SEIA, assuming an ILR of 1.2.

Presentation Outline

Bottom-Up Cost Model Inputs with GAAP and IFRS

Variable (cash) cost elements within the cost of goods sold:

- Input materials
- Direct manufacturing labor
- Electricity
- Maintenance of manufacturing equipment and facilities

Fixed (non-cash) cost elements within the cost of goods sold:

- Manufacturing equipment
- Building and any facilitation expenses that can be capitalized

Additional fixed (cash or non-cash) cost elements:

- Research and Development (R &D)
- Sales, General, and Administrative (S, G, & A)

NREL Methodology and Alignment with GAAP and IFRS

CELL AND MODULE TECHNOLOGIES

Crystalline Silicon
- Polysilicon production
- Ingot and wafering: Czochralski (Cz), directional solidification (DS), kerfless technologies yielding Cz and DS equivalents
- Cell conversion: Monofacial and bifacial PERC, PERT, SHJ, and IBC by screen-printing, electroplating, and busbarless
- Module assembly: Standard tabbing and stringing, busbarless, and shingling

Thin Film
- CdTe
- CIGS
- III-Vs
- Perovskites

Multi-junction
(Two and four terminal)
- All III-Vs and III-Vs on Si
- All Perovskites
- Perovskites on Si

STEP-BY-STEP COST OF OWNERSHIP (COO) INPUTS

Desired COO Format
- Production and throughput (Uptime and scheduled and unscheduled downtime)
- Equipment prices and relevant depreciation schedules
- Floor space
- Materials and consumables
- Utilities (Electricity, compressed air, cooling water)
- Waste disposal (Waste water and exhaust air)
- Labor: Person-hours per task and by labor class (Operators, Supervisors, Engineering, and Maintenance)
- Cost of yield loss

Location Specific Costs
- Local wage rates by task
- Local electricity rates
- Leasing versus purchasing the building business models

GAAP AND IFRS STANDARDS

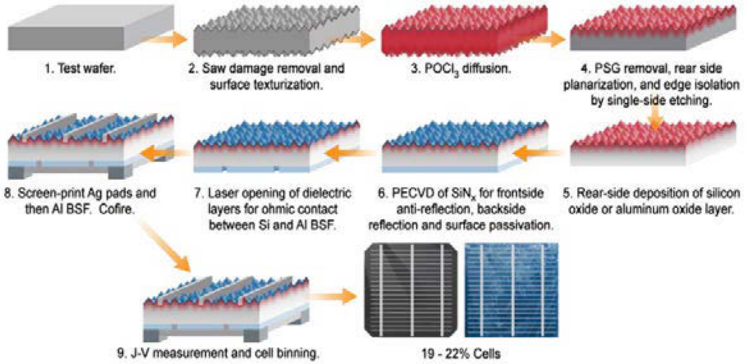
Variable (cash) costs within the cost of goods sold (COGS)
- Input materials
- Direct labor: Skilled and unskilled wages and benefits
- Electricity
- Maintenance of equipment and facilities

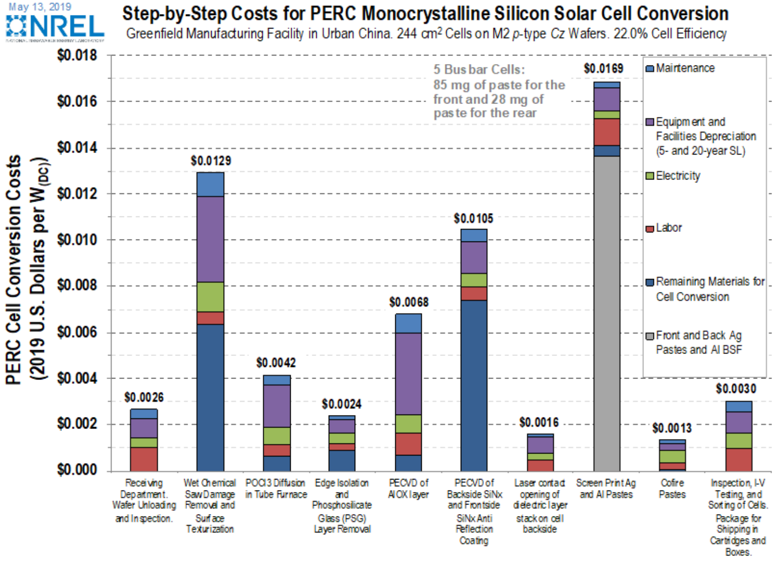
Fixed (non-cash) costs
- Equipment
- Building and facilitation

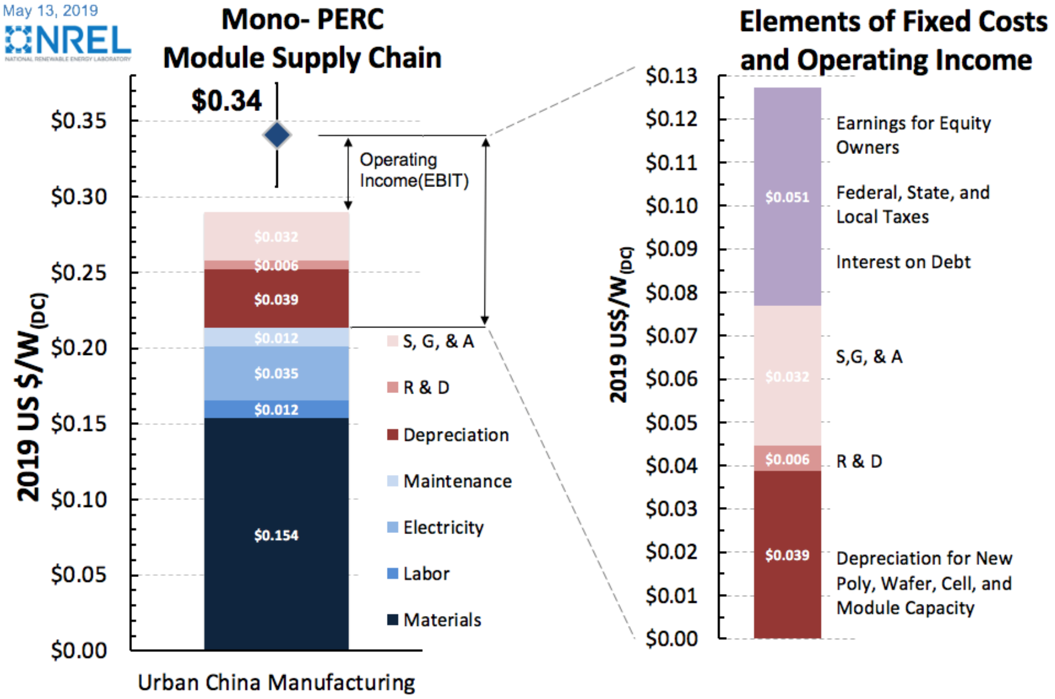
Research and Development (R&D) and Sales, General, and Administration (S, G, &A)
- Organization management
- Human resources
- Accounting staff
- Technology sales, marketing, and promotion to customers
- Future technology research and development

Total Module Supply Chain Costs

Example Cost Model Results for PERC Cell Conversion (Left) and a Complete Module Supply Chain (Right)

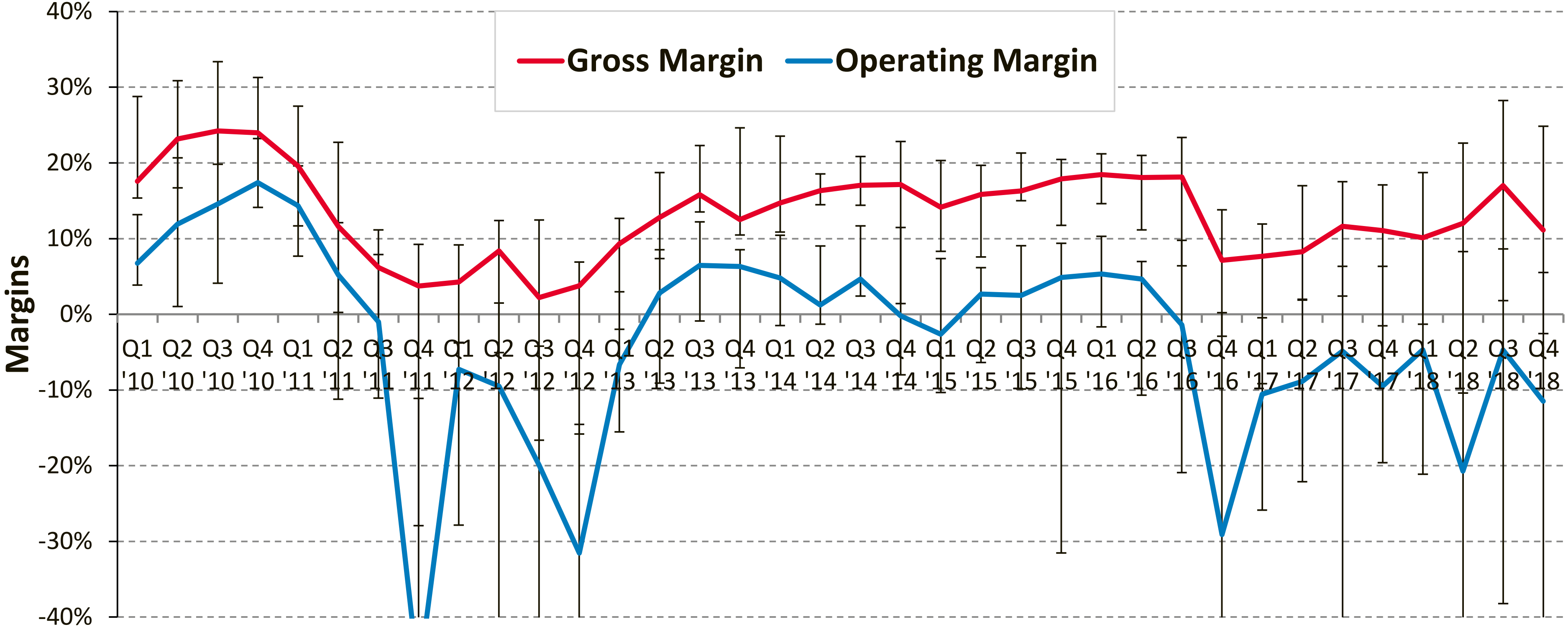






- 2018 industry medians: 2% of revenues reported for R&D and 11% of revenues reported for S, G, & A
- Minimum sustainable price based upon 15% operating (EBIT) margin. 5—20% operating margin used for error bars.
- Additional details given in “Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H2018 Benchmark and Cost Reduction Roadmap” by M Woodhouse, et al., *Available online*.

Historical PV Manufacturers’ Margins

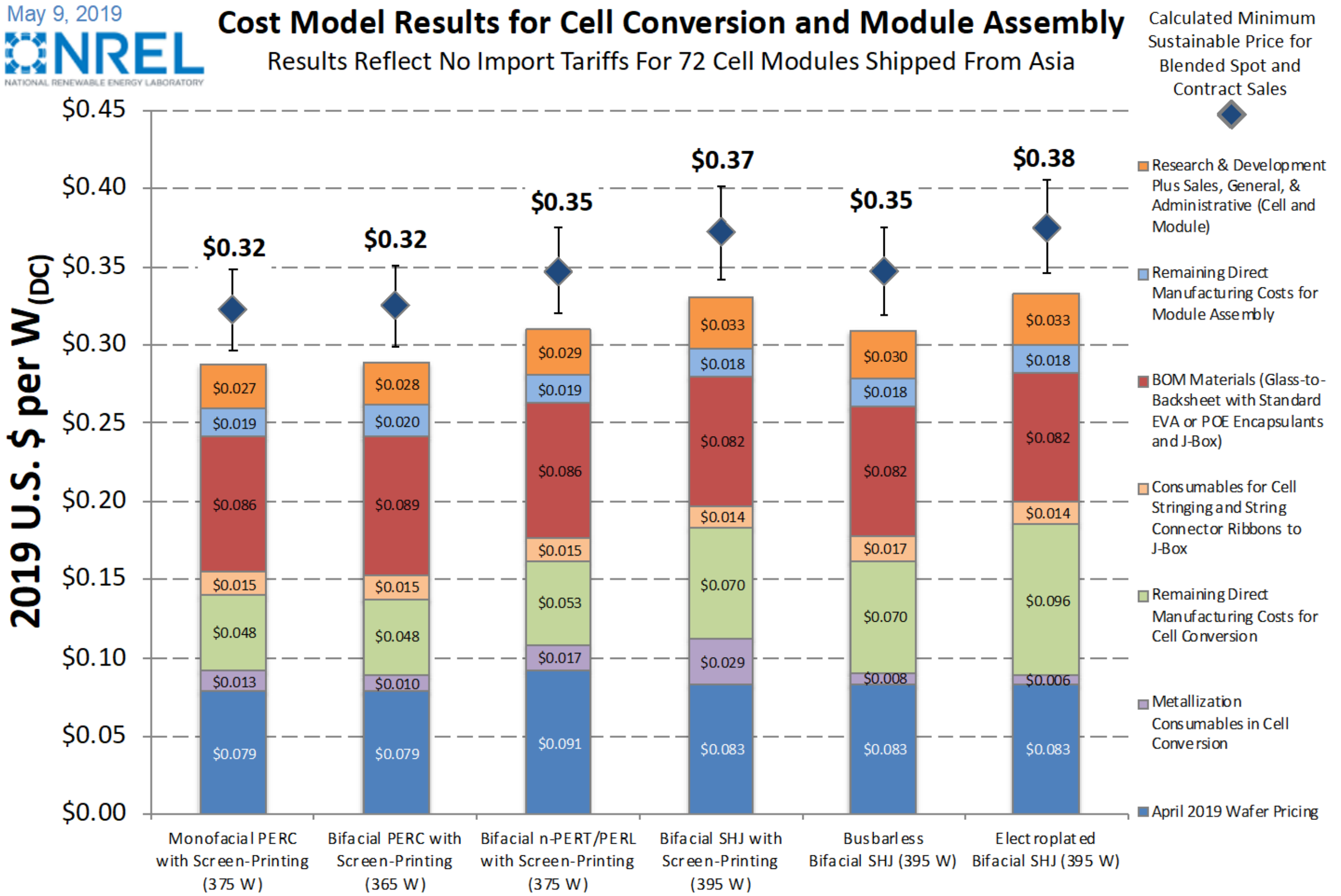


Line represents the median, with error bars representing 80th and 20th percentiles for the following companies in Q4 2018: Canadian Solar, First Solar, Hareon Solar, HT-SAAE, Jinko Solar, LONGi, Motech Industries, Neo Solar Power, Renesola, and SunPower. Margin data from Hanwha Q Cells, JA Solar, Trina, and Yingli are also included from Q1 2010 to Q3 2018 where available.

Sources: Company figures based on data from Bloomberg Terminal and SEC filings by the respective companies.

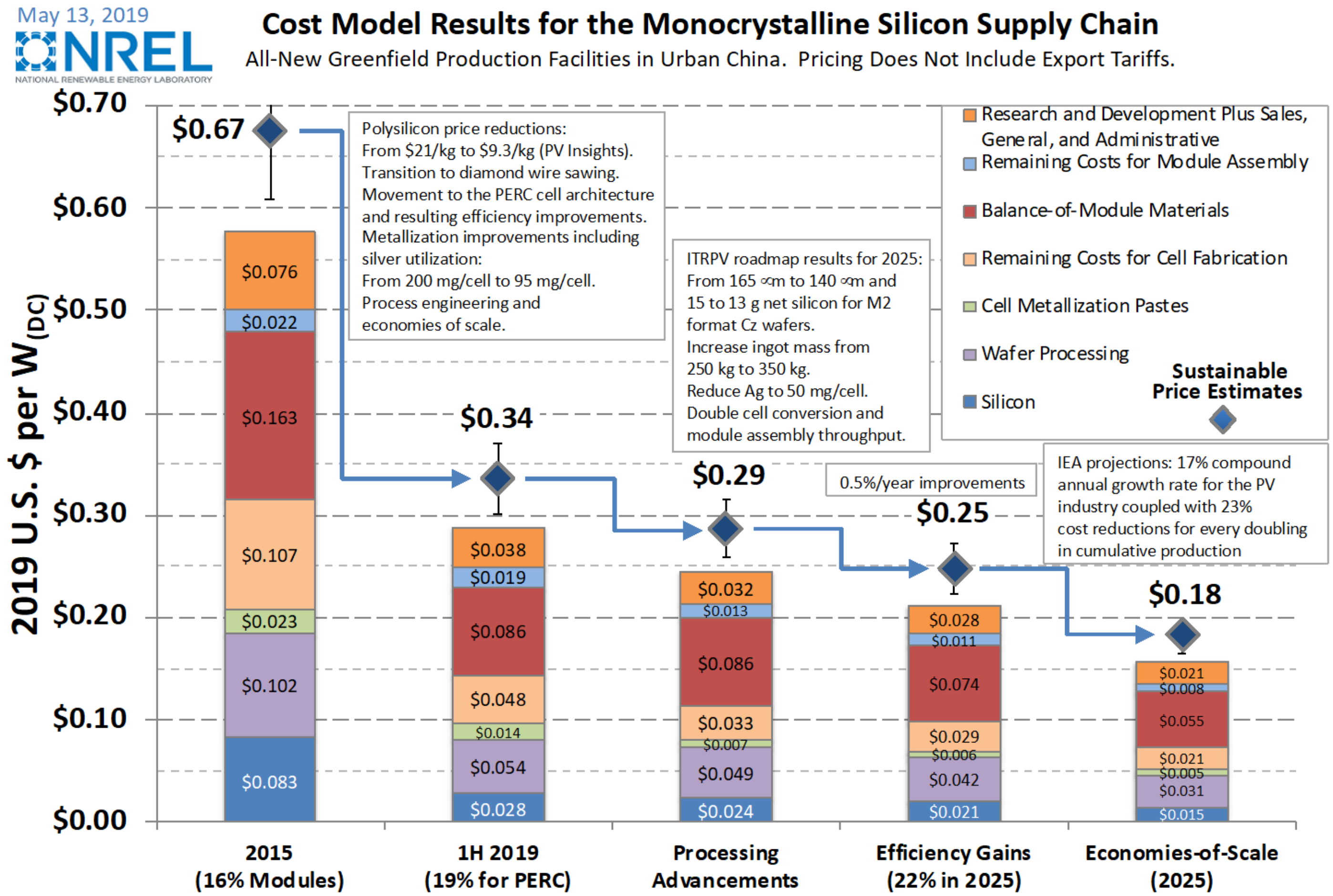
Presentation Outline

Example Cost Model Results for Different PV Technologies



- Higher efficiency benefits $/W balance of module (BOM) costs and CapEx
- 10% price premium given for the *n*-type cell architectures PERT, HIT, and IBC
- Industry median 13% of revenues budgeted for R&D plus S, G, & A
- Minimum sustainable price based upon 15% operating (EBIT) margin
- Additional details given in "Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H2018 Benchmark and Cost Reduction Roadmap" by M Woodhouse, et al., *Available online*.

Historical, Current, and Projected Pricing for Mono-



- Higher efficiency benefits $/W balance of module (BOM) costs and CapEx
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- Minimum sustainable price based upon 15% operating (EBIT) margin. 5—20% operating margin used for error bars.
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Presentation Outline

1 The International Supply Chain and Major Markets for Photovoltaics (PV)

2 The U.S. PV Market

3 Costs and Margins Analysis With the GAAP and IFRS Reporting Standards

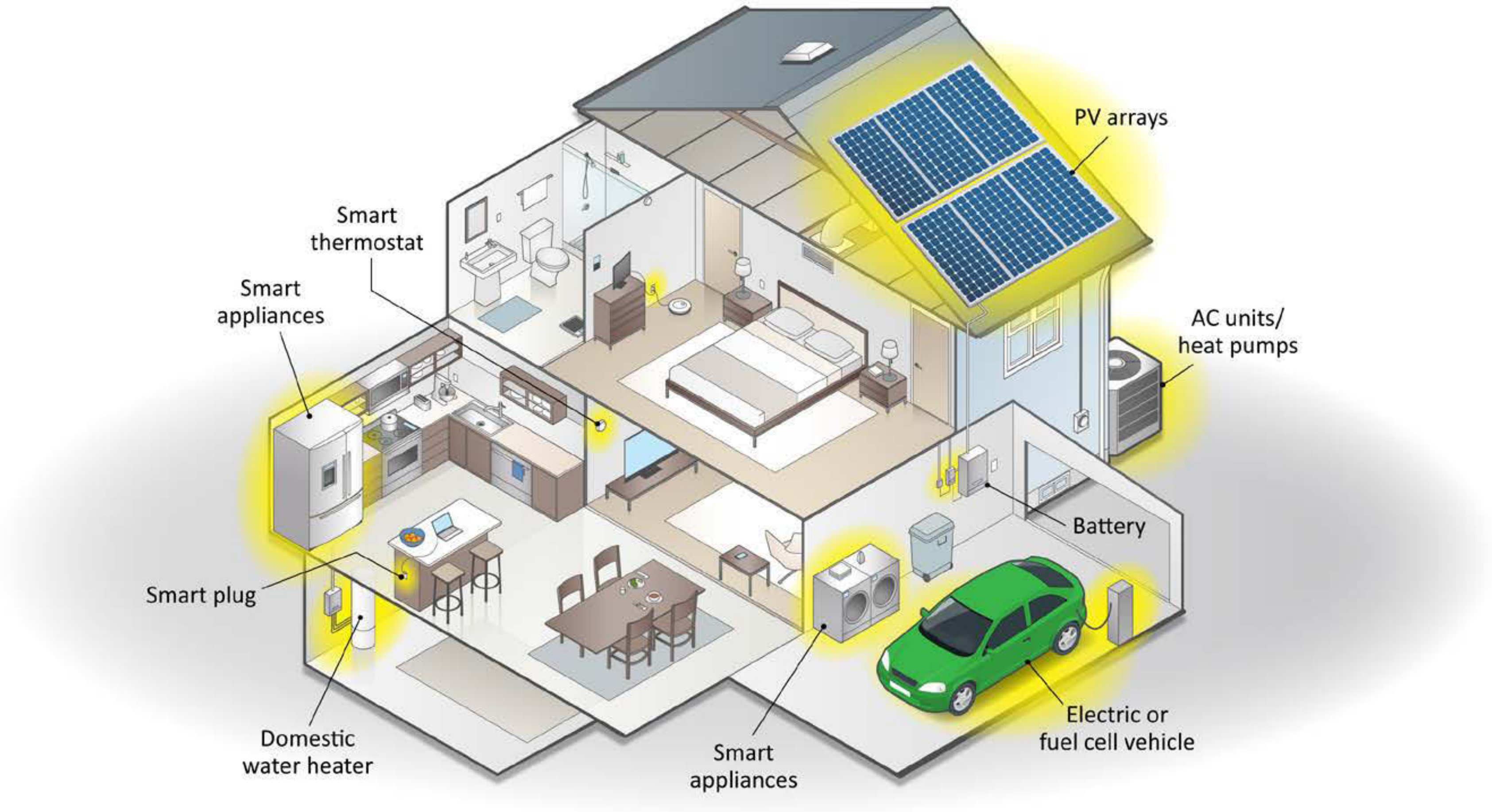
4 Roadmap and Cost Model Results for Standard, PERC, PERT, SHJ, and IBC

5 **Introduction to Solar Plus**

6 Results for PV System Cost Modeling with Storage

7 Conclusions

Introduction to Solar Plus



Introduction to Solar Plus

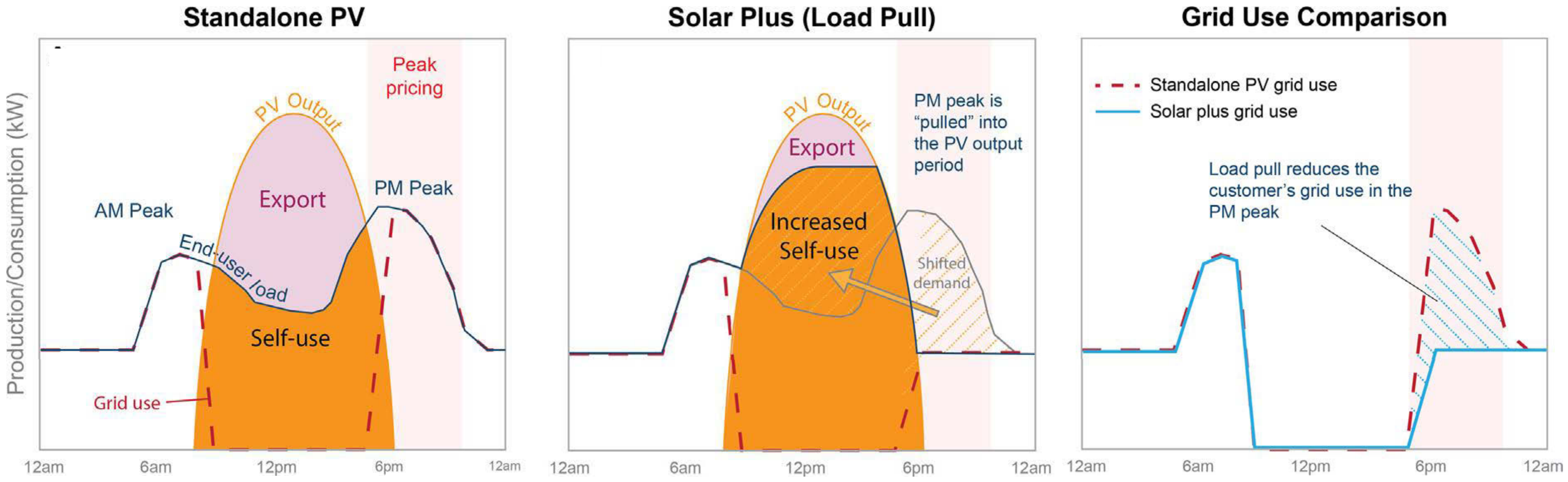
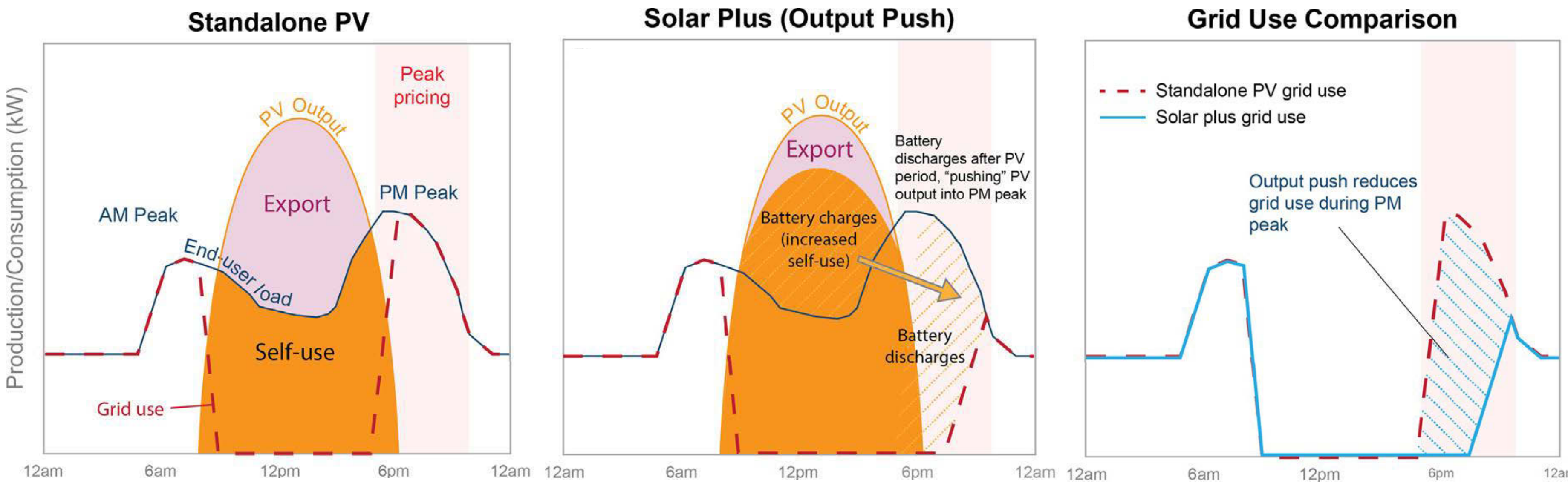


Figure source: E O'Shaughnessy, et. al. (NREL), "Solar plus: A review of end-user economics of solar PV integration with storage and load control in residential buildings", Applied Energy 228 (**2018**) 2165—2175

Introduction to Solar Plus



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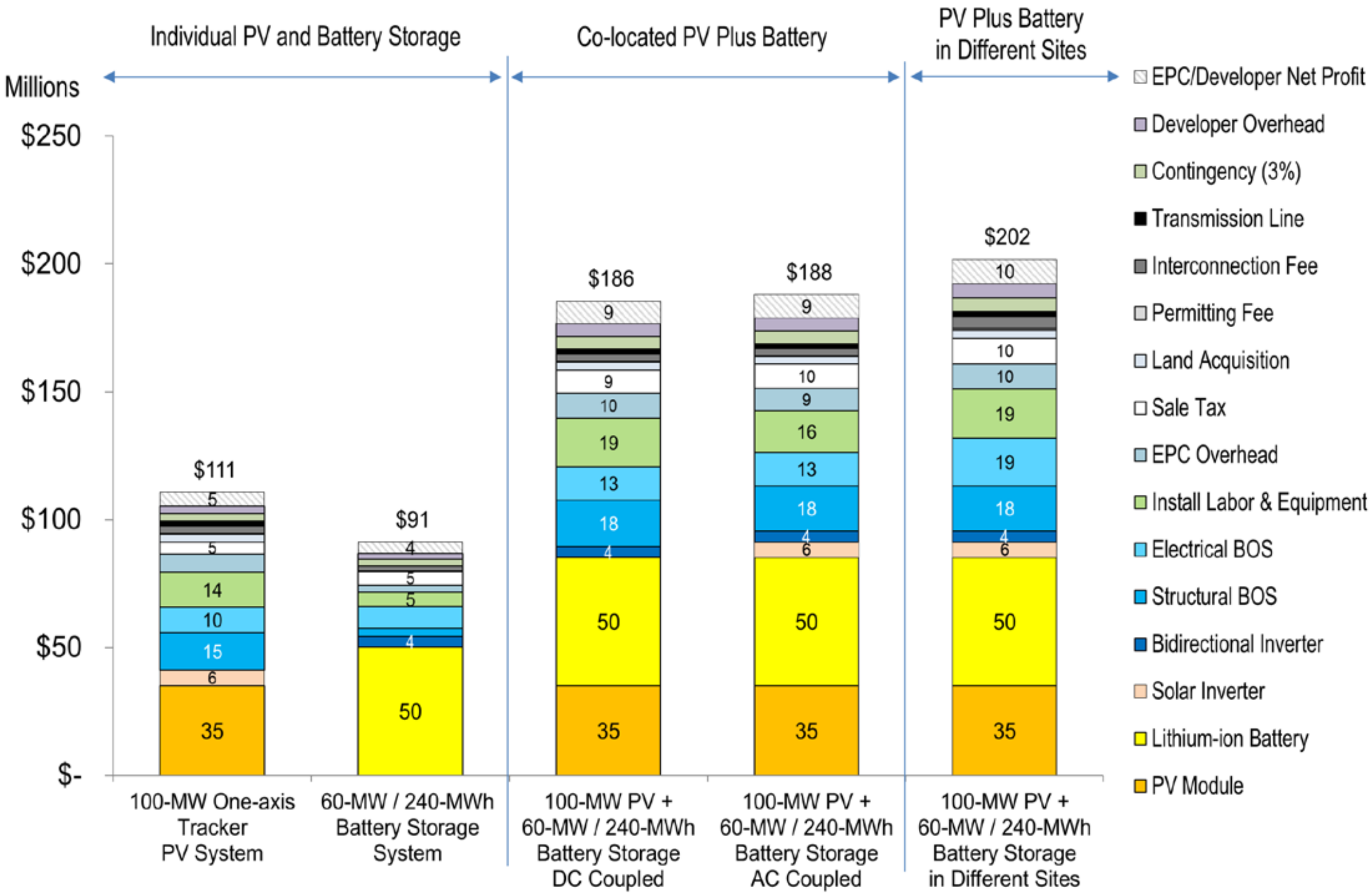
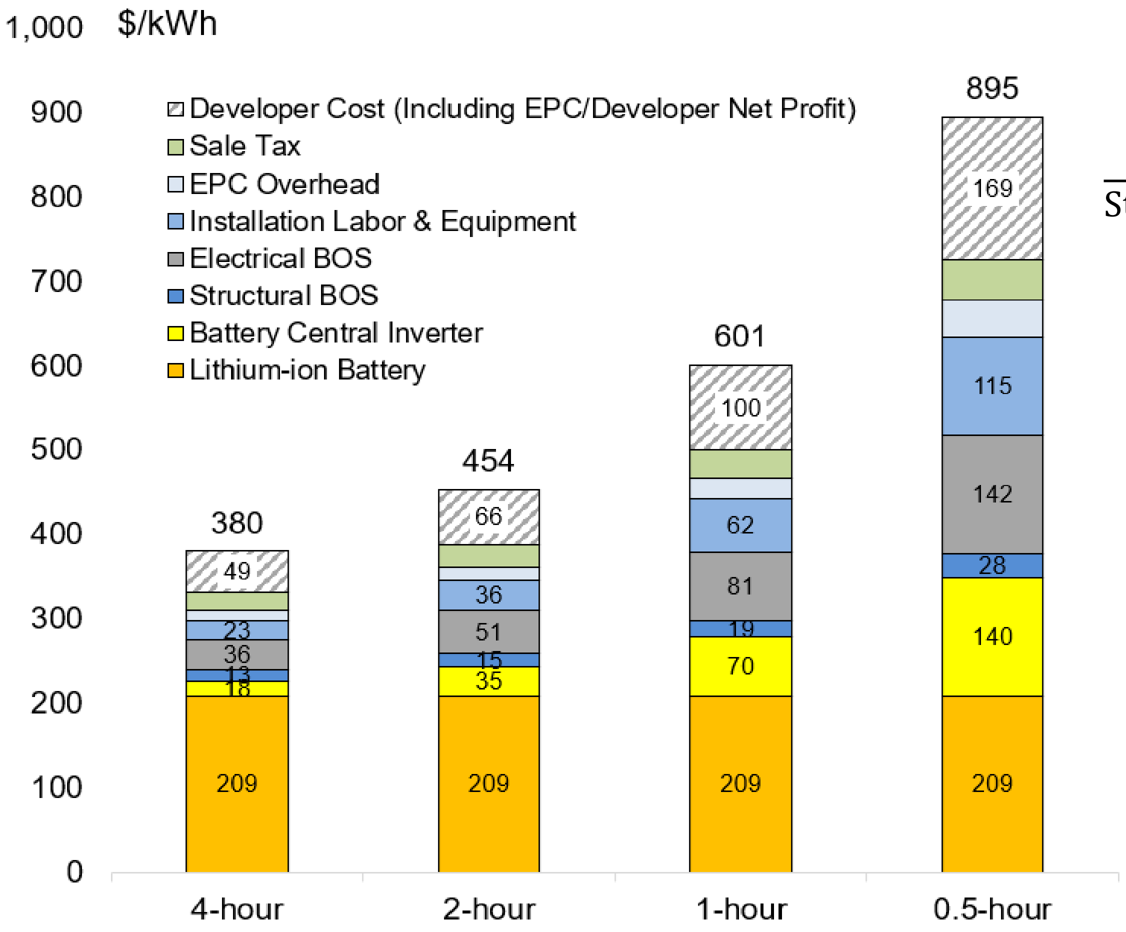
Utility-Scale PV Plus Batteries System Costs Analysis



- Li-ion battery price of $209/kWh
- $0.07/W battery central inverter price. 2.5 MW per inverter equals 24 inverters for 60 MW-DC.
- 5 MWh in a 12-meter container equals 48 battery containers for 4 hr duration

Additional details about this figure are given in “2018 U.S. Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark” by R Fu, et. al., *NREL technical report available online*.

Utility-Scale Batteries Cost Modeling Results

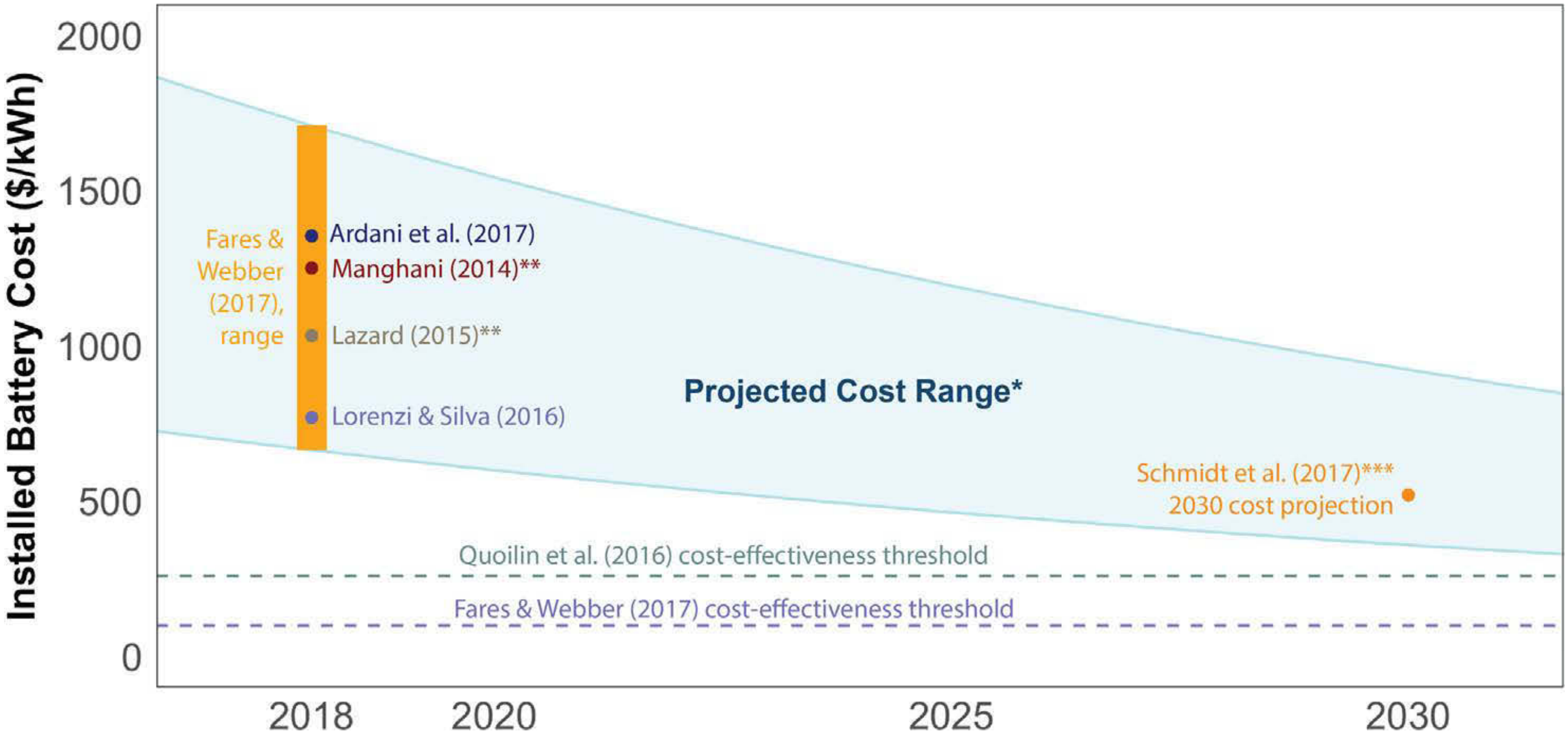


$$\text{Energy Storage Installation Cost}\left(\frac{\$}{\text{kWh}}\right) = \frac{\text{Battery Cost}\left(\frac{\$}{\text{kWh}}\right) + \text{Other cost components}(\$)}{\text{Storage system size (kW)} \times \text{Duration (hours)}}$$

- 60 $MW_{(DC)}$ battery systems with varying durations
- Battery costs account for 55% of total system cost in 4-hour duration systems but only 23% for 0.5-hour duration systems. This is because battery costs are held constant across those durations.
- Non-battery cost categories account for an increasing proportion of the $/kWh system cost as duration declines.

Additional details about this figure are given in "2018 U.S. Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark" by R Fu, et. al., *NREL technical report available online*.

2018 Benchmark Battery Costs and Projections to 2030



Source of Figure: E O'Shaughnessy, et. al. (NREL), "Solar plus: A review of end-user economics of solar PV integration with storage and load control in residential buildings", Applied Energy 228 (**2018**) 2165—2175

Presentation Outline

Conclusions

- The supply chain for solar PV module production is a global enterprise.
- The costs to produce PV modules has declined over time, but price pressures have constrained 2010—2018 industry median gross margins to the 10—20% range. Industry median operating margins were in negative territory for all of 2017 and 2018.
- NREL cost model results for the full mono- PERC supply chain are roughly $0.03/W silicon cost, $0.05/W for ingot and wafer production, $0.06/W for cell conversion, $0.11/W for module assembly, and $0.04/W for R & D plus S, G, & A. We also estimate around $0.05/W would be needed to achieve 15% operating margin.
- Additional portfolio technologies including PERT, SHJ, and IBC are now calculated to be within $0.05/W of the costs for standard Al BSF and PERC.
- Long-term growth scenarios for the solar PV industry may be less dependent upon further cost reductions in module and utility-scale systems than integration with storage technologies, advanced on-grid and off-grid engineering technologies, and other power generation systems.
- Please follow-up with any questions! https://www.nrel.gov/analysis/

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