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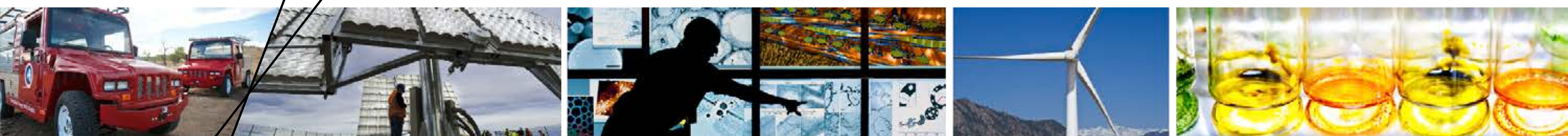
U.S. Solar Photovoltaic System Cost Benchmark: Q1 2016



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Introduction

(1) **NREL has been modeling U.S. photovoltaic (PV) system costs since 2009. This year, our report benchmarks costs of U.S. solar PV for residential, commercial, and utility-scale systems built in the first quarter of 2016 (Q1 2016).** Costs are represented from the perspective of the developer/installer; thus all hardware costs represent the price at which components are purchased by the developer/installer. Importantly, the benchmark this year also represents the sales price paid to the installer; therefore, it includes profit in the cost of the hardware and the profit the installer/developer receives, as a separate cost category. However, it does not include any additional net profit, such as a developer fee or price gross-up, which are common in the marketplace. We adopt this approach owing to the wide variation in developer profits in all three sectors, where project pricing is highly dependent on region and project specifics such as local retail electricity rate structures, local rebate and incentive structures, competitive environment, and overall project/deal structures

(2) **Our methodology includes bottom-up accounting for all system and project-development costs incurred when installing residential, commercial, and utility-scale systems, and it models the capital costs for such systems.** In general, we attempt to model typical installation techniques and business operations from an installed-cost perspective, and our benchmarks are national averages of installed capacities, weighted by state. The residential benchmark is further averaged across installer and integrator business models, weighted by market share. All benchmarks assume non-union construction labor, although union labor cases are considered for utility-scale systems.

Introduction

(3) This report was produced in conjunction with several related research activities at NREL and Lawrence Berkeley National Laboratory (LBNL):

- Chung, Donald, Carolyn Davidson, Ran Fu, Kristen Ardani, and Robert Margolis. 2015. *U.S. Photovoltaic Prices and Cost Breakdowns: Q1 2015 Benchmarks for Residential, Commercial, and Utility-Scale Systems*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-64746.

- Fu, Ran, Ted James, Donald Chung, Douglas Gagne, Anthony Lopez, and Aron Dobos. 2015. *Economic Competitiveness of U.S. Utility-scale Photovoltaics Systems in 2015: Regional Cost Modeling of Installed Cost ($/W) and LCOE ($/kWh)*. IEEE 42nd Photovoltaic Specialist Conference, New Orleans, LA.

- Feldman, David, Galen Barbose, Robert Margolis, Mark Bolinger, Donald Chung, Ran Fu, Joachim Seel, Carolyn Davidson, Naïm Darghouth, and Ryan Wiser. 2015. *Photovoltaic System Pricing Trends, Historical, Recent, and Near-Term Projections*. Golden, CO: National Renewable Energy Laboratory. NREL/PR-6A20-64898.

- Barbose, Galen, and Naïm Darghouth. 2015. *Tracking the Sun VIII: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States.* Berkeley, CA: Lawrence Berkeley National Laboratory.

- Bolinger, Mark, and Joachim Seel. 2015. *Utility-Scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States*. Berkeley, CA: Lawrence Berkeley National Laboratory.

- Ardani, Kristen, and Robert Margolis. 2015. *Decreasing Soft Costs for Solar Photovoltaics by Improving the Interconnection Process: A Case Study of Pacific Gas and Electric*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-65066.

Introduction

(4) Download the full technical report along with the data file:

- **Download the full report: http://www.nrel.gov/docs/fy16osti/66532.pdf**

- **Download the data file: https://doi.org/10.7799/1325002**

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Ran Fu, Donald Chung, Travis Lowder, David Feldman, Kristen Ardani, and Robert Margolis
National Renewable Energy Laboratory (NREL)

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Key Definitions

Unit	Description
Value	2016 U.S. dollar (USD)
System Size	In direct current (DC) terms; inverter prices are converted by DC-to-alternating current (AC) ratios.

Sector Category	Description	Size Range
Residential PV	Residential rooftop systems	3 kW – 10 kW
Commercial PV	Commercial rooftop systems, ballasted racking	10 kW – 2 MW
Utility-scale PV	Ground-mounted systems, fixed-tilt and one-axis tracker	> 2 MW

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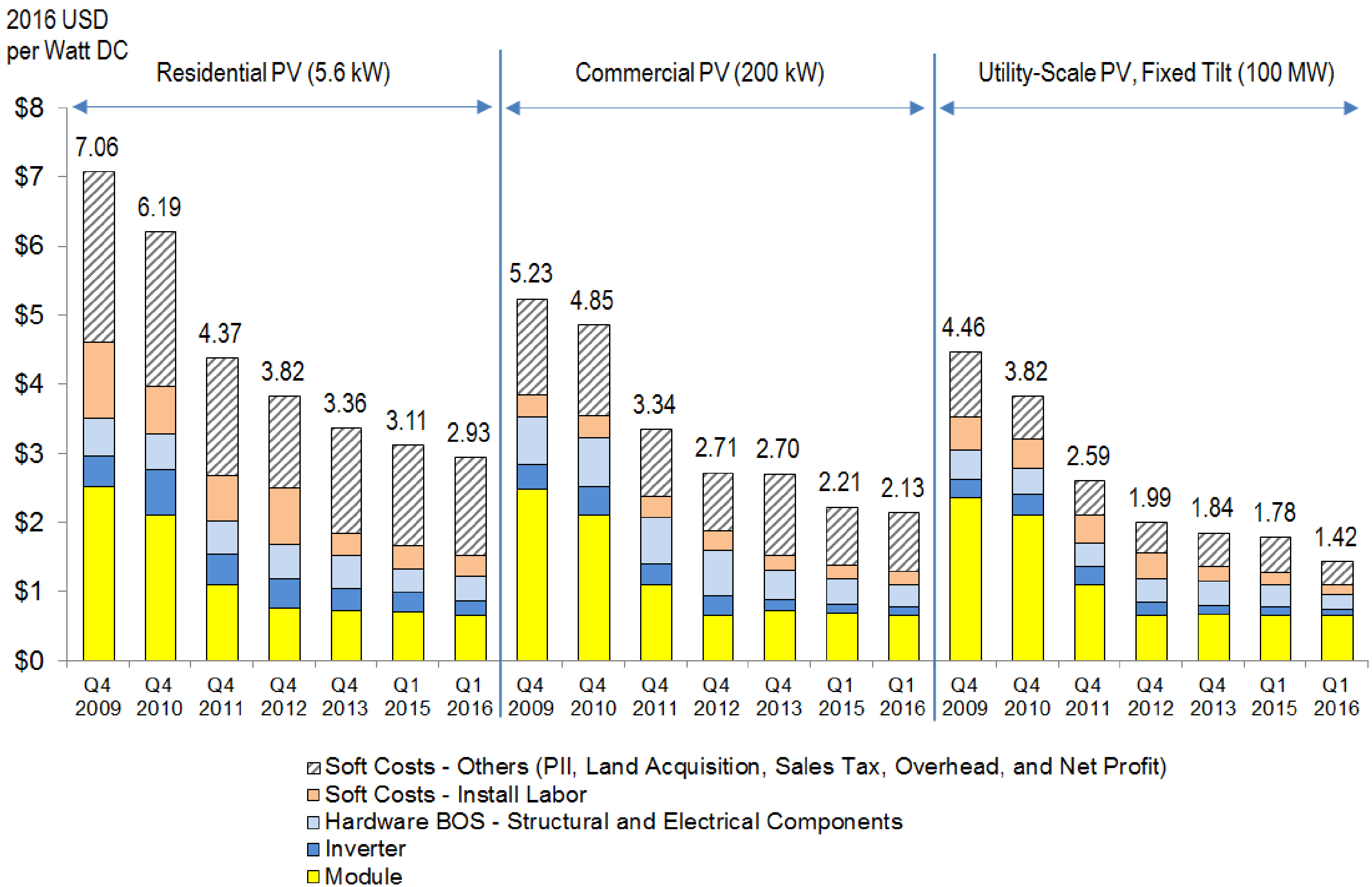
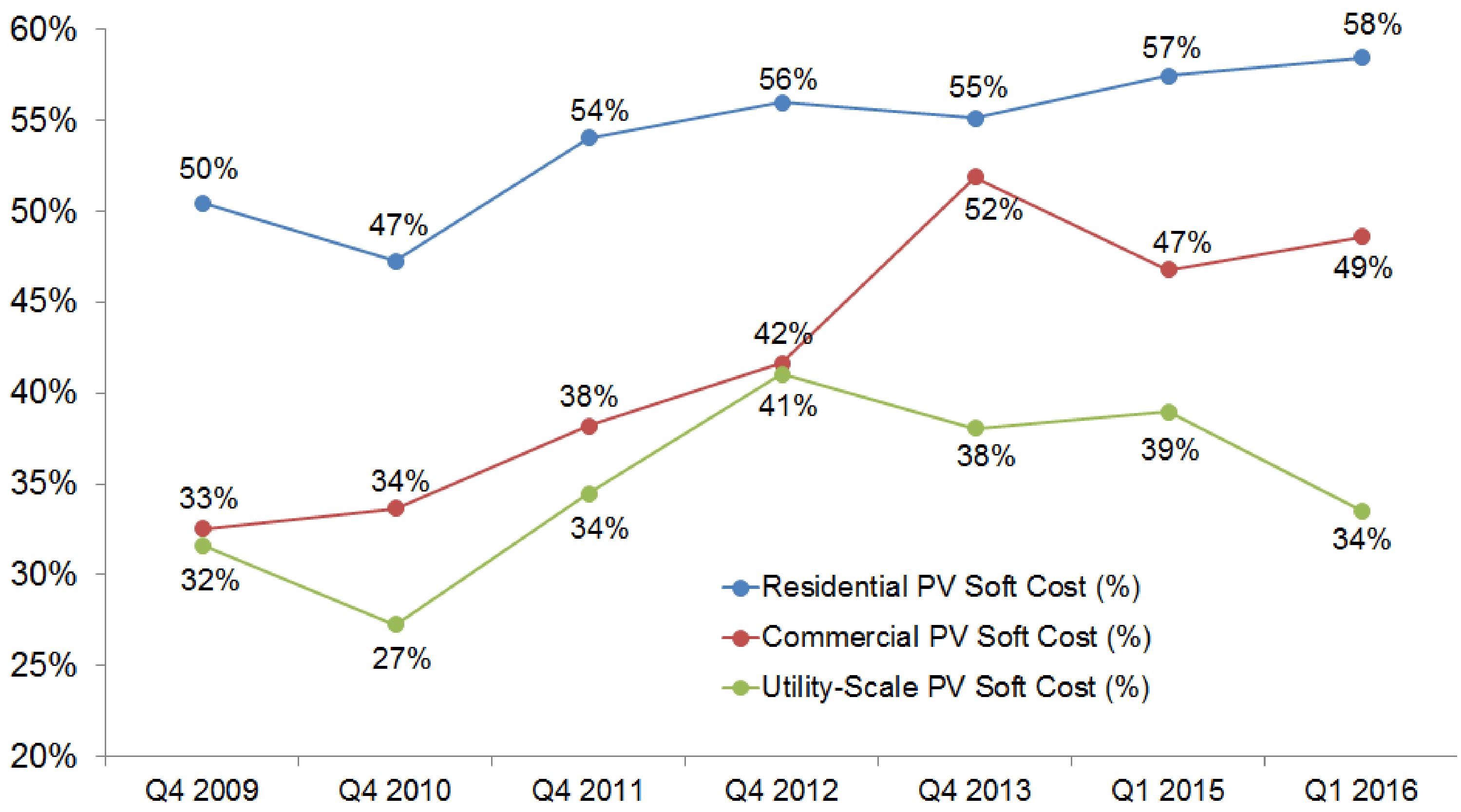
Overall Model Results



1. Values are inflation adjusted using the Consumer Price Index. Thus, historical values from our models are adjusted and presented as real USD instead of nominal USD.
2. Cost categories are aggregated for comparison purposes. For instance, “Soft Costs – Others” represents PII, land acquisition, sales tax, and EPC/developer overhead and net profit.

Overall Model Results (Soft Cost)



1. "Soft Cost" in this report is defined as non-hardware cost—i.e., "Soft Cost" = Total Cost – Hardware Cost (module, inverter, and structural and electrical BOS).
2. Residential and commercial sectors have larger soft cost percentage than the utility-scale sector.
3. Soft costs and hardware costs also interact with each other. For instance, module efficiency improvements have reduced the number of modules required to construct a system of a given size, thus reducing hardware costs, and this trend has also reduced soft costs from direct labor and related installation overhead.
4. An increasing soft cost proportion in this figure indicates that soft costs declined more slowly than hardware costs; it does not indicate that soft costs increased on an absolute basis.

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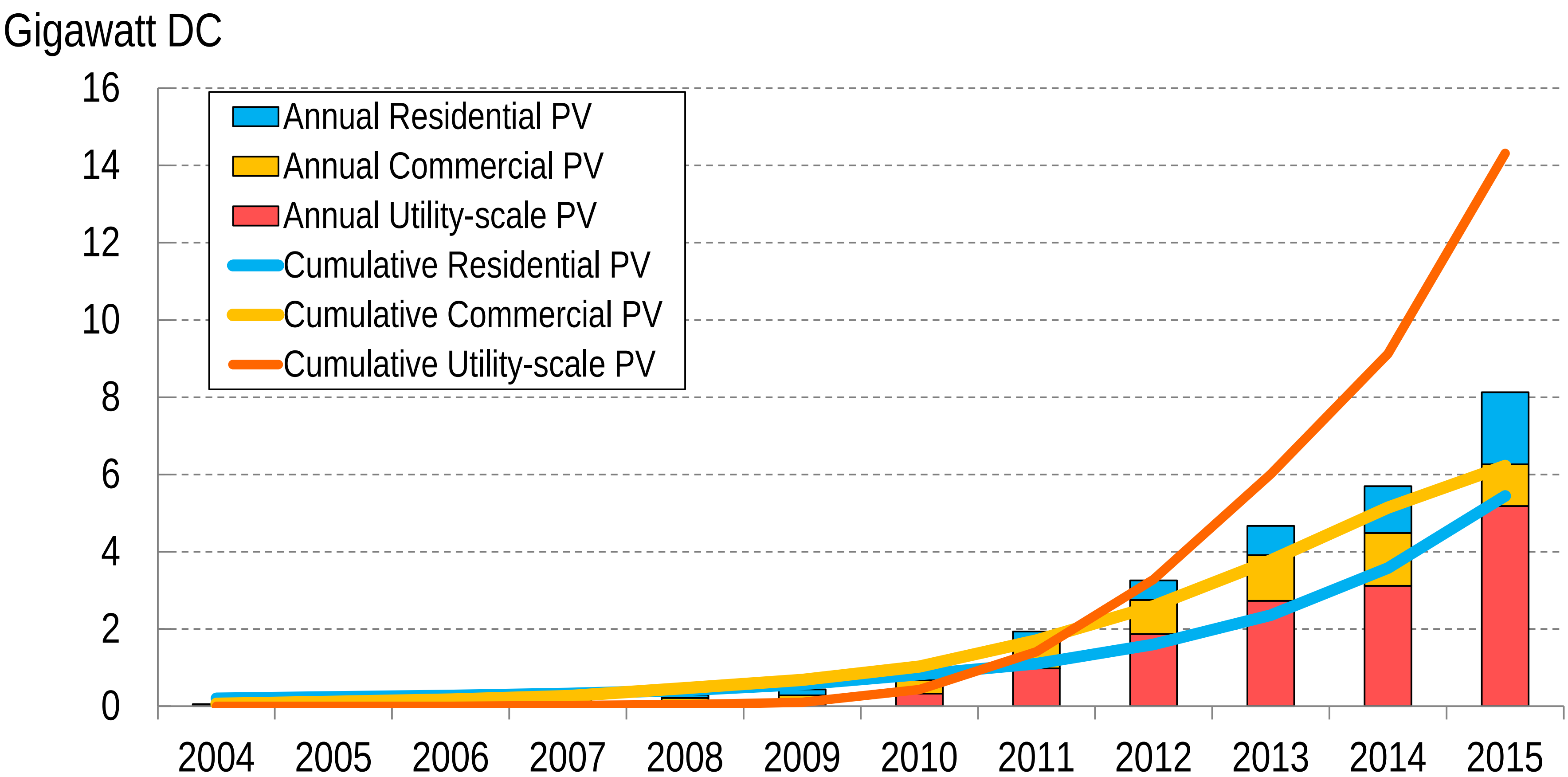
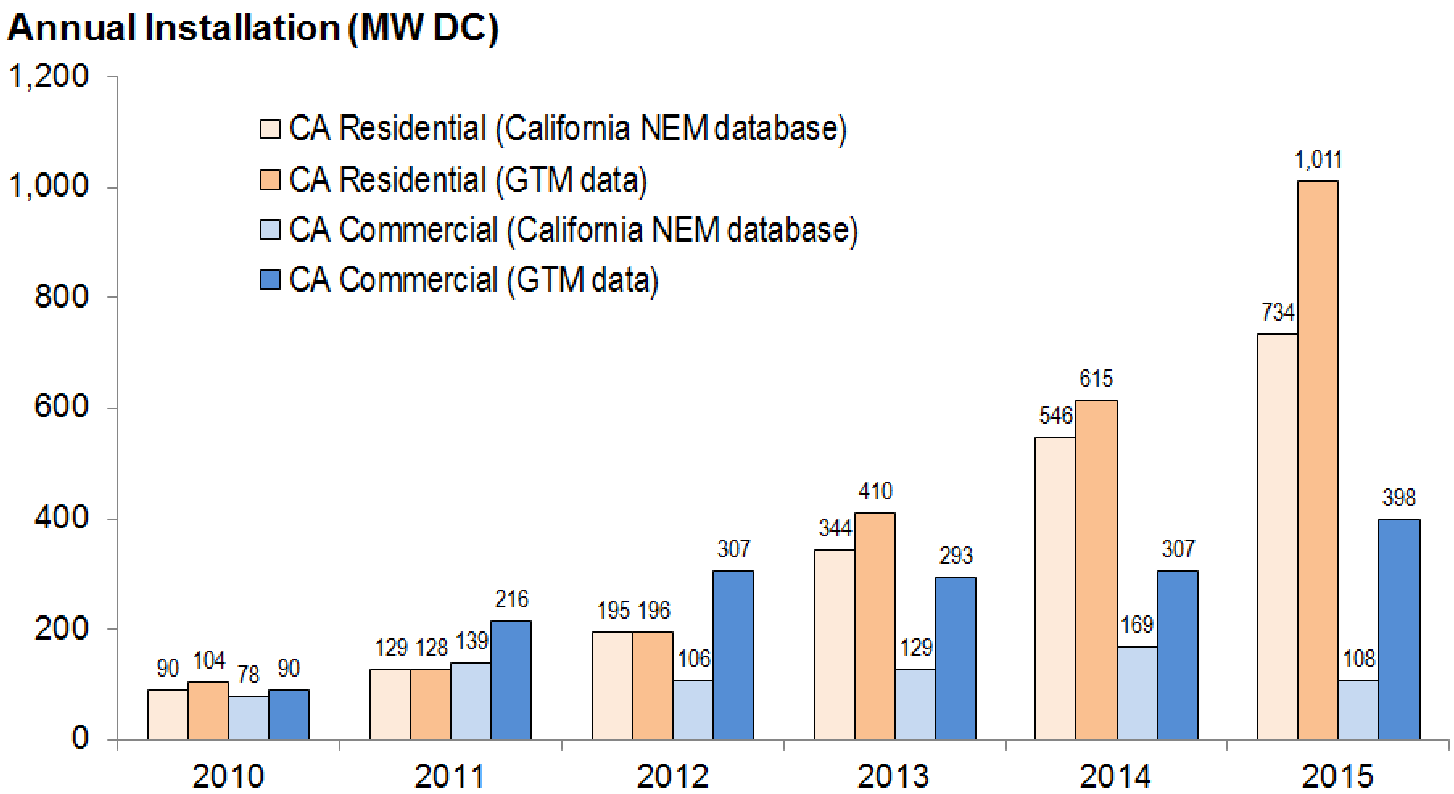
US Solar PV Market Growth



U.S. PV market growth, 2004–2015, in gigawatts of direct current (DC) capacity (Bloomberg 2016)

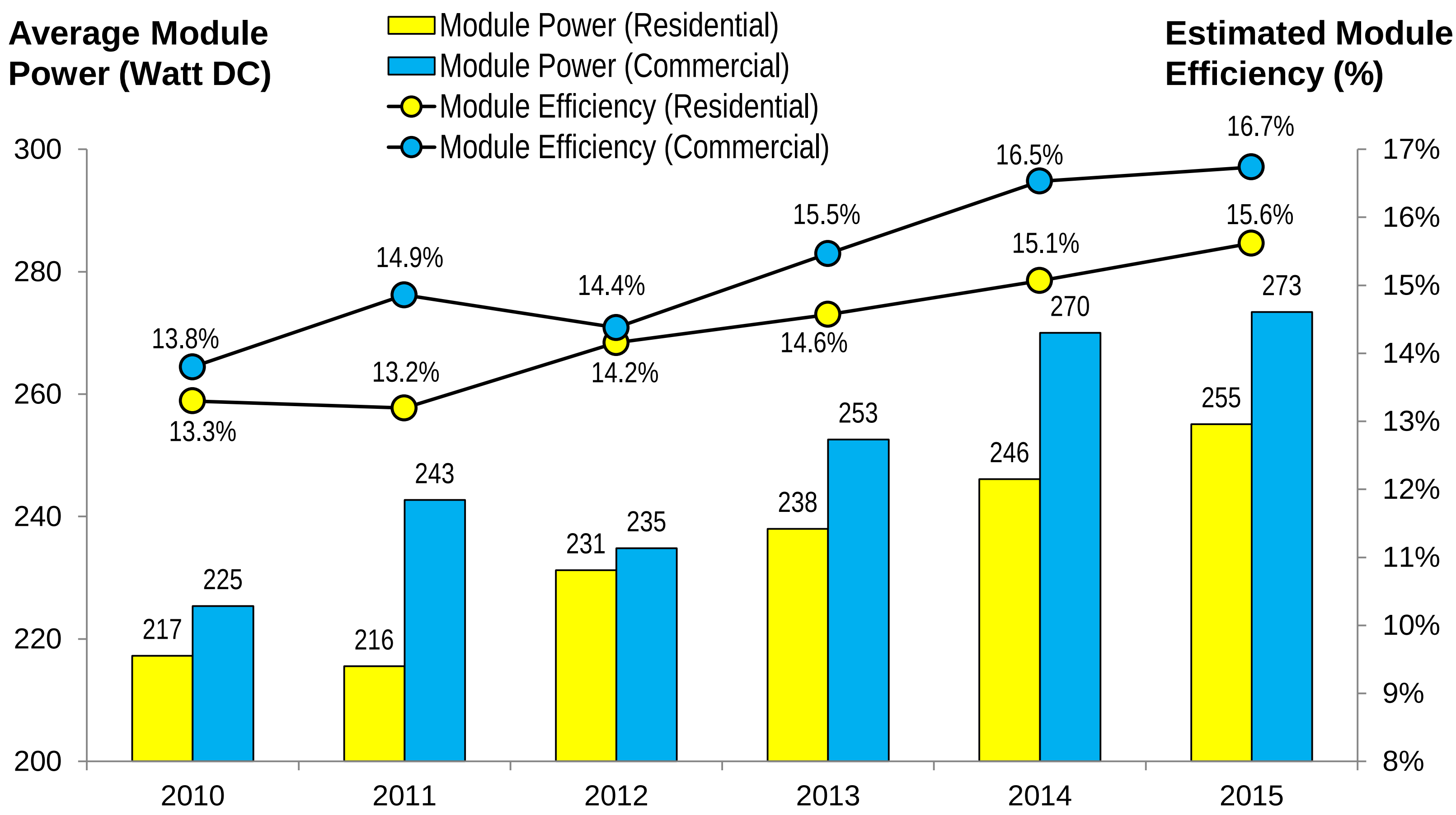
Solar photovoltaic (PV) deployment has grown rapidly in the United States over the past several years. As the figure shows, the compound annual growth rates for the U.S. residential, commercial, and utility-scale PV sectors from 2010 to 2015 were 46%, 43%, and 101% respectively. Utility-scale PV has been the solar industry's largest segment consistently since 2012 (Bloomberg 2016).

Database for Residential and Commercial Sectors



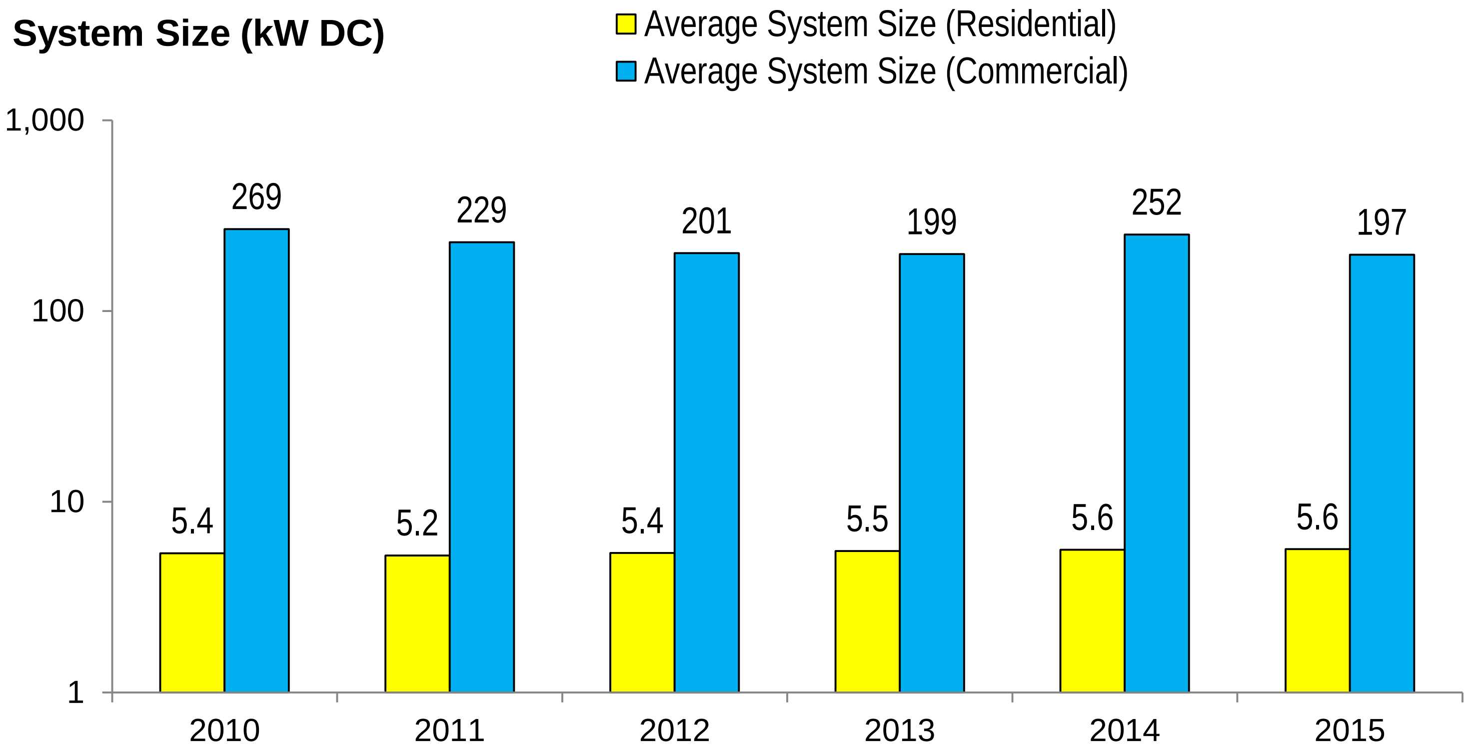
Previous NREL analyses used the California Solar Initiative Data Set (CSI 2016), but, as that program has wound down, the number of new PV incentive applications (and consequently the data collection) has decreased substantially. As a result, for this analysis we use the robust California NEM Interconnection Applications Data Set instead (Go Solar CA 2016). This database is updated monthly and contains all interconnection applications in the service territories of the state's three investor-owned utilities (Pacific Gas & Electric, Southern California Edison, and San Diego Gas & Electric). Collectively, 47% of the PV in the United States is integrated into these three utilities (SEPA 2016). We use the database to benchmark generic system characteristics, such as system size, module power and efficiency, and choice of power electronics. Although there are other databases for other markets, such as Massachusetts and New York, we use only the California NEM database because of its higher granularity and consistency. However, we do not use the California NEM database for regional cost analyses; inputs and sources for regional analyses are described in subsequent sections of this report.

Module Power and Efficiency Trend (California)



This figure displays module power and efficiency data from the California NEM database. Since 2010, module power and efficiency have been consistently higher in the commercial sector than in the residential sector, although both sectors have been steadily improving. We use the values of 15.6% (residential) and 16.7% (commercial and utility-scale) module efficiency.

PV System Size Trend (California)



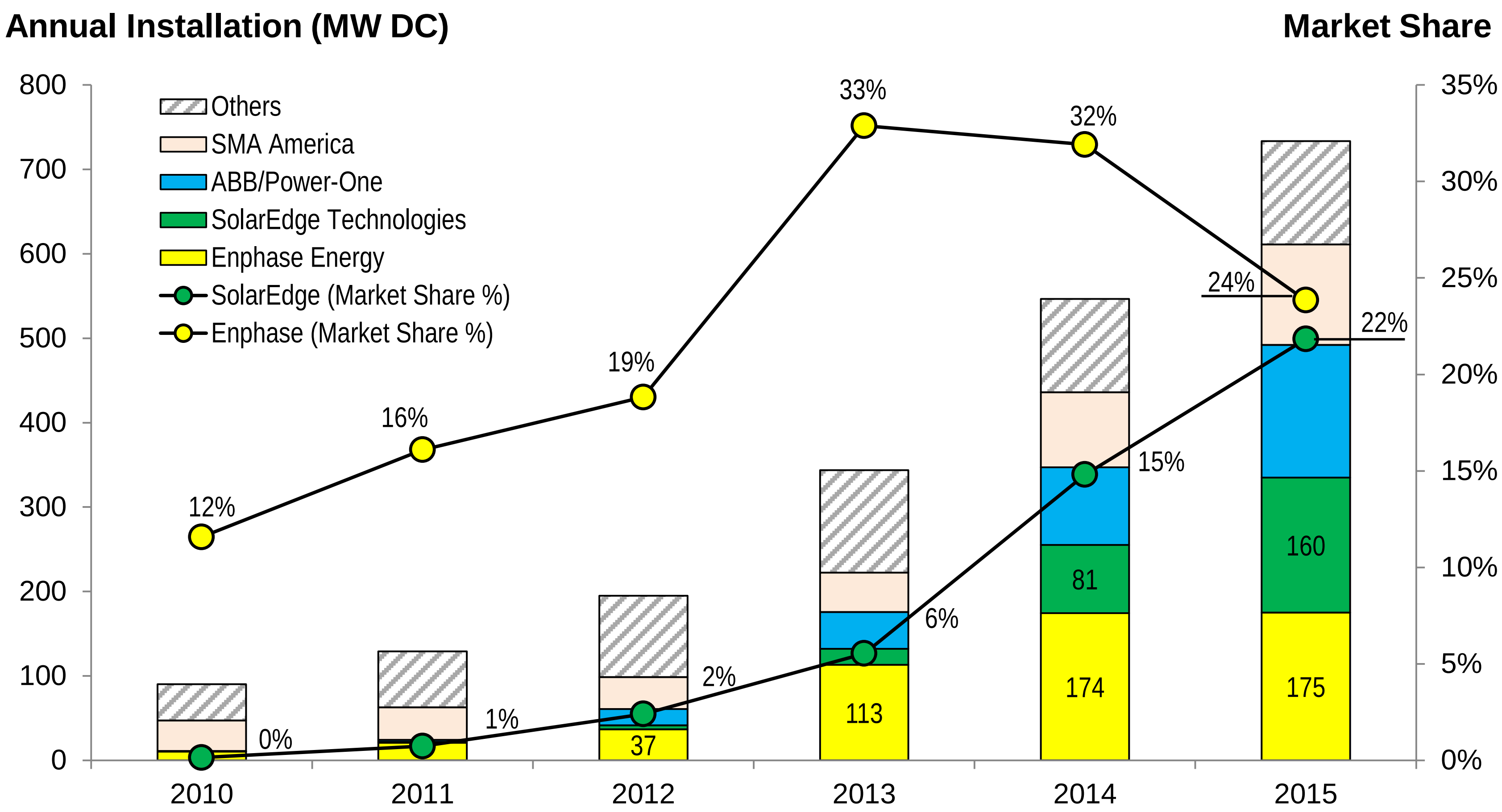
This figure displays average system sizes from the California NEM database. Average residential system sizes have not changed significantly over the past five years. We use the 2015 value of 5.6 kilowatts (kW) as the baseline case in our cost model. Conversely, commercial system sizes have changed more frequently, likely reflecting the wide scope for “commercial customers,” which include schools, office buildings, malls, retail stores, and government projects. We use 200 kW as the baseline case in our model.

Inverter Solutions – Microinverter and DC Power Optimizer

Microinverters and DC power optimizers are collectively referred to as module-level power electronics (MLPE). By allowing designs with different roof configurations (orientations and tilts) and constantly tracking the maximum power point for each module, MLPE provide an optimized design solution at the module level. Today, Enphase (microinverters) and SolarEdge (DC power optimizers) are the leading companies offering MLPE solutions. The table below provides a brief comparison between traditional string inverters and MLPE.

	String Inverter	**DC Power Optimizer**	**Microinverter**
Function	PV modules are connected in parallel by one or multiple strings and then directly connected to the string inverter for DC-to-AC conversion. If one module is shaded, the whole string is impacted.	Each PV module has one power optimizer for DC-to-DC conversion, so the traditional junction box is replaced, and all modules are connected by string inverter for DC-to-AC conversion. Shading only impacts individual modules.	Each PV module has one microinverter for DC-to-AC conversion, and thus no string inverter is used. Shading only impacts individual modules.
Relative product price	Low	Medium	High
Performance in shading	Poor	More efficient	More efficient
Performance in various directions or on irregular roofs	Low	Medium	High
Module-level monitoring and troubleshooting	No	Yes (e.g., SolarEdge Cellular Kit)	Yes (e.g., Enphase “Envoy + Enlighten”)
Improved energy yield from module mismatch reduction	No	Yes	Yes
Number of electronic components	Normal	Greater (thus may have some component risks)	Greater (thus may have some component risks)
Safety for installation	Normal	Safer; easier wiring work	Safest; Use only AC cable with no high-voltage DC power.

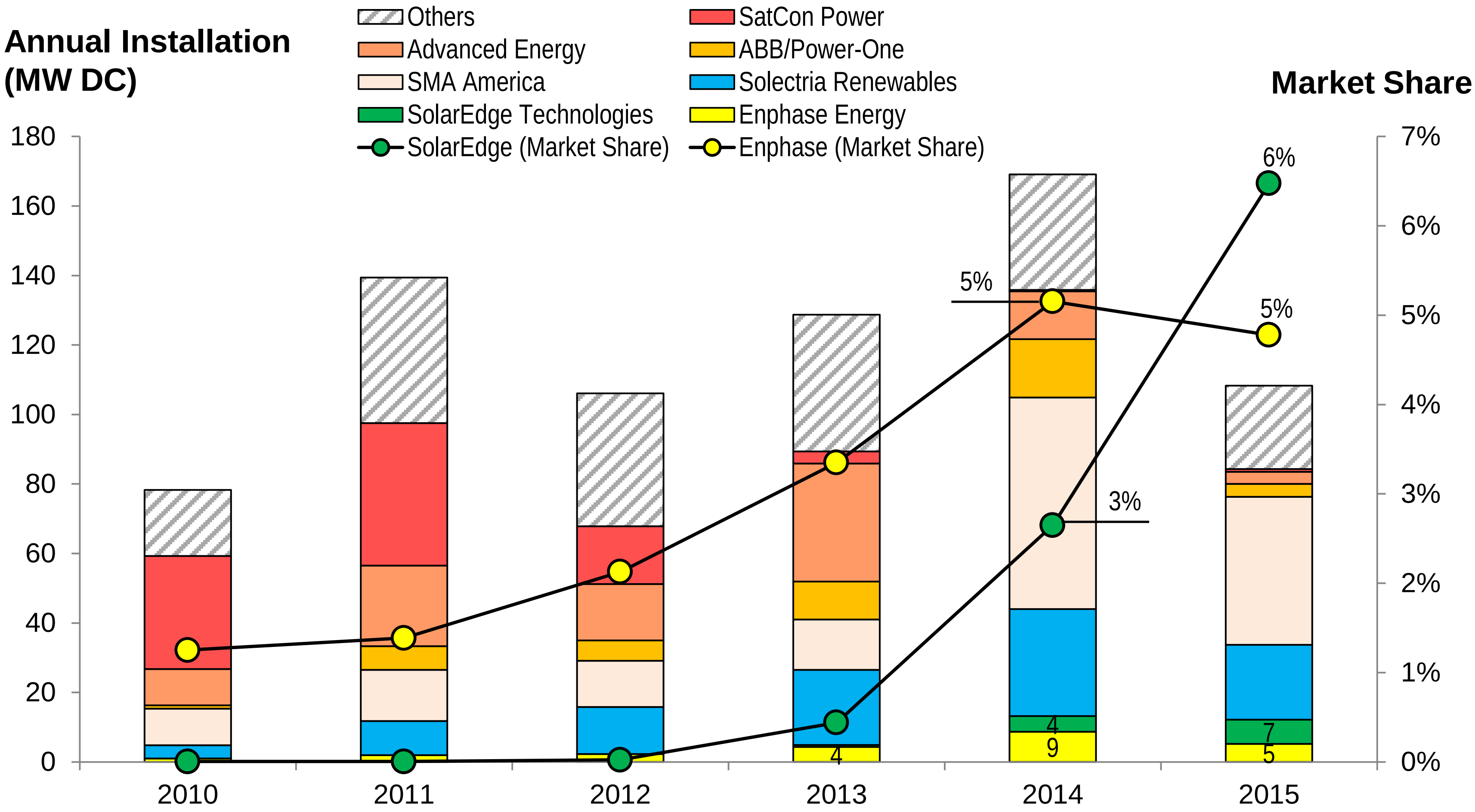
Inverter Market – Residential PV Sector (California)



According to the California NEM database, market uptake of MLPE has been growing rapidly since 2010 in California's residential sector (in this figure). This increasing market growth may be driven by the decreasing MLPE costs and by the "rapid shutdown" on buildings required by Article 690.12 of the National Electric Code since 2014—MLPE inherently meet rapid-shutdown requirements without the need to install additional electrical equipment.

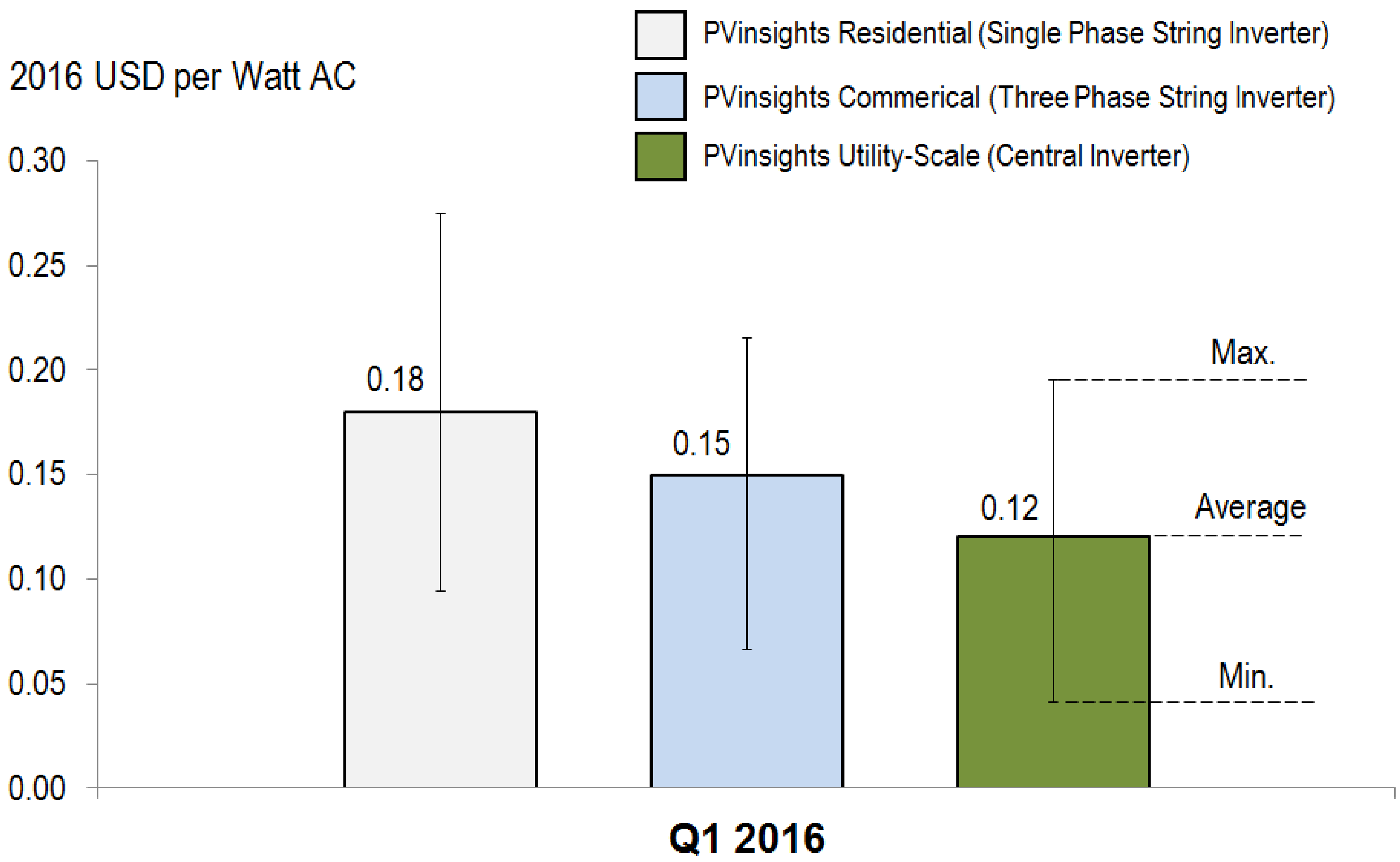
In 2015, the combined Enphase and SolarEdge inverter solutions reached 46% of the total California residential market share. Therefore, we update our residential system cost model with new functions to estimate the costs of these MLPE inverter solutions.

Inverter Market – Commercial PV Sector (California)



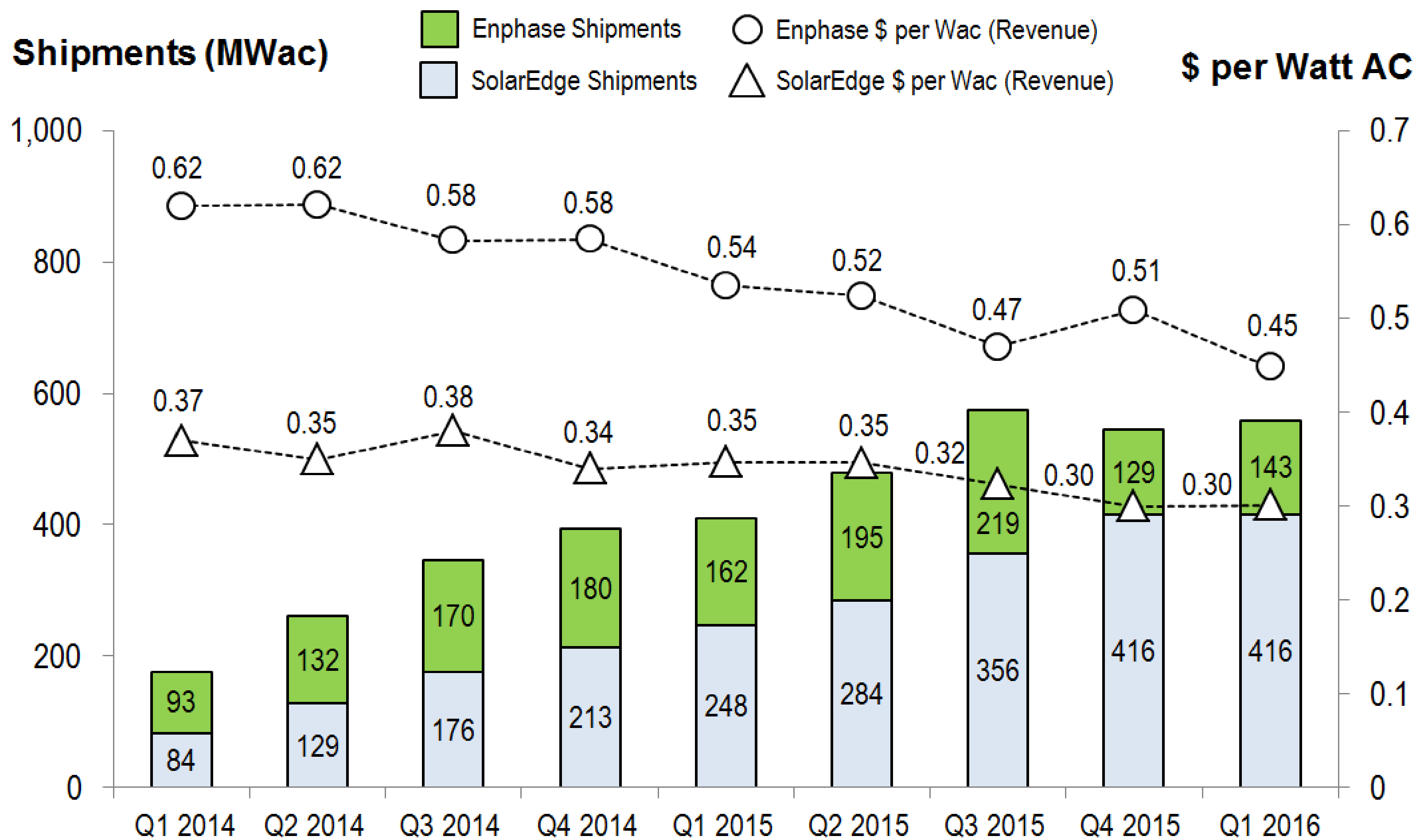
Conversely, according to the California NEM database, MLPE growth has been slow in California's commercial sector, reaching a share of only 11% in 2015 (in this figure). Thus, we do not build MLPE inverter solutions into our commercial model.

Inverter Price for non-MLPEs



We source non-MLPE inverter prices—in U.S. dollars (USD) per watt AC (Wac)—from the PVinsights (2016) database, which contains typical prices between Tier 1 suppliers and developers in the market.

Inverter Price for MLPEs



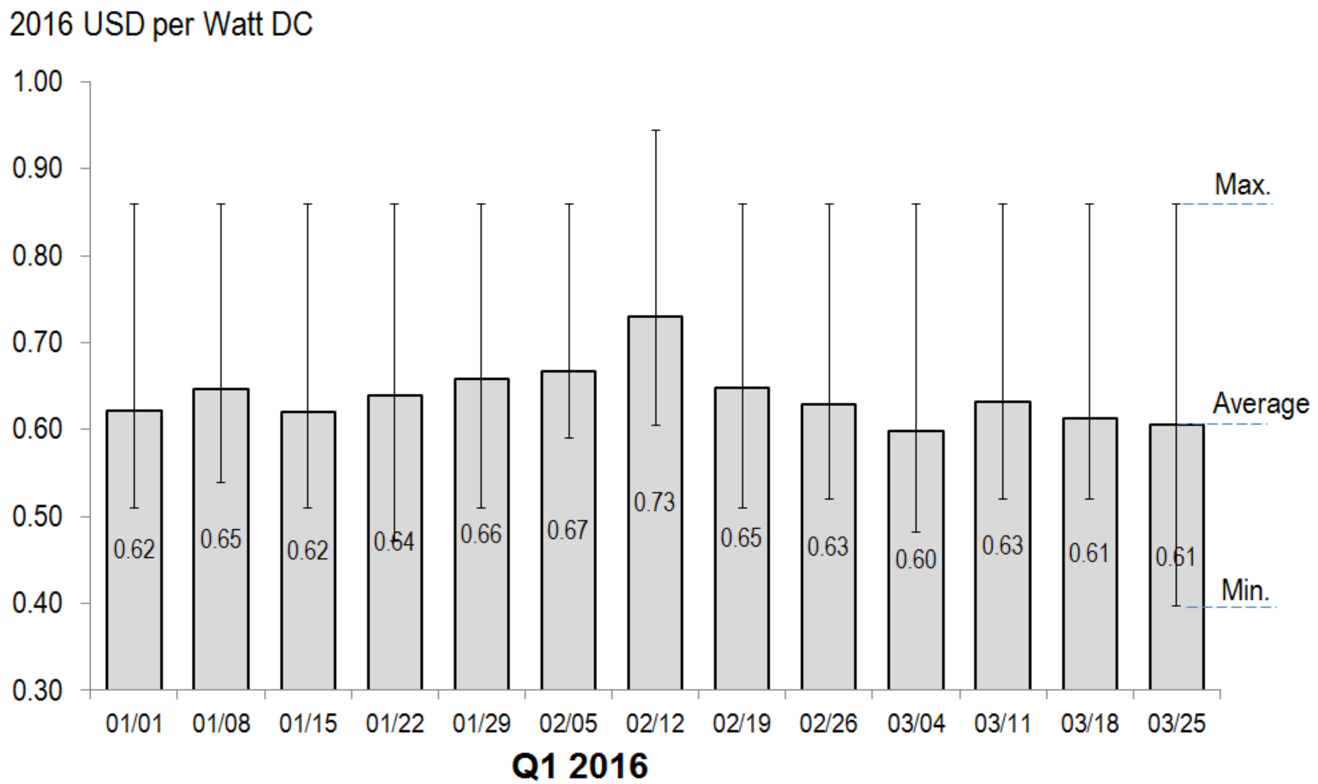
For MLPE inverter prices, we use data from public corporate filings, shown in this figure (Enphase 2016; SolarEdge 2016). Q1 2016 Enphase revenue was $0.45/Wac, which represents the typical microinverter price. Q1 2016 SolarEdge revenue was $0.30/Wac, including sales from DC power optimizers, string inverters, and monitoring equipment, typically included in one product offering. GTM Research estimates that the DC power optimizer cost $0.10/Wac (GTM Research 2015), implying a string inverter and monitoring equipment price of $0.20/Wac, which is consistent with average residential string inverter costs of $0.18/Wac in Q1 2016 (assuming a $0.02-0.03/Wac cost for monitoring equipment) (GTM Research and SEIA 2016).

Inverter Price and DC-to-AC ratios

$ per Watt AC from previous two slides are converted to be $ per Watt DC in this table by using the different DC-to-AC ratios. In our benchmark, we use $ per Watt DC for all costs including inverter prices.

Inverter Type	Sector	$ per Watt AC	DC-to-AC Ratio	$ per Watt DC
Single Phase String Inverter	Residential PV (non-MLPE)	0.176	1.15	0.15
Microinverter	Residential PV (MLPE)	0.45	1.15	0.39
DC Power Optimizer String Inverter	Residential PV (MLPE)	0.20	1.15	0.17
Three Phase String Inverter	Commercial PV (non-MLPE)	0.15	1.15	0.13
Central Inverter	Utility-scale PV (fixed-tilt)	0.12	1.40 (Oversized)	0.09
Central Inverter	Utility-scale PV (1-axis tracker)	0.12	1.20	0.10

Module Price

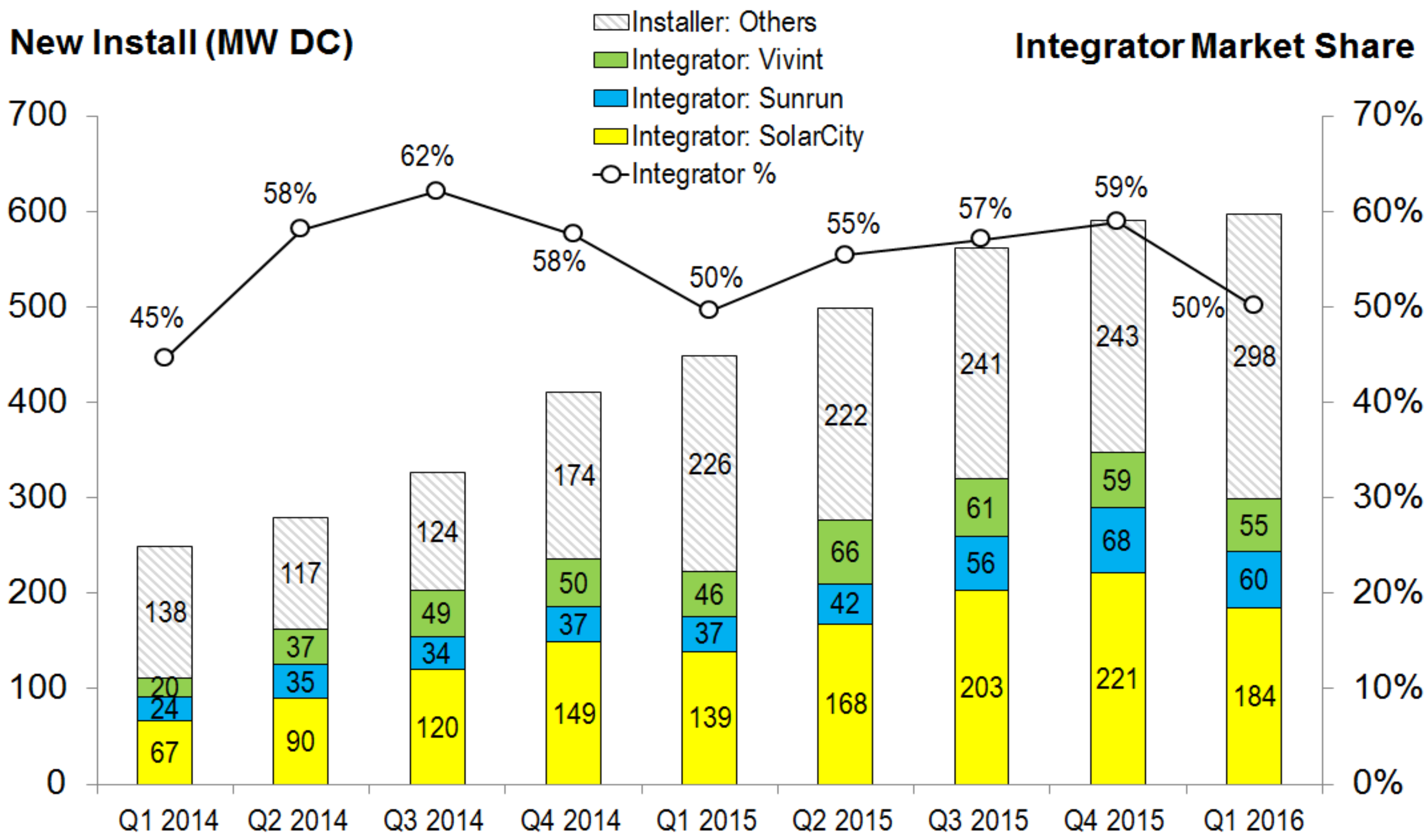


(1) We use Bloomberg (2016) data to represent the typical average selling price (ASP) between Tier 1 module suppliers and first buyers in the global market (see Section 2.6.1 in our full report for a discussion on "first buyers"). Also, a 2016 Solar PV Market Research survey indicates a U.S. ASP discount of about 6% compared to the global market because of the country's large demand and competitive market condition (Mints 2016). Using this regional discount, we adjust the Bloomberg (2016) global module price data in this figure and benchmark the Q1 2016 average U.S. crystalline silicon module ASP at $0.64/W for all three sectors.

(2) Interviews conducted for this analysis suggest even lower prices ($0.58–$0.60/W) due to the recent liquidity issues of some large developers (NREL 2016). However, because this report only covers Q1 2016, we do not include the impact from company bankruptcy in April 2016.

(3) Compared with module prices in 2015, module prices in 2016 have also been influenced by changes in currency exchange rates. The USD appreciated against the Chinese Yuan by 5% between Q1 2015 and Q1 2016 (XE Currency Charts 2016).

Residential PV: Integrator vs. Installer



Our residential PV benchmark is based on two different business structures: “installer” and “integrator.” We define installers as businesses that engage in lead generation, sales, and installation but do not provide financing solutions. The integrator performs all of the installer’s functions but does provide financing and system monitoring for third-party-owned systems. In our models, the difference between installers and integrators manifests in the overhead cost category, where the integrator is modeled with higher expenses for customer acquisition, financial structuring, and asset management.

To estimate the split in market share between installers and integrators, we use data compiled from corporate filings (SolarCity 2016; Sunrun 2016; Vivint Solar 2016; GTM Research and SEIA 2016). Lastly, we use the 50% integrator and 50% installer market shares evident in Q1 2016 to compute the national weighted-average case in our residential PV model.

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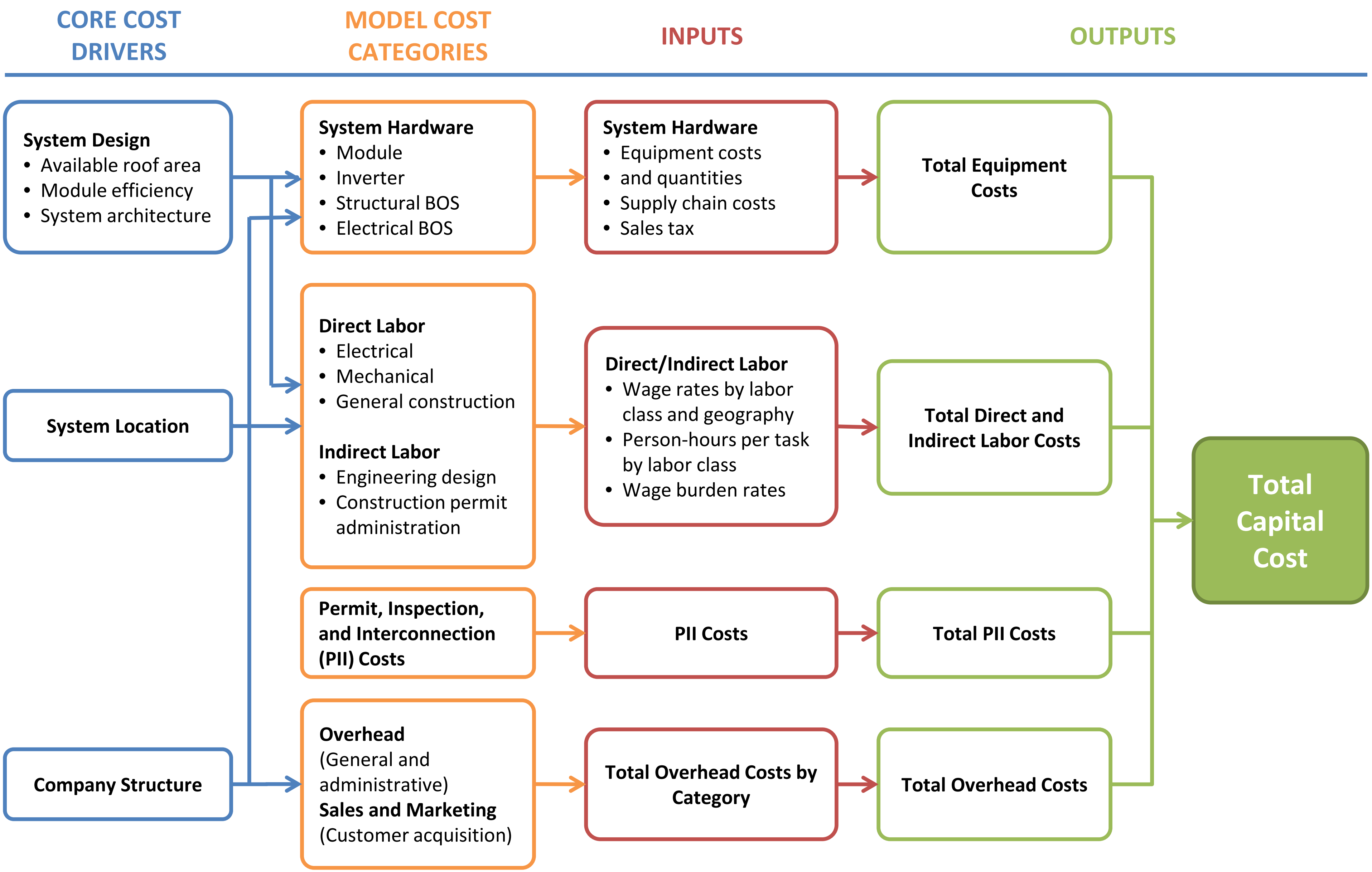
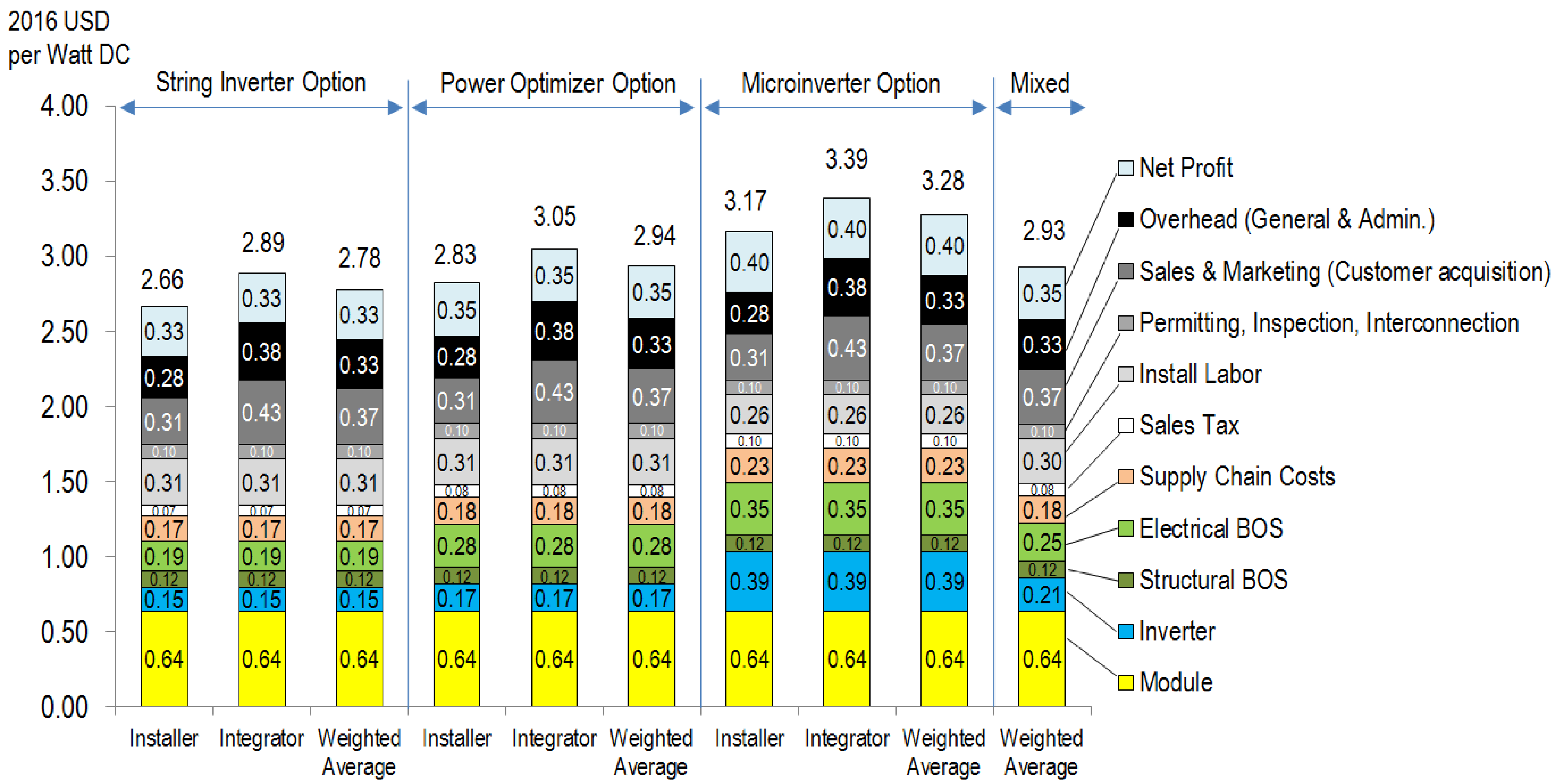
Residential PV: Model Structure



Residential PV: Modeling Inputs and Assumptions

Category	Modeled Value	Description	Sources
System size	5.6 kW	Average installed size per system	Go Solar CA (2016)
Module efficiency	15.6%	Average module efficiency	Go Solar CA (2016)
Module price	$0.64/Wdc	Ex-factory gate (first buyer) ASP, Tier 1 modules	Bloomberg (2016), Mints (2016), NREL (2016)
Inverter price	Single-phase string inverter: $0.15/Wdc; DC power optimizer string inverter: $0.17/Wdc Microinverter: $0.39/Wdc	Ex-factory gate prices (first buyer) ASP, Tier 1 inverters	Go Solar CA (2016), NREL (2016), PVinsights (2016), corporate filings (Enphase 2016; SolarEdge 2016)
Structural balance of system (BOS, racking)	$0.12/Wdc	Ex-factory gate prices; includes flashing for roof penetrations	Model assumptions, NREL (2016)
Electrical BOS	$0.19–$0.35/Wdc Varies by inverter option	Wholesale prices for conductors, switches, combiners and/or transition boxes, conduit, grounding equipment, monitoring system/production meter, fuses, and breakers	Model assumptions, NREL (2016), RSMeans (2015)
Supply chain costs (% of equipment costs)	15.2%	15% costs and fees associated with inventory, shipping, and handing of equipment multiplied by the cost of doing business index (101%)	NREL (2016)
Sales tax	Varies by location	Sales tax on the equipment; national benchmark applies an average (by state) weighted by 2015 installed capacities	DSIRE (2016), RSMeans (2015)
Direct installation labor	Electrician: $19.01–$37.52 per hour Laborer: $12.41–$24.63 per hour Varies by location and inverter option	Modeled labor rate depends on state; national benchmark uses weighted average of state rates.	BLS (2016), NREL (2016)
Burden rates (% of direct labor)	Total nationwide average: 31.8%	Workers compensation (state-weighted average), federal and state unemployment insurance, Federal Insurance Contributions Act (FICA), builders risk, public liability	RSMeans (2015)
PII	$0.10/Wdc	Includes assumed building permitting fee of $400 and six office staff hours for building permit preparation and submission, and interconnection application preparation and submission	NREL (2016), Vote Solar (2015), Vote Solar and IREC (2013)
Sales & marketing (customer acquisition)	$0.31/Wdc (installer) $0.43/Wdc (integrator)	Total cost of sales and marketing activities over the last year—including marketing and advertising, sales calls, site visits, bid preparation, and contract negotiation; adjusted based on state “cost of doing business” index	Feldman et al. (2013)
Overhead (general & administrative)	$0.28/Wdc (installer) $0.38/Wdc (integrator)	General and administrative expenses—including fixed overhead expenses covering payroll (excluding permitting payroll), facilities, administrative, finance, legal, information technology, and other corporate functions as well as office expenses; adjusted based on state “cost of doing business” index	Feldman et al. (2013)
Profit (%)	17%	Applies a fixed percentage margin to all direct costs including hardware, installation labor, direct sales and marketing, design, installation, and permitting fees (note: $0.19/Wdc of the total sales& marketing and overhead is classified as direct costs)	Chung et al. (2015)

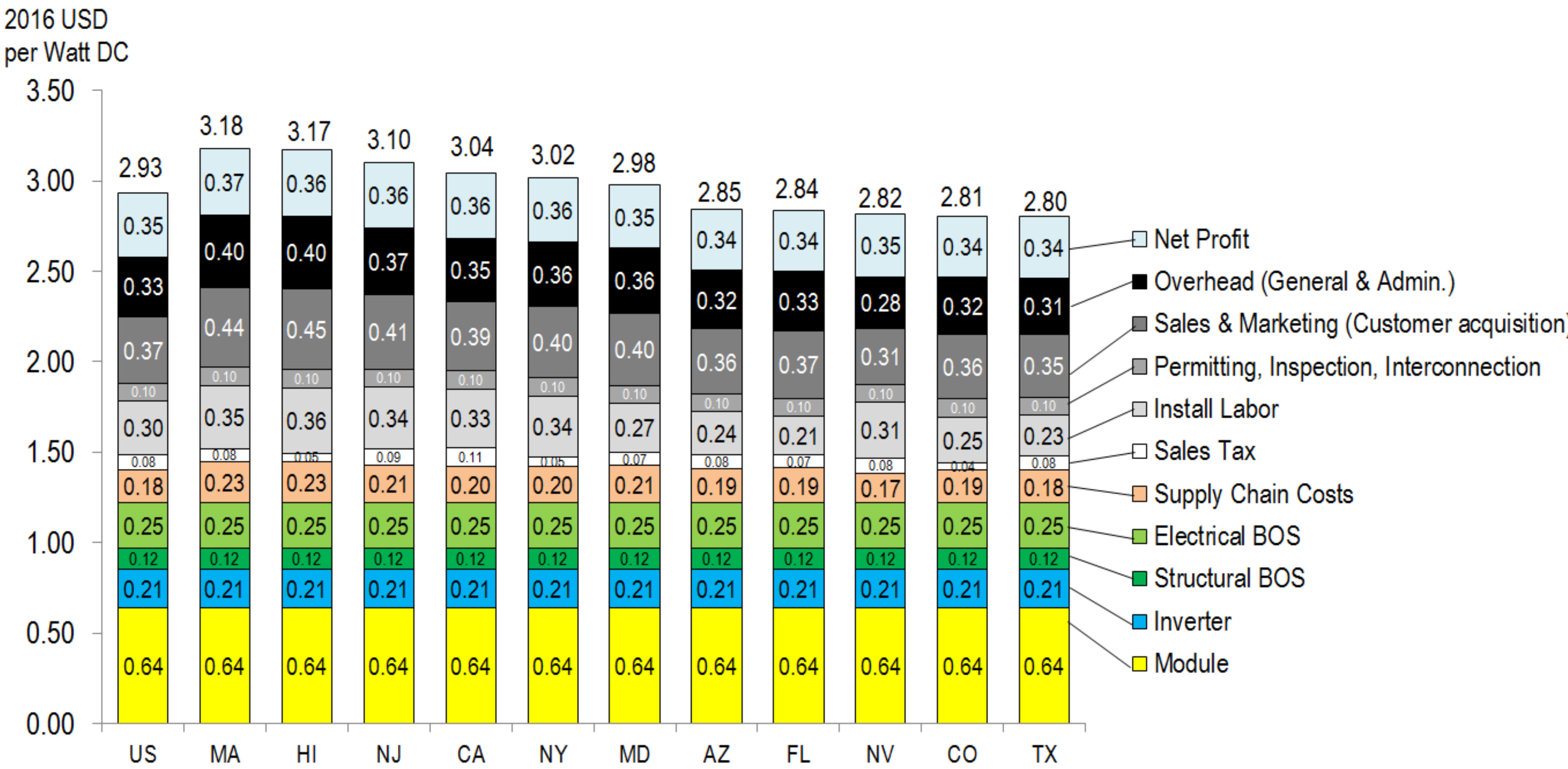
Residential PV: Model Outputs



Q1 2016 U.S. benchmark: 5.6-kW residential system cost (2016 USD/Wdc)

This figure presents the U.S. national benchmark from our residential model. The national benchmark represents an average weighted by 2015 state installed capacities. Market shares of 50% for installers and 50% for integrators are used to compute the national weighted average. String inverter, power optimizer, and microinverter options are each modeled individually, but the “Mixed” case applies their market shares (54%, 22%, and 24%) as weightings.

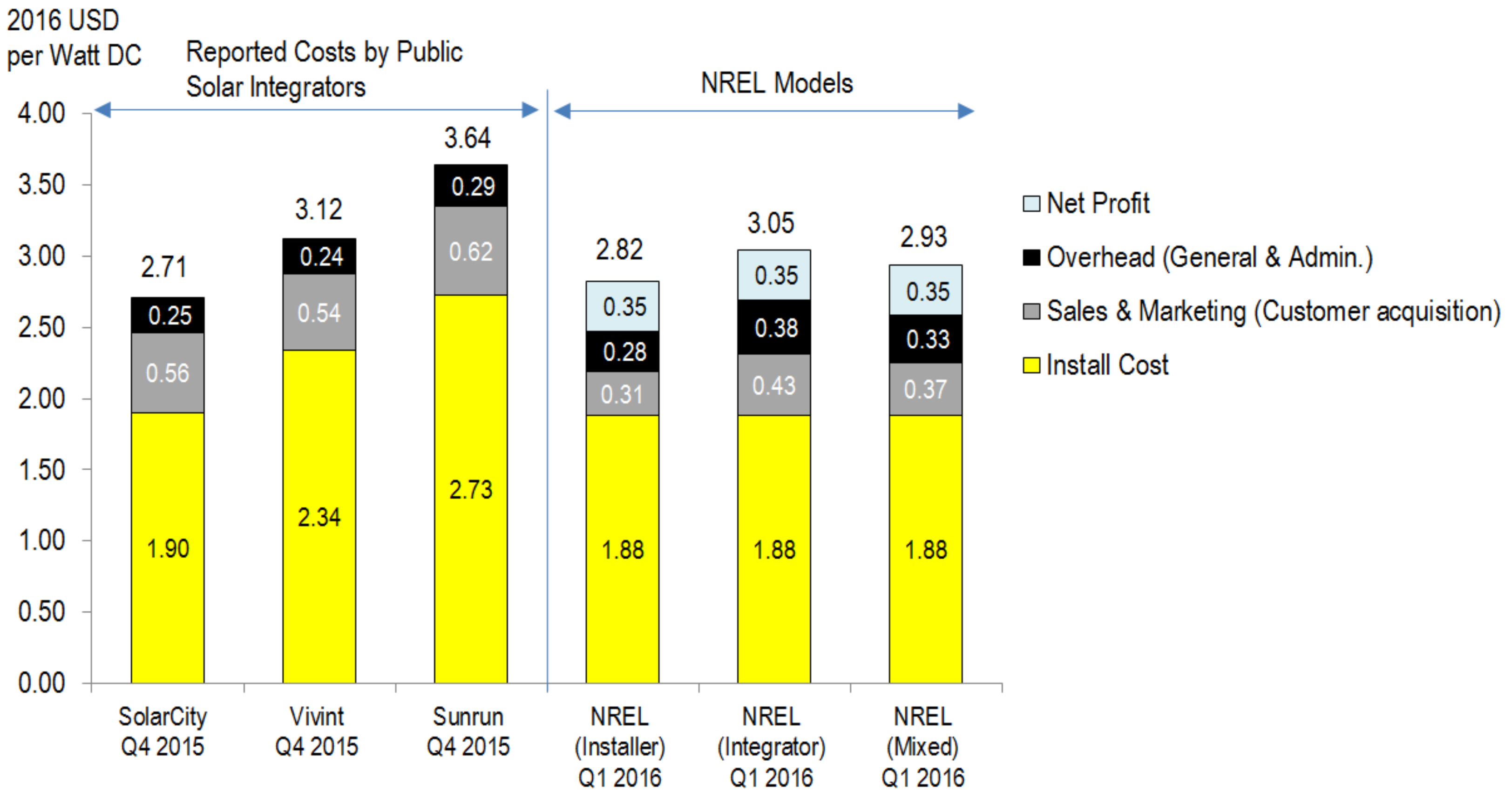
Residential PV: Model Outputs



Q1 2016 benchmark by location: 5.6-kW residential system cost (2016 USD/Wdc)

This figure presents the benchmark in the top U.S. solar markets (by 2015 installations), reflecting differences in supply chain and labor costs, sales tax, and selling, general, and administrative (SG&A) expenses—that is, the cost of doing business (Case 2012).

Residential PV: Model Outputs



Our bottom-up modeling approach yields a different cost structure than those reported by public solar integrators in their corporate filings (SolarCity 2016; Sunrun 2016; Vivint Solar 2016). Because integrators sell and lease PV systems, they practice a different method of reporting costs than businesses that only sell goods. Many of the costs for leased systems are reported over the life of the lease rather than the period in which the system is sold; therefore, it is difficult to determine the actual costs at the time of the sale. While the corporate filings from SolarCity, Sunrun, and Vivint Solar do report system costs on a quarterly basis, the lack of transparency in the public filings makes it difficult to determine the underlying costs as well as the timing of those costs. Note also that the Q4 2015 reported costs are used here instead of Q1 2016, because the NEM reforms in several state markets, such as Nevada, slowed down residential PV integrator installation in Q1 2016 and then inflated the calculated cost from those companies' Q1 2016 filings. To remove the market and policy impacts from this comparison, we use the Q4 2015 reported costs.

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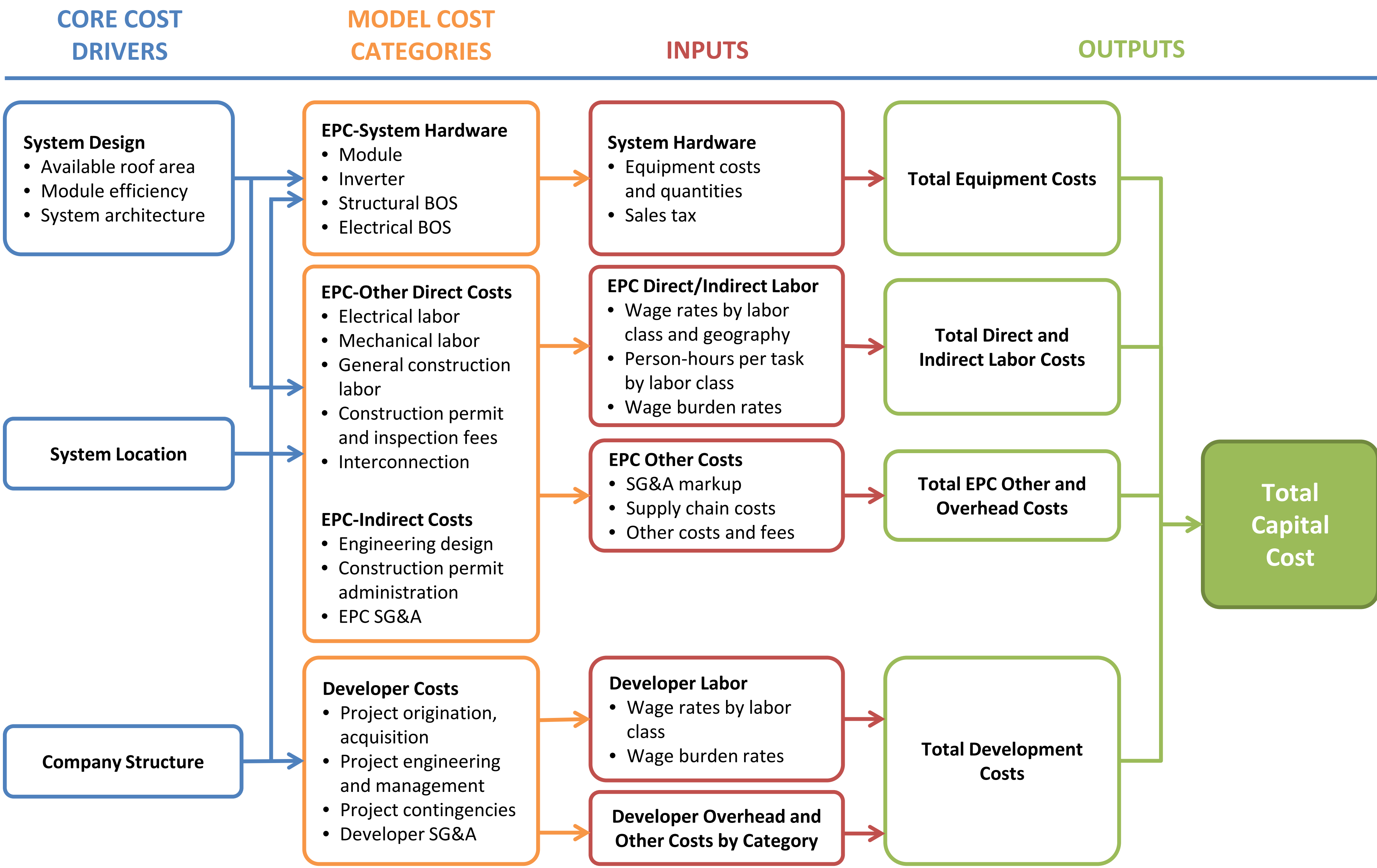
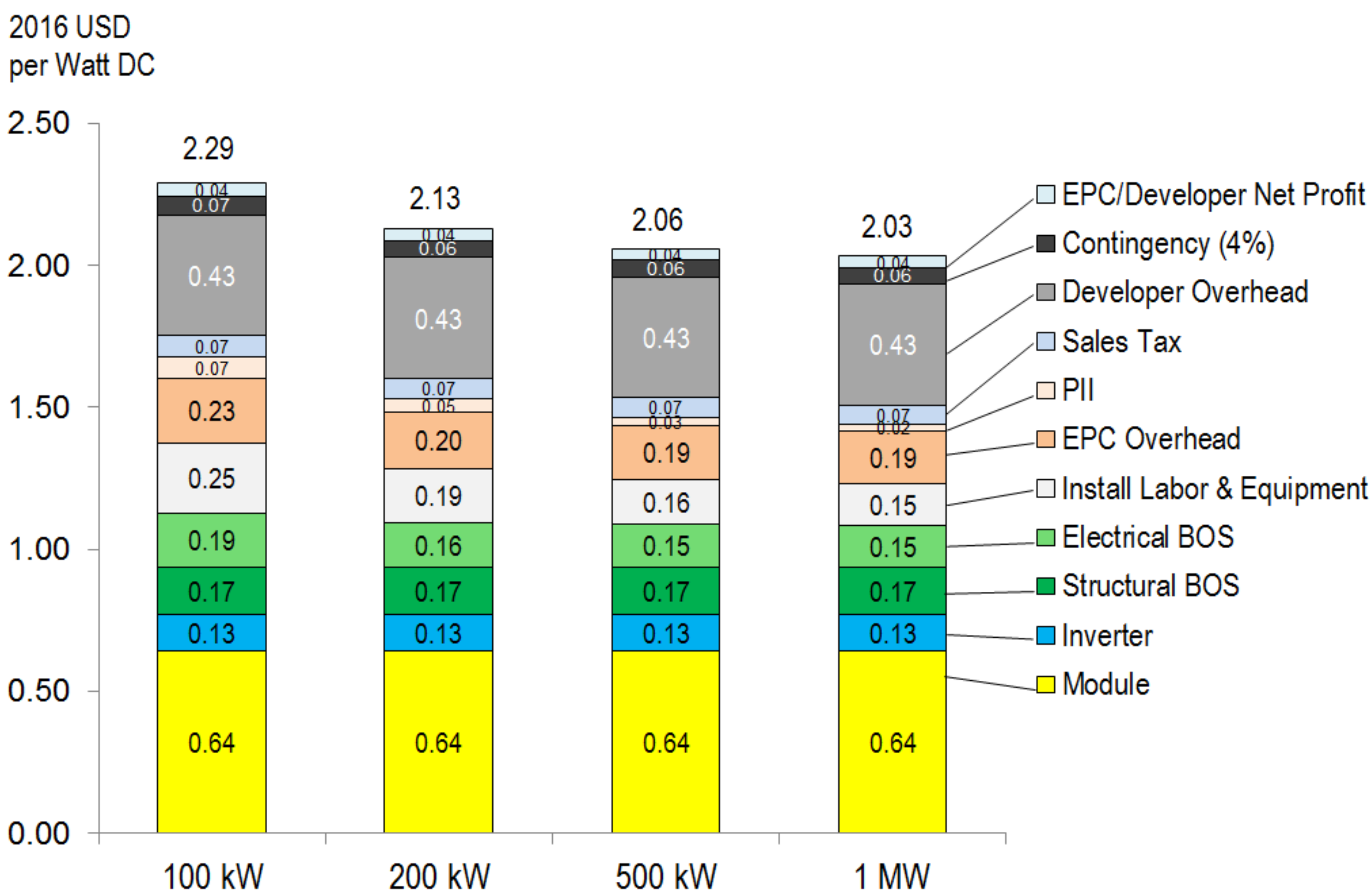
Commercial PV: Model Structure



Commercial PV: Modeling Inputs and Assumptions

Category	Modeled Value	Description	Sources
System size	200 kW	Average installed size per system	Go Solar CA (2016)
Module efficiency	16.7%	Average module efficiency	Go Solar CA (2016)
Module price	$0.64/Wdc	Ex-factory gate (first buyer) ASP, Tier 1 modules	Bloomberg (2016), Mints (2016), NREL (2016)
Inverter price	$0.13/Wac	Ex-factory gate prices (first buyer) ASP, Tier 1 inverters	NREL (2016), PVinsights (2016)
Structural components (racking)	$0.14–$0.30/Wdc; varies by location and system size	Ex-factory gate prices; flat-roof ballasted racking system	ASCE (2006), model assumptions, NREL (2016)
Electrical components	Varies by location and system size	Conductors, conduit and fittings, transition boxes, switchgear, panel boards, etc.	Model assumptions, NREL (2016), RSMeans (2015)
EPC overhead (% of equipment costs)	13%	Costs and fees associated with EPC overhead, inventory, shipping, and handling	NREL (2016)
Sales tax	Varies by location	Sales tax on equipment costs; national benchmark applies an average (by state) weighted by 2015 installed capacities	DSIRE (2016), RSMeans (2015)
Direct installation labor	Electrician: $19.01–$37.52 per hour Laborer: $12.41–$24.63 per hour Varies by location and inverter option	Modeled labor rate assumes non-union labor and depends on state; national benchmark uses weighted average of state rates	BLS (2016), NREL (2016)
Burden rates (% of direct labor)	Total nationwide average: 31.8%	Workers compensation (state-weighted average), federal and state unemployment insurance, FICA, builders risk, public liability	RSMeans (2015)
PII	$0.04–$0.05/Wdc	For construction permits fee, interconnection, testing, and commissioning	NREL (2016)
Developer overhead	Assume 10-MW system development and installation per year for a typical developer	Includes fixed overhead expenses such as payroll, facilities, travel, insurance, administrative, business development, finance, and other corporate functions; assumes 10 MW/year of system sales	Model assumptions, NREL (2016)
Contingency	4%	Estimated as markup on EPC price; value represents actual cost overruns above estimated price.	NREL (2016)
Profit	2%	Includes 2% EPC markup (bringing the EPC total markup of overhead and profit to 15%) and a 2% markup on all overhead costs	Feldman et al. (2013)

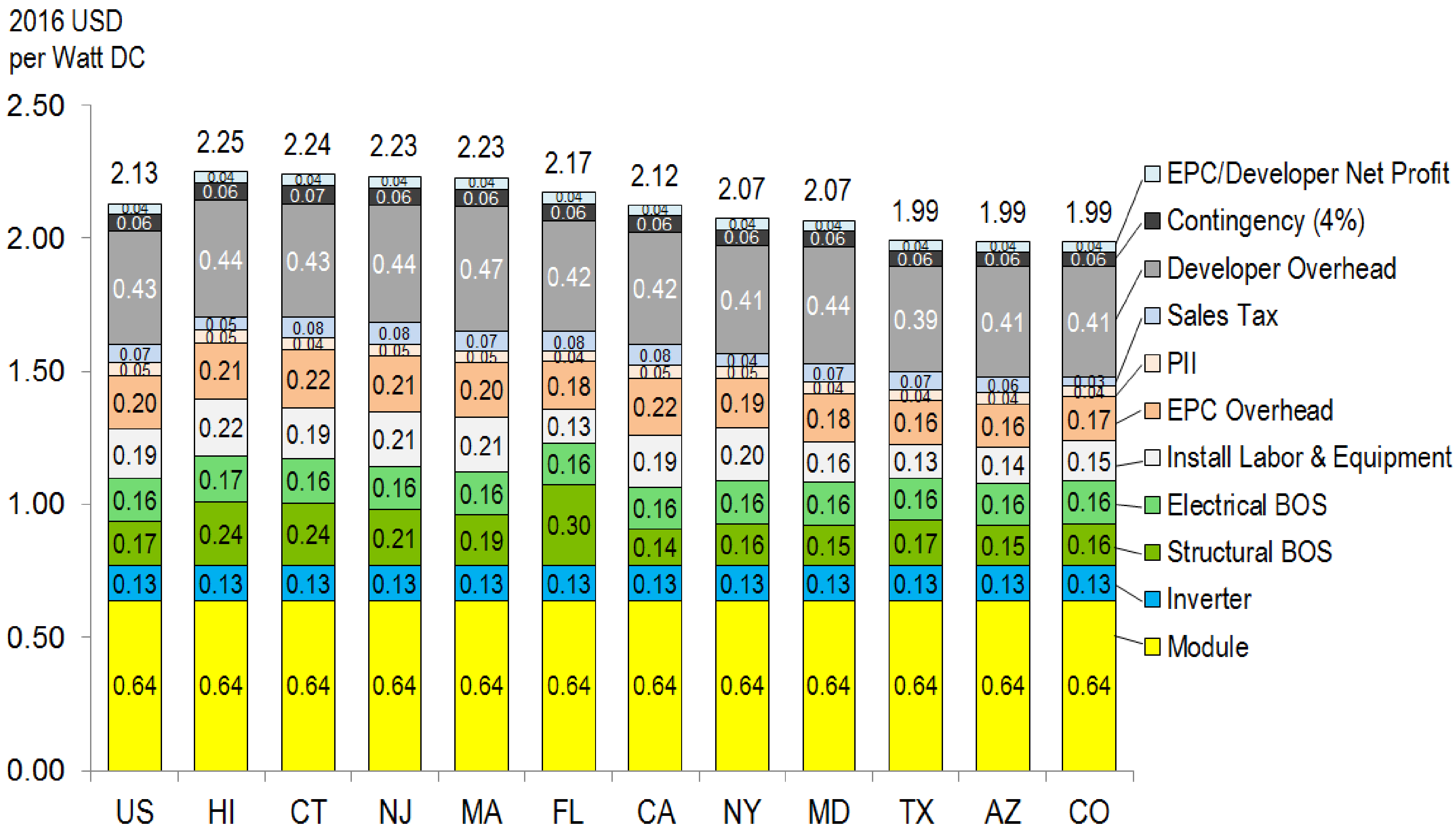
Commercial PV: Model Outputs



Q1 2016 U.S. benchmark: commercial system cost (2016 USD/Wdc)

As in the residential model, the national benchmark represents an average weighted by 2015 state installed capacities. We model different system sizes because of the wide scope of the “commercial” sector, which comprises a diverse customer base occupying a variety of building sizes. Also, economies of scale—driven by hardware, labor, and related markups—are evident here. That is, as system sizes increase, the per-watt cost to build them decreases. Meanwhile, because we assume that a typical developer has 10 MW of system development and installation per year, the developer overheads on this 10 MW total capacity do not vary for different system sizes. When a developer installs more capacity annually, that developer’s overhead per watt in each system declines.

Commercial PV: Model Outputs



Q1 2016 benchmark by location: 200-kW commercial system cost (2016 USD/Wdc)

This figure presents the benchmark from our commercial model by location in the top U.S. solar markets (by 2015 installations). The main cost drivers for different regions in the commercial PV market are the same as in the residential model (labor rates, sales tax, and cost of doing business index) but also include costs associated with wind/snow loading.

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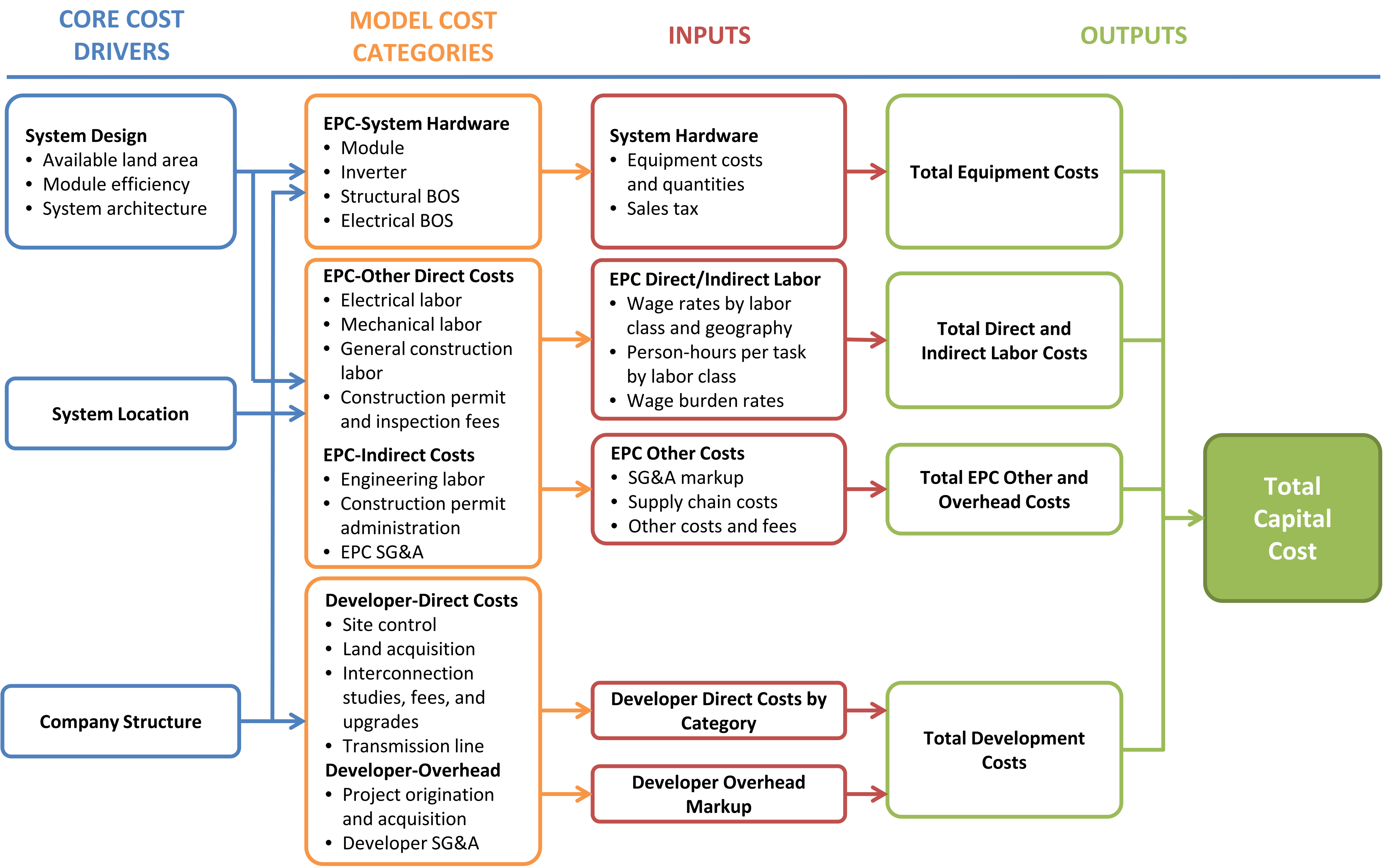
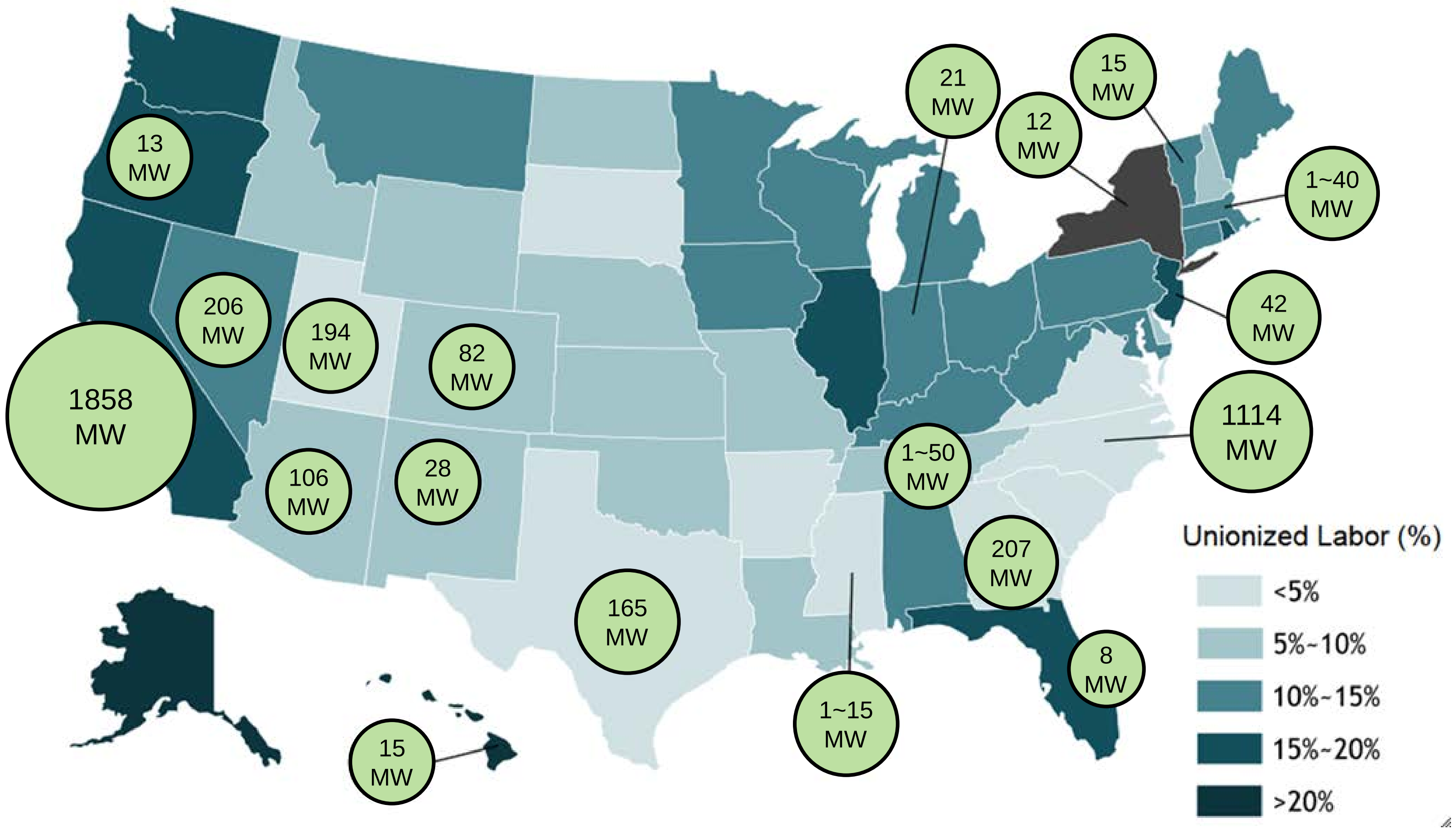
Utility-Scale PV: Model Structure



Utility-Scale PV: Modeling Inputs and Assumptions

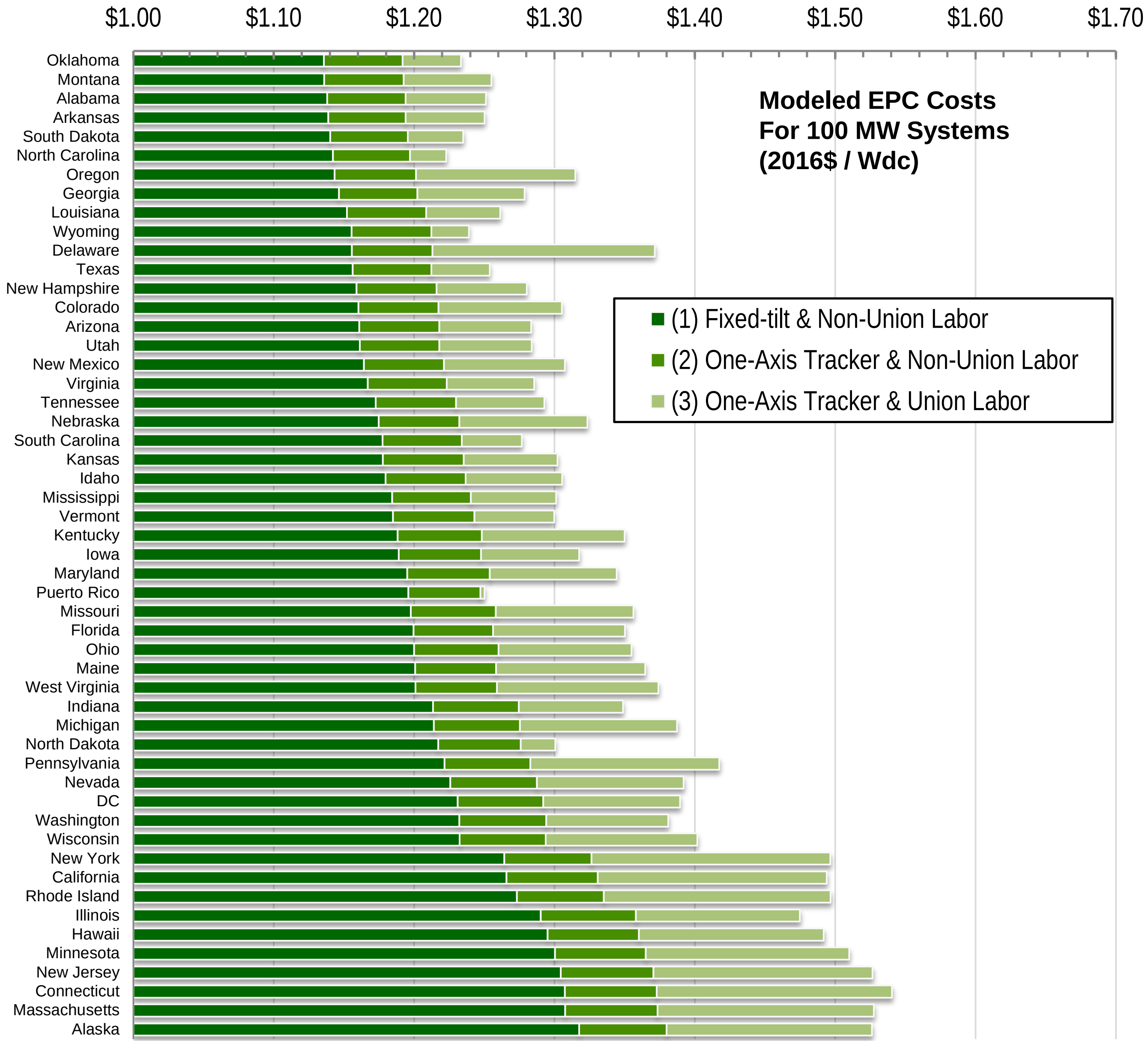
Category	Modeled Value	Description	Sources
System size	100 MW	A large utility-scale system capacity	Model assumption
Module efficiency	16.7%	Average module efficiency	NREL (2016)
Module price	$0.64/Wdc	Ex-factory gate (first buyer) ASP, Tier 1 modules	Bloomberg (2016), Mints (2016), NREL (2016)
Inverter price	$0.09/Wdc (fixed-tilt) $0.10/Wdc (one-axis tracker)	Ex-factory gate prices (first buyer) ASP, Tier 1 inverters DC-to-AC ratio = 120% for one-axis tracker DC-to-AC ratio = 140% for fixed-tilt	NREL (2016), PVinsights (2016)
Structural components (racking)	$0.14–$0.30/Wdc; varies by location and system size	Ex-factory gate prices; fixed-tilt racking or one-axis tracking system	ASCE (2006), model assumptions, NREL (2016)
Electrical components	Varies by location and system size	Conductors, conduit and fittings, transition boxes, switchgear, panel boards, onsite transmission, etc.	Model assumptions, NREL (2016), RSMeans (2015)
EPC overhead (% of equipment costs)	8.67%–13% for equipment and material (except for transmission line costs); 23%–69% for labor costs; varies by system size, labor activity, and location	Costs associated with EPC SG&A, warehousing, shipping, and logistics	NREL (2016)
Sales tax	Varies by location	National benchmark applies an average (by state) weighted by 2015 installed capacities	DSIRE (2016), RSMeans (2015)
Direct installation labor	Electrician: $19.01–$37.52 per hour Laborer: $12.41–$24.63 per hour Varies by location and inverter option	Modeled labor rate assumes non-union and union labor and depends on state; national benchmark uses weighted average of state rates	BLS (2016), NREL (2016)
Burden rates (% of direct labor)	Total nationwide average: 31.8%	Workers compensation (state-weighted average), federal and state unemployment insurance, FICA, builders risk, public liability	RSMeans (2015)
PII	$0.03–0.09/Wdc Varies by system size and location	For construction permits fee, interconnection, testing, and commissioning	NREL (2016)
Transmission line (gen-tie line)	$0.00–0.02/Wdc Varies by system size	System size < 10 MW, use 0 mile System size > 200 MW, use 5 miles 10–200 MW, use linear interpolation	Model assumptions, NREL (2016)
Developer overhead	3%–12% Varies by system size (100 MW uses 3%; 5 MW uses 12%)	Includes overhead expenses such as payroll, facilities, travel, legal fees, administrative, business development, finance, and other corporate functions	Model assumptions, NREL (2016)
Contingency	3%	Estimated as markup on EPC cost	NREL (2016)
Profit	1.33%–2% Varies by system size (100 MW uses 1.33%; 5 MW uses 2%.)	Includes EPC markup (bringing the EPC total markup of overhead and profit to 10%–15%) as well as a markup on all overhead costs; 5 MW system profit margin consistent with commercial market assumptions; larger system profit scale-down consistent with EPC overhead and profit scale-down from 15% to 10%	Feldman et al. (2013), model assumptions, NREL (2016)

Utility-Scale PV: Union Labor Case

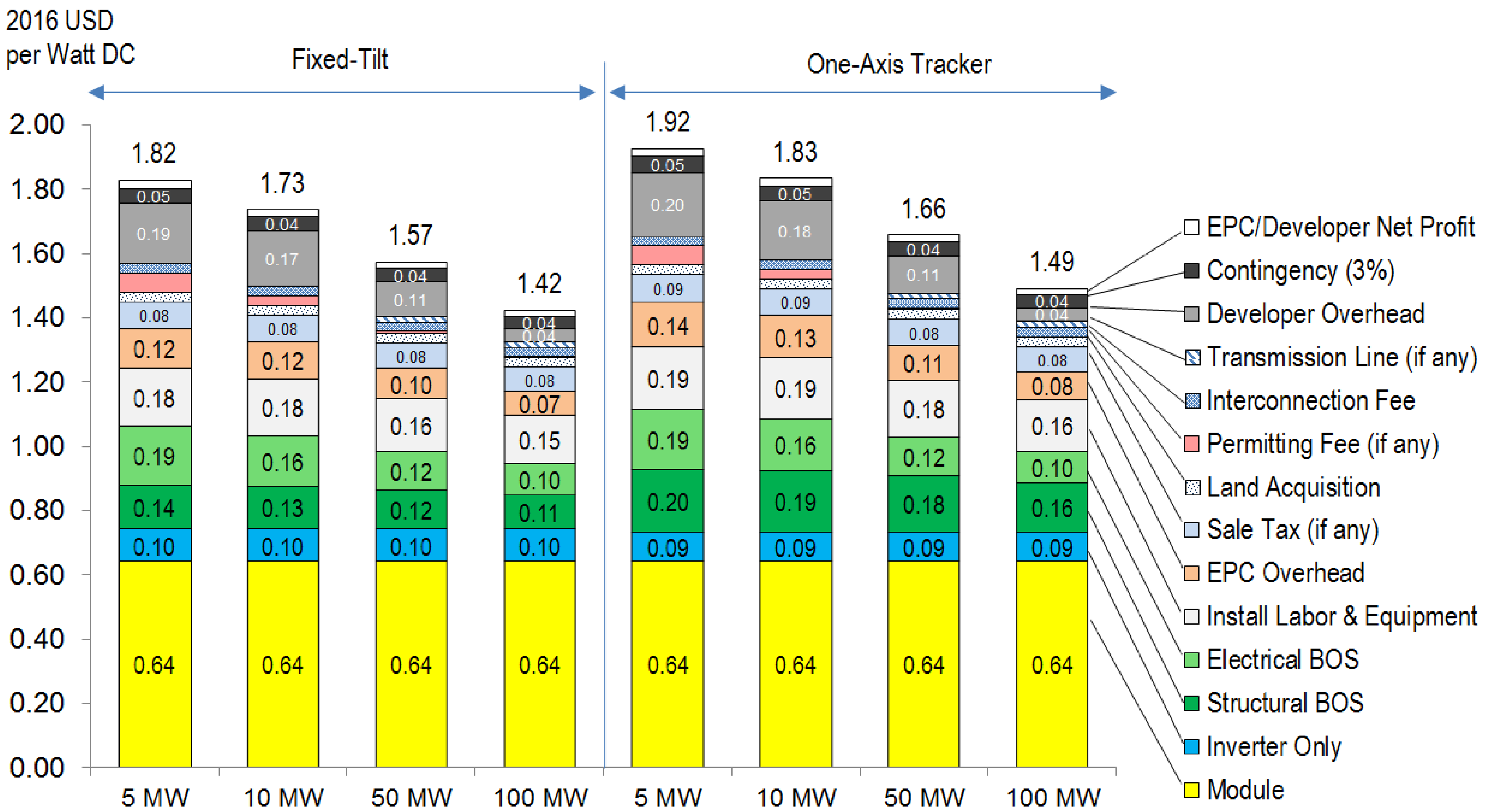


Although EPCs and developers tend to employ low-cost, non-union labor (based on data from BLS 2016) for PV system construction when possible, union labor is sometimes mandated. Construction trade unions may negotiate with the local jurisdiction and EPC/developer during the public review period of the permitting process. This figure shows 2015 utility-scale PV capacity installed (GTM Research and SEIA 2016) and the proportion of unionized labor in each state (BLS 2016). The unionized labor number represents the percentage of employed workers in each state's entire construction industry who are union members. In our utility-scale model, both non-union and union labor rates are considered.

Utility-Scale PV: Model Outputs, EPC Only



Utility-Scale PV: Model Outputs, EPC + Developer

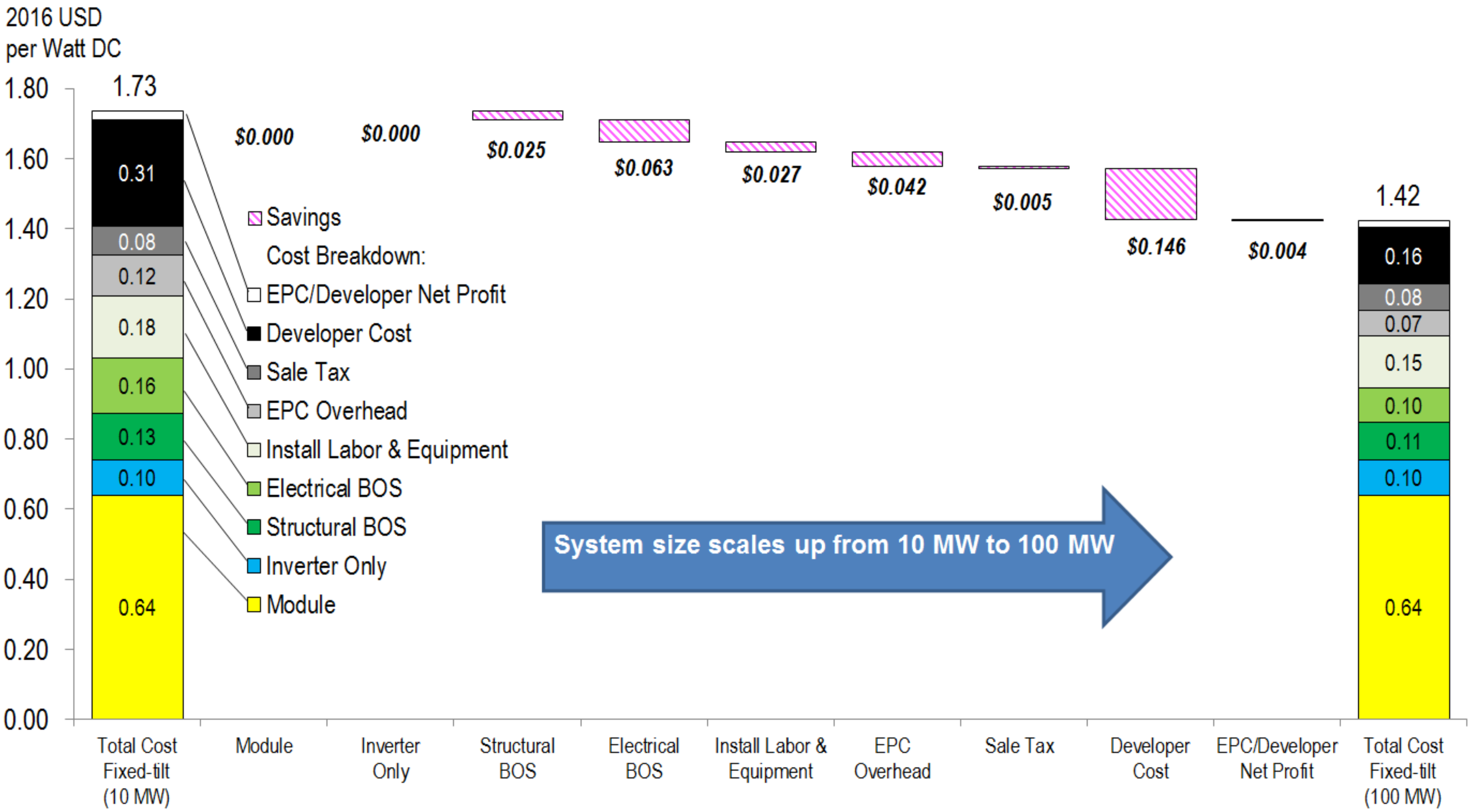


Q1 2016 U.S. benchmark: utility-scale PV total cost (EPC + developer) 2016 USD/Wdc

(1) The national benchmark applies an average weighted by 2015 installed capacities.
(2) Non-union labor is used.
(3) Economies of scale—driven by BOS, labor, related markups, and development cost—are demonstrated.

Contents

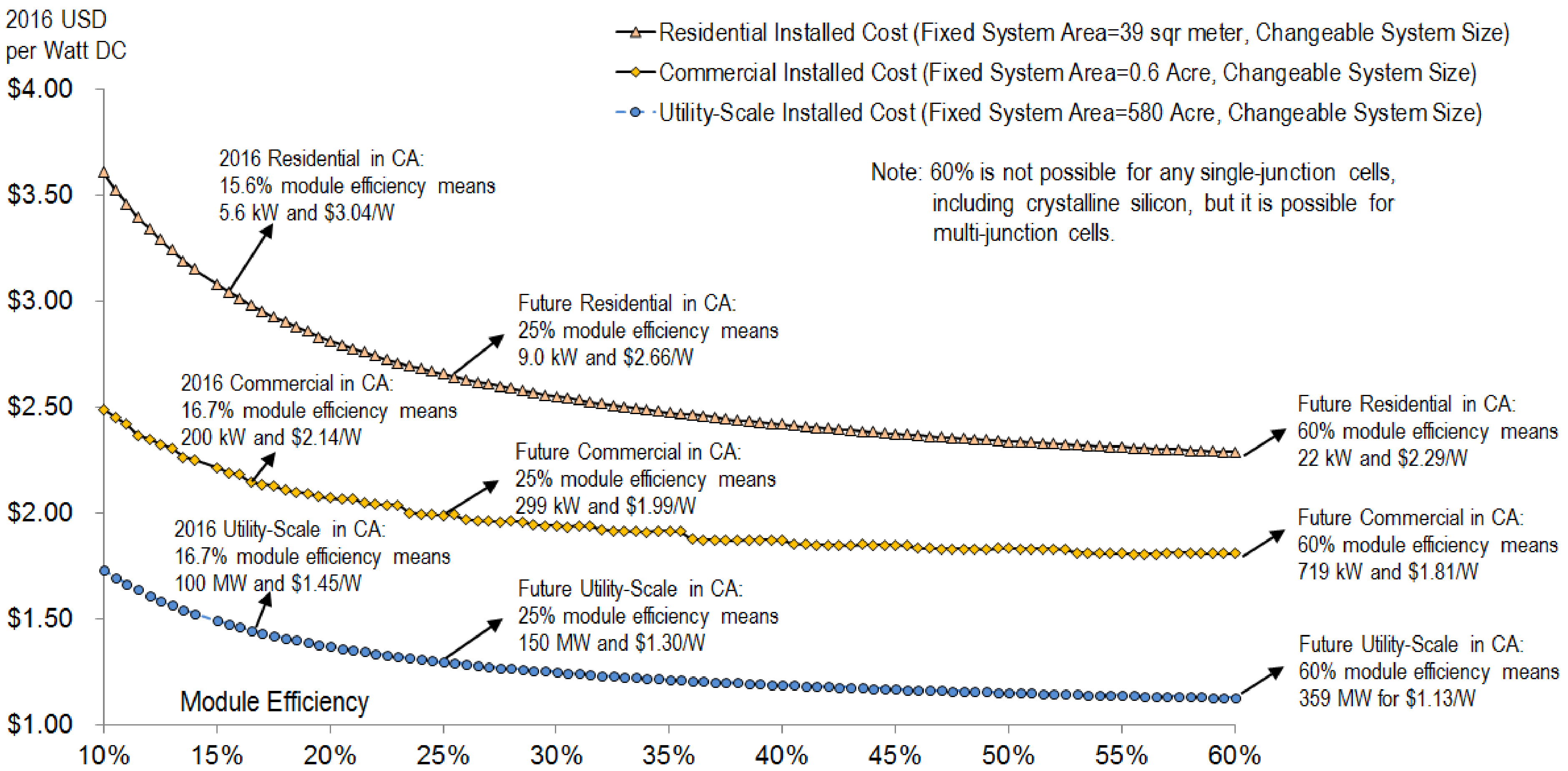
Model Application – Economies of Scale



Model application: U.S. utility-scale fixed-tilt PV system cost reduction from economies of scale (2016 USD/Wdc)

This figure demonstrates the cost savings from different system configurations—scaling up system size from 10 MW to 100 MW can gain savings from BOS bulk price, labor learning curve, and lower developer overhead. Note that non-union labor is used in this figure.

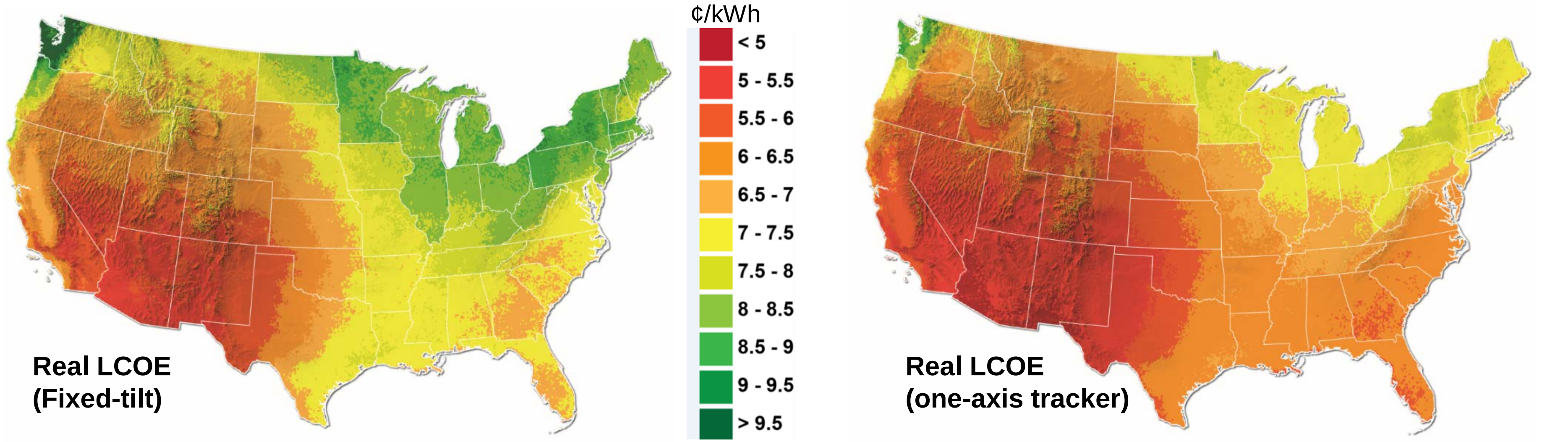
Model Application – Module Efficiency Impacts



Modeled impacts of module efficiency on total system costs, 2016

Our system cost models can also assess the economic benefits of high module efficiency. Because higher module efficiency reduces the number of modules required to reach a certain system size, the related racking/mounting hardware, foundation, BOS, EPC/developer overhead, and labor hours are reduced accordingly. This figure presents the relation between module efficiency and installed cost (with module prices held equal for any given efficiency) and demonstrates the cost-reduction potential due to high module efficiency.

Model Application – Utility-Scale PV Regional LCOE, 2016



		Fixed-Tilt			One-Axis Tracker			One-Axis Tracker vs. Fixed-Tilt		
State	Location	Total Installed Costs ($/W)	Nominal LCOE (cent per kWh)	Real LCOE (cent per kWh)	Total Installed Costs ($/W)	Nominal LCOE (cent per kWh)	Real LCOE (cent per kWh)	Installed Costs Premium (%)	Nominal LCOE Change (%)	Real LCOE Change (%)
CA	Bakersfield	$ 1.45	$ 7.94	$ 6.02	$ 1.52	$ 6.50	$ 4.93	4.74%	-18.14%	-18.11%
CA	Imperial	$ 1.45	$ 7.19	$ 5.45	$ 1.52	$ 5.80	$ 4.40	4.74%	-19.33%	-19.27%
AZ	Prescott	$ 1.33	$ 7.03	$ 5.33	$ 1.39	$ 5.55	$ 4.21	4.87%	-21.05%	-21.01%
AZ	Tucson	$ 1.33	$ 6.78	$ 5.14	$ 1.39	$ 5.38	$ 4.08	4.87%	-20.65%	-20.62%
NV	Las Vegas	$ 1.40	$ 7.03	$ 5.33	$ 1.47	$ 5.59	$ 4.24	5.05%	-20.48%	-20.45%
NM	Albuquerque	$ 1.33	$ 6.84	$ 5.19	$ 1.40	$ 5.52	$ 4.19	5.15%	-19.30%	-19.27%
CO	Alamosa	$ 1.33	$ 6.85	$ 5.19	$ 1.39	$ 5.43	$ 4.11	4.51%	-20.73%	-20.81%
NC	Jacksonville	$ 1.31	$ 8.10	$ 6.14	$ 1.37	$ 7.21	$ 5.47	4.49%	-10.99%	-10.91%
TX	San Antonio	$ 1.32	$ 8.02	$ 6.08	$ 1.38	$ 6.82	$ 5.17	4.55%	-14.96%	-14.97%
NJ	Newark	$ 1.49	$ 9.98	$ 7.57	$ 1.56	$ 8.67	$ 6.57	4.58%	-13.13%	-13.21%
FL	Orlando	$ 1.37	$ 9.01	$ 6.83	$ 1.43	$ 7.68	$ 5.82	4.61%	-14.76%	-14.79%
HI	Kona	$ 1.48	$ 8.63	$ 6.54	$ 1.55	$ 7.41	$ 5.61	4.73%	-14.14%	-14.22%

- Our model can demonstrate regional LCOE by using modeled regional installed costs and localized solar irradiance and weather data (NREL SAM).
- ITC = 30%, Discount Rate = Target IRR = 7%, Inflation = Escalator = 2.5%, Analysis period = 30-Yr. Thus, PPA = LCOE for both real and nominal cases. Degradation rate = 0.5% per year. System size = 100 MW utility-scale PV.
- Fixed-tilt: DC-to-AC ratio = 1.40 and Fixed O&M cost = $15/kW per year. One-axis tracker: DC-to-AC ratio = 1.20 and Fixed O&M cost = $18/kW per year.

Contents

Conclusions

(1) Based on our bottom-up modeling, the Q1 2016 PV cost benchmarks are $2.93/Wdc for residential systems, $2.13/Wdc for commercial systems, $1.42/Wdc (or $1.99/Wac) for fixed-tilt utility-scale systems, and $1.49/Wdc (or $1.79/Wac) for one-axis-tracking utility-scale systems. Overall, modeled PV installed costs continued to decline in Q1 2016 for all three sectors.

(2) Lower module and inverter prices contributed to these cost reductions. Increased competition, lower installer and developer overheads, improved labor productivity, and optimized system configurations also contributed, particularly for EPC firms building commercial and utility-scale projects. Hardware cost reductions (module and inverter prices, in particular) were an even more important driver of system cost reductions in earlier years, but the size of these gains has decreased recently. This has increased the importance of non-hardware, or "soft," costs, particularly in the residential and commercial sectors. Soft costs and hardware costs also interact with each other. For instance, module efficiency improvements have reduced the number of modules required to construct a system of a given size, thus reducing hardware costs, and this trend has also reduced soft costs from direct labor and related installation overhead.

(3) When making more detailed comparisons in our models, cost differences due to regional variations, system configurations (such as MLPE vs. non-MLPE, fixed-tilt vs. one-axis tracker, and small vs. large system size), and business structures (such as installer vs. integrator, and EPC vs. developer) are considered. Different scenarios result in different costs, so consistent comparisons can only be made when cost scenarios are aligned.

For More Information

(1) Download the full technical report along with the data file:

- Download the full report: http://www.nrel.gov/docs/fy16osti/66532.pdf
- Download the data file: https://doi.org/10.7799/1325002

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