Cost-Reduction Roadmap for Residential Solar Photovoltaics (PV), 2017–2030

Kristen Ardani, Jeffrey J. Cook, Ran Fu, and Robert Margolis
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-6A20-70748
January 2018

Contract No. DE-AC36-08GO28308

Cost-Reduction Roadmap for Residential Solar Photovoltaics (PV), 2017–2030

Kristen Ardani, Jeffrey J. Cook, Ran Fu, and Robert Margolis
National Renewable Energy Laboratory

Suggested Citation
Kristen Ardani, Jeffrey J. Cook, Ran Fu, and Robert Margolis. 2018. *Cost-Reduction Roadmap for Residential Solar Photovoltaics (PV), 2017–2030*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-70748.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-6A20-70748
January 2018

Contract No. DE-AC36-08GO28308

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Available electronically at SciTech Connect http:/www.osti.gov/scitech

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
OSTI http://www.osti.gov
Phone: 865.576.8401
Fax: 865.576.5728
Email: reports@osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312
NTIS http://www.ntis.gov
Phone: 800.553.6847 or 703.605.6000
Fax: 703.605.6900
Email: orders@ntis.gov

Cover Photos by Dennis Schroeder: (left to right) NREL 26173, NREL 18302, NREL 19758, NREL 29642, NREL 19795.

NREL prints on paper that contains recycled content.

Acknowledgements

This work was funded by the U.S. Department of Energy's (DOE) Solar Energy Technologies Office. The authors would like to thank all the interviewees for contributing their expertise to this study. We also would like to thank the following individuals and organizations for their review of this work: Casey Canfield (Department of Energy), Chris Fisher (CertainTeed), Kelsey Horowitz (National Renewable Energy Laboratory), Daniel Margolis (Lennar Corporation), Aaron Nitzkin (Solar Roof Dynamics), Eric O'Shaughnessy (National Renewable Energy Laboratory), Carolyn Pino (Lennar Corporation), and Brian Warshay (Tesla). Finally, we would like to thank Nick Gilroy, Jarett Zuboy, Christina Komeshian, and Harrison Dreves for their editing and graphics support.

List of Acronyms and Abbreviations

¢/kWh	Cents per kilowatt-hour
($/Wdc)	Dollars per watt direct current
AHJ	Authority having jurisdiction
ASP	Average selling price
ATB	Annual Technology Baseline
BOS	Balance of system
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EPC	Engineering, procurement, and construction
GW	Gigawatts
LCOE	Levelized cost of energy
kW	Kilowatts
NREL	National Renewable Energy Laboratory
O&M	Operations and maintenance
PII	Permitting, inspection, and interconnection
PV	Photovoltaic(s)
Q1	Quarter one
RECS	Residential Energy Consumption Survey
SETO	Solar Energies Technologies Office
USD	U.S. dollars

Executive Summary

The installed cost of solar photovoltaics (PV) has fallen rapidly in recent years and is expected to continue declining in the future. In this report, we focus on the potential for continued PV cost reductions in the residential market. From 2010 to 2017, the levelized cost of energy (LCOE) for residential PV declined from 52 cents per kilowatt-hour (¢/kWh) to 15.1 ¢/kWh (Fu et al. 2017). The U.S. Department of Energy's (DOE's) Solar Energy Technologies Office (SETO) recently set new LCOE targets for 2030, including a target of 5 ¢/kWh for residential PV. We present a roadmap for achieving the SETO 2030 residential PV target.

Because the 2030 target likely will not be achieved under business-as-usual trends (NREL 2017), we examine two key market segments that demonstrate significant opportunities for cost savings and market growth: installing PV at the time of roof replacement and installing PV as part of the new home construction process. We estimate that, between 2017 and 2030, an average of 3.3 million homes per year will be built or require roof replacement. This translates into a residential PV technical potential of roughly 30 gigawatts (GW) per year (Figure ES-1). Capturing even a relatively small fraction of this technical potential could have a significant impact on the evolution of the U.S. electricity system.

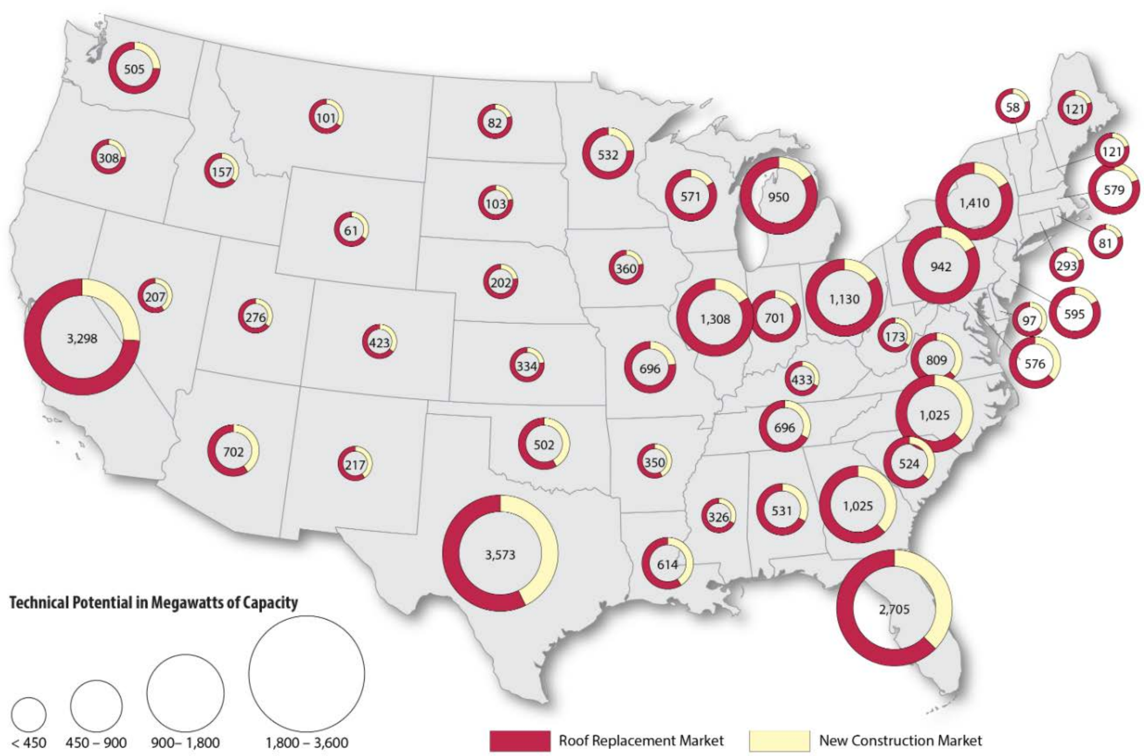


Figure ES-1. Annual average technical potential for residential rooftop PV at time of roof replacement and new construction projected between 2017 and 2030

Within both market segments, we identify four key cost-reduction opportunities: market maturation, business model integration, product innovation, and economies of scale. To assess the potential impact of these cost reductions, we compare modeled residential PV system prices in 2030 to the National Renewable Energy Laboratory's (NREL's) quarter one 2017 (Q1 2017) residential PV system price benchmark (Fu et al. 2017). We use a bottom-up accounting framework to model all component and project-development costs incurred when installing a PV system. The result is a granular accounting for 11 direct and indirect costs associated with installing a residential PV system in 2030.

It is unlikely that all PV installers in these two market segments will pursue the same cost-reduction strategies, so we model four pathways that could be pursued to achieve low-cost residential PV in 2030 (Table ES-1). The two less-aggressive pathways represent a more conservative shift from current technologies and business practices, whereas the two visionary pathways represent a higher level of innovation. We assume that market maturation and subsequent supply chain efficiencies will yield cost reductions across all four modeled pathways by 2030.

Table ES-1. Four Modeled Pathways by Market and Magnitude of Cost Reductions

	Pathway			
	Roof Replacement Market		New Construction Market	
Cost-Reduction Opportunity	**Less Aggressive**	**Visionary**	**Less Aggressive**	**Visionary**
Market Maturation	High	High	High	High
Business Model Integration	Low	High	Low	High
Product Innovation	Low	High	Low	High
Economies of Scale	NA	NA	Low	High

All four modeled pathways demonstrate significant installed-system price savings over the Q1 2017 benchmark, with the visionary pathways yielding the greatest price benefits (Figure ES-2). The largest modeled cost savings are in the supply chain, sales and marketing, overhead, and installation labor cost categories.

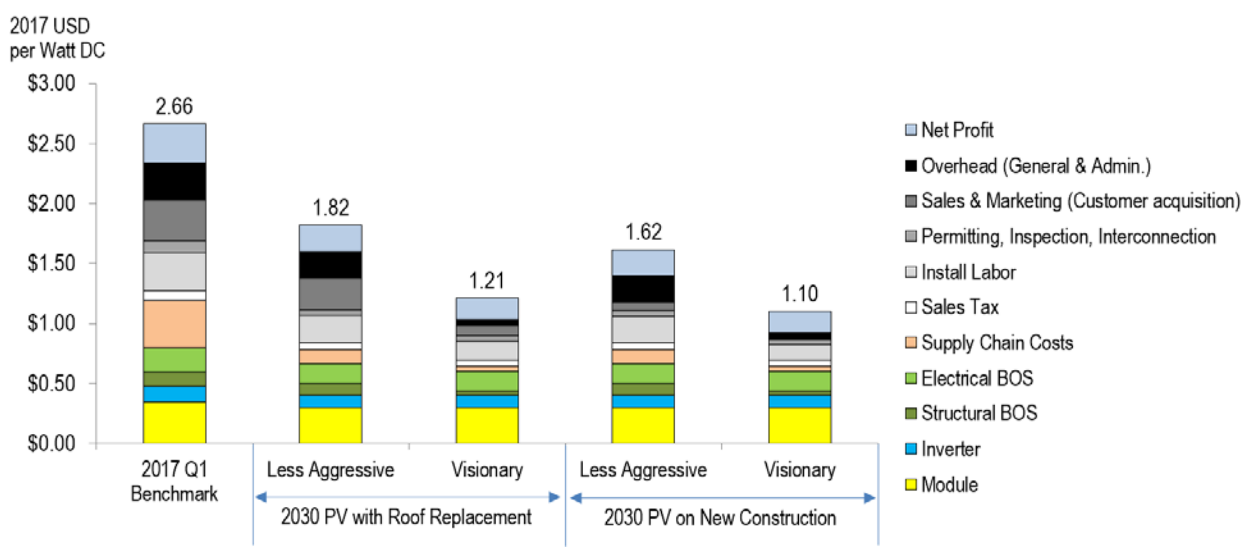


Figure ES-2. Modeled installed residential PV system prices at time of roof replacement and new construction in 2030, compared with a weighted average of the Q1 2017 benchmark

When we translate these installed-system costs into LCOE, we find that the less-aggressive pathways achieve significant cost reductions, but may not achieve the 2030 LCOE target (Figure ES-3). On the other hand, both visionary pathways could result in PV system prices that get very close to (for roof replacement) or achieve (for new construction) the 2030 target in each market segment.

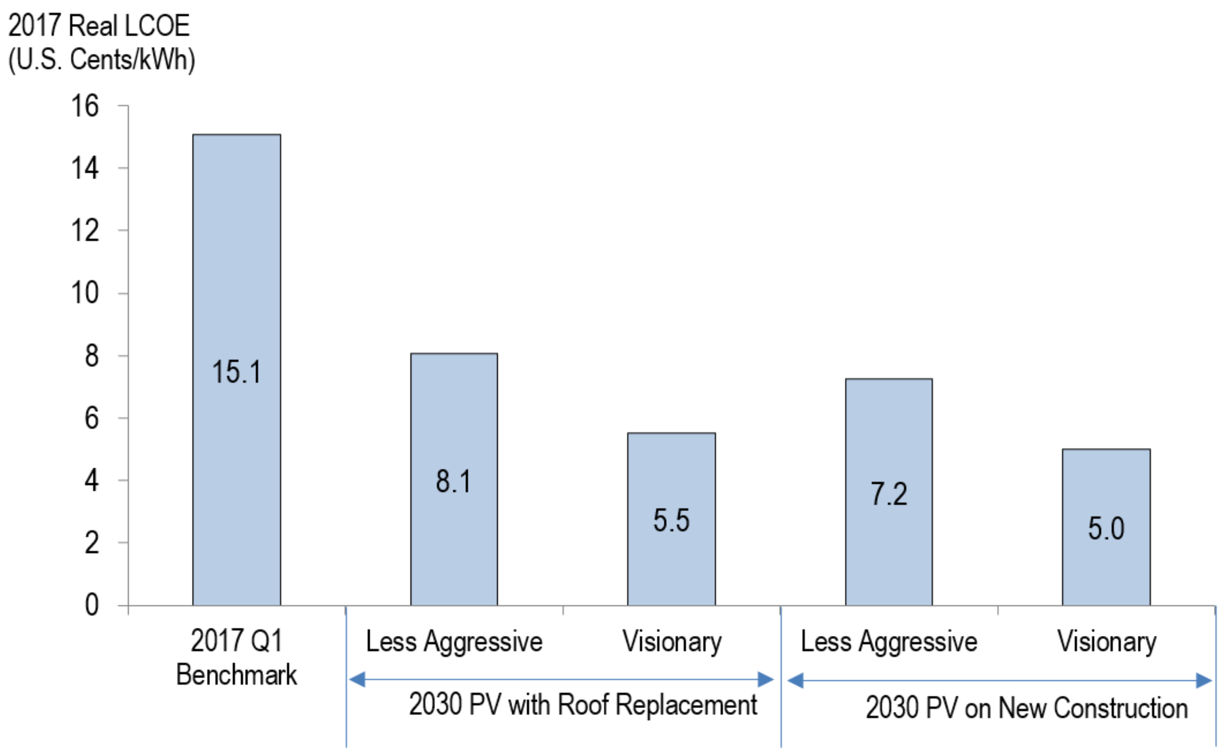


Figure ES-3. Modeled residential PV LCOE at time of roof replacement and new construction in 2030, compared with the LCOE for a weighted average of the Q1 2017 benchmark

Figure ES-4 compares the LCOE impacts of our modeled installed-system cost reductions with the impacts of improvements in other parameters, for the new construction visionary pathway. The results indicate that savings associated with installed-system soft costs account for about 65% of the total savings. Therefore, reducing these soft costs likely will be critical for achieving the 2030 residential PV target.

Although we identify pathways toward the 2030 residential PV target, various barriers and considerations must be addressed to realize this future. First, all four pathways benefit from anticipated market maturation that could significantly reduce supply chain costs. This analysis assumes that PV installers can procure modules at or near spot market prices in 2030. This future is likely to require significant innovation in business models as well as the proliferation of efficient procurement processes.

Second, the two visionary pathways assume that a low-cost integrated PV and roofing product is available by 2030, which could significantly reduce supply chain, installation labor, and permitting costs. Although integrated PV products have been or are being developed, achieving low-cost residential PV with an integrated product is very challenging and will likely require significant investments in research and development.

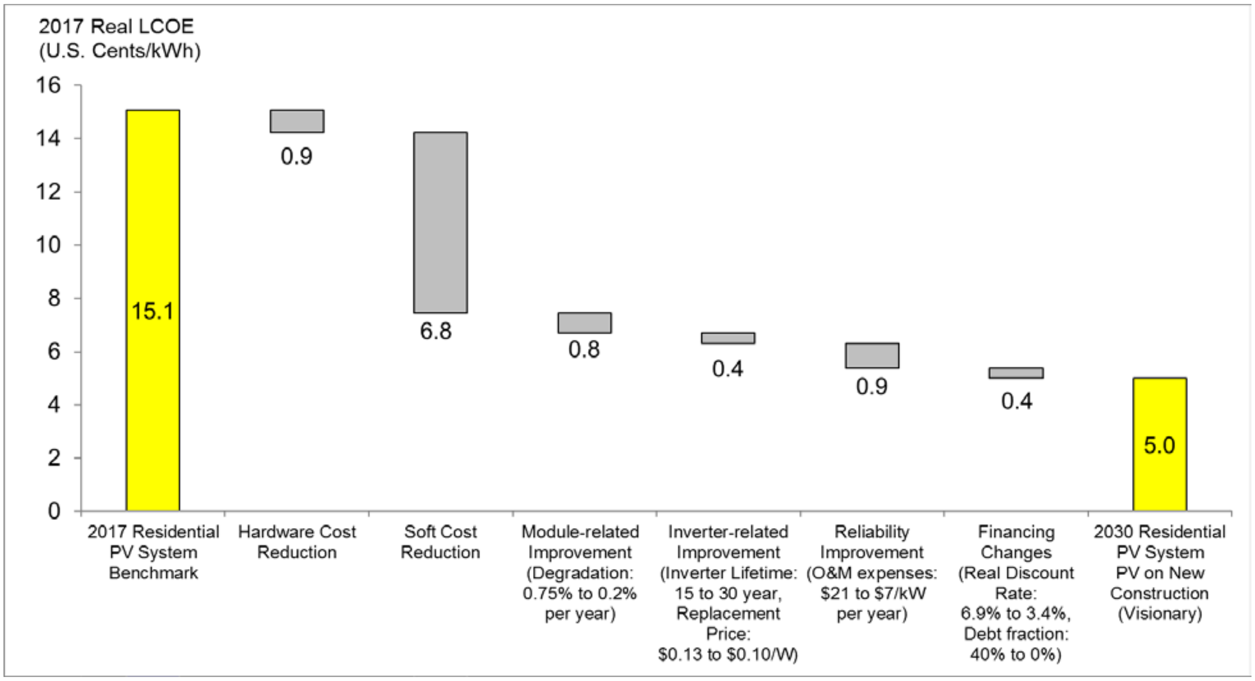


Figure ES-4. Modeled residential PV LCOE reductions for the new home construction market visionary pathway in 2030, compared with the Q1 2017 benchmark

Third, business model integration could provide significant sales, marketing, overhead, and labor savings that reduce installed PV system prices. Although there have been efforts to collaborate across the solar and roofing industries—and across the solar and housing industries—fully integrating across these types of businesses will require significant changes to existing practices. In addition, regulatory challenges such as variation in PV permitting requirements across more than 18,000 authorities having jurisdiction across the United States could serve as another barrier to increasing business model integration.

Fourth, economies of scale yield considerable cost savings, especially for the new construction market. However, the benefits of scale may be less than those assumed in our analysis, resulting from construction timelines, project sizes, and workforce management. In addition, those homebuilders that construct comparatively few homes (e.g., 20 or fewer homes annually), are unlikely to experience the same process efficiencies as those that construct hundreds of homes. In addition, potential permitting challenges and delays associated with deploying PV on new homes could result in additional costs that offset the savings benefits of economies of scale.

Overall, the results of our analysis suggest that it will be challenging but possible to achieve the SETO 2030 residential PV target. We identify two pathways that could play a transformative role in the residential PV sector: one by installing PV at the time of roof replacement, and the other by installing PV as part of the new home construction process. Achieving the SETO target via either pathway will require very aggressive reductions in hardware and soft costs driven by the development of new technologies, services, and business practices.

Table of Contents

List of Figures

List of Tables

1 Introduction

In 2011, the U.S. Department of Energy launched the SunShot Initiative to reduce residential, commercial, and utility-scale photovoltaic (PV) costs by 75% between 2010 and 2020 (DOE 2016). For residential PV systems, this meant reducing the average levelized cost of energy (LCOE) from 52 cents per kilowatt-hour (¢/kWh) to 10 ¢/kWh in 2020 (in 2017 dollars).[1] In 2016, DOE set even more aggressive targets to be achieved by 2030, including a residential PV LCOE of 5 ¢/kWh. This report outlines potential pathways for achieving the 5 ¢/kWh residential PV target by 2030.

Achieving the SETO 2030 target will require significant cost reductions beyond a business-as-usual scenario. In 2017, the average residential PV LCOE in the United States reached 15.1 ¢/kWh (Fu et al. 2017). Based on projections in the "mid" case of the NREL's Annual Technology Baseline (ATB), residential PV would reach an LCOE of 9 ¢/kWh in 2030 (NREL 2017).[2] Thus an additional reduction of 4 ¢/kWh would be required to achieve the SETO 2030 target.

To envision feasible pathways to realizing this aggressive 2030 target, we focus on two particularly promising residential PV markets: installing PV at the time of roof replacement and installing PV as part of the new construction process. We provide detailed component-level cost and system-level price projections for residential PV in these markets in 2030 based on four specific and plausible cost-reduction opportunities: market maturation, business model integration, product innovation, and economies of scale. We then convert the system price projections into LCOE values and analyze the potential of our modeled pathways to achieve the SETO 2030 target, along with the barriers that must be overcome to do so.

The remainder of this report is structured as follows: Section 2 describes the residential market opportunities for PV at time of roof replacement and on new home construction from 2017–2030. Section 3 describes the cost-accounting method we use to assess cost-reduction opportunities. Section 4 discusses our modeled cost-reduction opportunities and pathways. Section 5 shows our results, including the installed-system cost and LCOE reductions enabled by each pathway. Section 6 describes potential barriers to achieving the projected cost-reduction opportunities, and Section 7 discusses conclusions, study limitations, and directions for future research. Appendix A contains our underlying assumptions used to calculate the market potential for residential PV. Appendix B provides additional data and assumptions used in our modeling.

[1] LCOE is calculated by summing the cost to build and operate a PV system over the system's assumed financial life and dividing that total cost by the estimated lifetime electricity generation, yielding a value in cents per kilowatt-hour (EIA 2017a).

[2] This estimate is based on the ATB's mid-level cost projection in 2030 for residential PV with a 16.1% capacity factor (NREL 2017).

2 Technical Potential for Residential PV at Time of Roof Replacement and New Home Construction

From 2010 through 2016, cumulative installed residential PV capacity in the United States increased from 0.6 GW to 8.3 GW (GTM and SEIA 2016). Gagnon et al. (2016) estimate the continental U.S. technical potential for residential PV at 731 GW.[3] Thus residential PV installed through 2016 accounted for about 1% of the technical potential, suggesting opportunities for large-scale expansion.

We focus on two key market segments that offer significant opportunities for reducing costs and expanding the residential PV market: installing PV at the time of roof replacement and installing PV as part of the new home construction process. In the roof replacement market—after accounting for solar suitability and rooftop-replacement schedules—we project that an average of 2.3 million single-family detached homes per year could install PV between 2017 and 2030 in the continental United States (for detailed analysis assumptions see Appendix A). Assuming an average installed-system size of 5 kilowatts (kW) (roughly the average for residential systems installed in 2016), this would represent a potential of 11.5 GW per year. Installing the maximum suitable system size on all these homes would yield a potential of 22 GW per year.

In the new home construction market—taking into account historical suitability and construction rates—we project that an average of one million new single-family homes per year could install PV between 2017 and 2030 across the continental United States.[4] Assuming an average installed-system size of 5 kW, this would represent a potential of 4.8 GW per year. Installing the maximum suitable system size on all these homes would yield a potential of 9.3 GW per year (see Appendix A).

Summing these two potential markets together yields an average market size of 3.3 million homes per year. At an average system size of 5 kW, this would represent a potential of 16.3 GW per year. Installing the maximum suitable system size would yield a potential of 31.4 GW per year (Figure 1). The five states with the largest combined potential are Texas, California, Florida, New York, and Illinois. Capturing even a relatively small fraction of this potential could have a significant impact on the evolution of the U.S. electricity system.

[3] Gagnon et al. (2016) estimate the national technical potential of rooftop PV at 1,118 GW, with residential buildings—defined as those with a footprint of less than 5,000 square feet—accounting for 731 GW.
[4] It is possible that all new homes could be designed to avoid shading and other suitability barriers, which would increase the potential for rooftop PV.

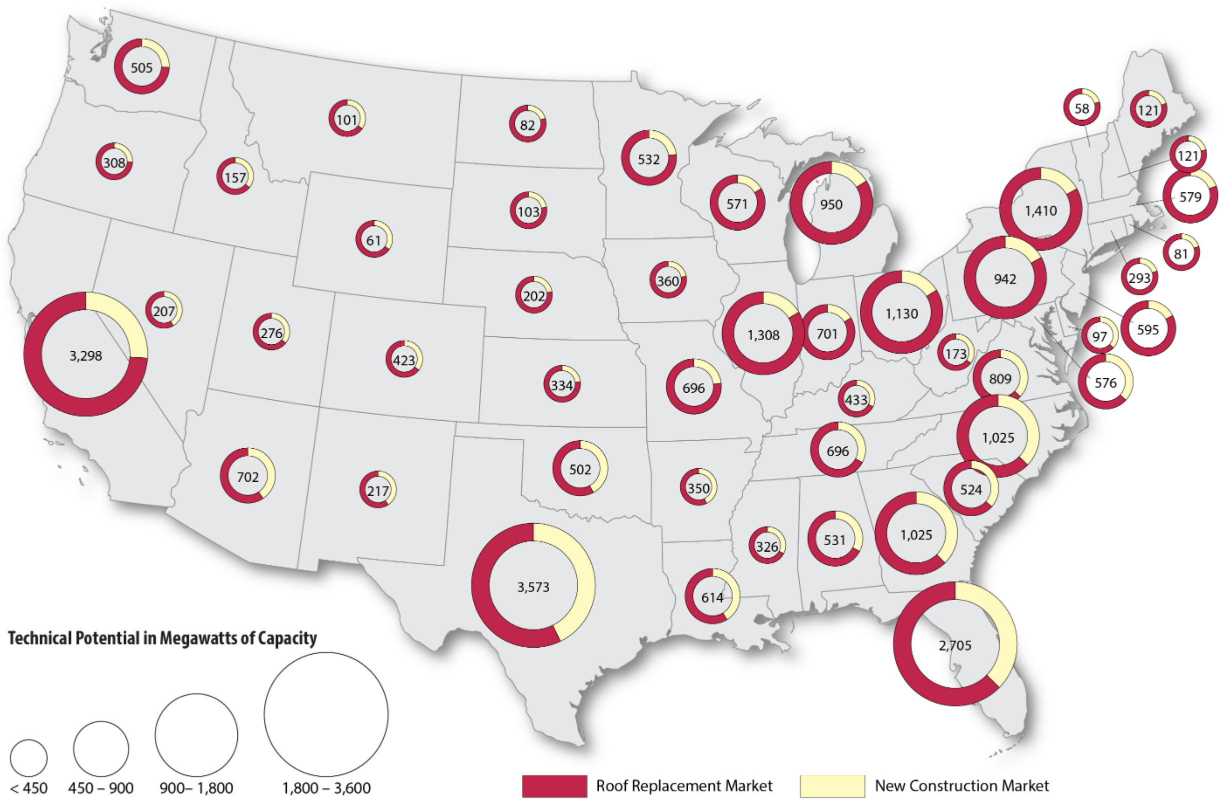


Figure 1. Annual average technical potential for residential rooftop PV at time of roof replacement and new construction projected between 2017 and 2030 (assuming the maximum suitable system size installed on all homes in these markets)

3 Methodology

To assess the potential impact of specific cost-reduction opportunities, we compare modeled residential PV system costs in 2030 to NREL's quarter one 2017 (Q1 2017) residential PV system price benchmark (Fu et al. 2017). Since 2010, NREL has benchmarked current PV system prices for the residential, commercial, and utility-scale sectors (Goodrich et al. 2012, Ardani et al. 2012, Chung et al. 2015, Fu et al. 2016, Fu et al. 2017). These benchmarks are generated using a bottom-up accounting framework for all component and project-development costs incurred when installing PV systems. The residential benchmark models the cash purchase price for systems excluding the federal investment tax credit.

All modeled costs represent the typical average selling price (ASP) between Tier 1 equipment suppliers and first buyers in the global market.[5] Generally, first buyers of equipment from the factory can be developers, engineering, procurement, and construction (EPC) contractors, installers, distributors, retailers, or other end users. Specifically, in our model, costs are represented from the perspective of the installer; thus all hardware benchmarks represent the ASP at which components are purchased by the installer. Importantly, we also apply a 17% fixed margin to all direct costs to model the sales price paid by the end user to the installer. This 17% fixed margin is referred to as "net profit" and is added to total installed costs as a separate category. Although we include assumptions for indirect costs such as business overhead, supply chain costs, and permitting costs, we do not include any additional end-user price gross-up, which is common in the marketplace. We use this approach owing to the wide variation in installer profits in the residential sector, 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 or deal structures.

In general, the model captures typical installation techniques and business operations within a detailed bottom-up accounting framework. The result is a granular accounting for direct and indirect costs associated with installing a PV system. These cost categories include hardware costs, such as module and inverter prices, as well as "soft costs," such as costs related to the supply chain, labor, and sales and marketing (see Table 1).

For comparison to our 2030 modeled PV system prices, we use the benchmarked national weighted-average Q1 2017 system price for a retrofitted PV installation consisting of a 5.7kW system using 60-cell, multicrystalline, 16.2%-efficient modules from a Tier 1 supplier and a standard flush mount, pitched-roof racking system. The modeled costs of such a system, by category, are displayed in dollars per watt direct current ($/Wdc) in Table 1. In the Q1 2017 benchmark, the highest costs are related to the supply chain, modules, and sales and marketing.

[5] A Tier 1 supplier refers to an established company with its own branded solar panels and at least six projects with non-recourse financing from six different institutions. For more information on these firms, see BNEF (2017).

Table 1. National Weighted-Average Q1 2017 System Cost Benchmark for Residential Retrofit PV Installation by Cost Category (adapted from Fu et al. 2017)

Category	Modeled Value	Description
Module price	$0.35/Wdc	Ex-factory gate (first buyer) price, Tier 1 modules
Inverter price	$0.13/Wdc	Single-phase string inverter, ex-factory gate (first buyer) prices, Tier 1 inverter
Structural balance of system (BOS)	$0.11/Wdc	Includes racking and flashing for roof penetrations
Electrical BOS	$0.20/Wdc	Conductors, switches, combiners, and transition boxes, as well as conduit, grounding equipment, monitoring system or production meters, fuses, and breakers
Supply chain costs	$0.39/Wdc	Includes shipping and handling of equipment, historical inventory and small-scale procurement expenses for both modules and inverters
Sales tax	$0.08/Wdc	Sales tax on the equipment; national benchmark applies an average (by state) weighted by 2016 installed capacities
Direct installation labor	$0.32/Wdc	Modeled labor rate uses weighted average of state rates
Permitting, inspection, and interconnection (PII)	$0.10/Wdc	Includes assumed building permitting and interconnection application fees of $400 and six office staff hours for building permit preparation and submission, and interconnection application preparation and submission
Sales and marketing (customer acquisition)	$0.34/Wdc	Total cost of sales and marketing activities over the last year—including system engineering, marketing and advertising, sales calls, site visits, bid preparation, and contract negotiation; adjusted based on state "cost of doing business" index
Overhead (general and administrative)	$0.31/Wdc	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
Profit	$0.32/Wdc	Applies a fixed 17% margin to all direct costs including hardware, installation labor, direct sales and marketing, design, installation, and permitting fees

We use the same cost-accounting framework to model residential PV system costs in 2030 for the roof replacement and new construction markets. Section 4 describes our specific cost-reduction opportunities and pathways.

Consistent with previous benchmarking efforts (Goodrich et al. 2012, Ardani et al. 2012, Chung et al. 2015, Fu et al. 2016, Ardani et al. 2017, Fu et al. 2017), we derived inputs for our model and validated our draft results via interviews with industry and other subject-matter experts. We interviewed 16 representatives from 13 leading organizations closely involved with PV product development and installation, roofing, and new home construction, including PV manufacturers, PV and roofing installation companies, project developers, and industry associations. In these interviews, we focused on gaining a deeper understanding of future trends related to PV product integration, new business models that enhance collaboration across the PV, roofing, and new construction industries, deployment challenges, future cost-reduction opportunities, and cost-model refinement and validation. Our results highlight common themes from interviews. Finally, we also gathered information and data through a review of the published literature.

4 Pathways to Low-Cost Residential PV

The residential PV market is likely to evolve substantially between 2017 and 2030. Although the system cost reductions required to achieve the SETO 2030 target may seem very challenging today, we identify pathways to this goal that are plausible if significant and sustained technology and business-model innovations are realized. We model a total of four pathways, which are characterized by market (roof replacement vs. new construction) and magnitude of cost reductions achieved via four specific cost-reduction opportunities. Section 4.1 describes the cost-reduction opportunities, and Section 4.2 describes the pathways.

4.1 Key Plausible Cost-Reduction Opportunities through 2030

Although there are various opportunities to reduce residential PV costs through 2030, we identify four key opportunities—market maturation, business model integration, product innovation, and economies of scale—and their potential impacts on PV system cost categories.

4.1.1 Market Maturation

Since 2014, the top five residential PV installers captured between 39%–57% of the U.S. market on a quarterly basis (Shiao et al. 2017). The remaining market has been served by a wide array of midsize and small installers. In recent years, there has also been a rapidly evolving set of back office support, software, and other types of firms that serve midsize and small installers. Today, high-volume installers typically have the purchasing power to negotiate lower module and component prices compared with lower-volume installers, especially when bulk purchasing modules and other components from suppliers. With increased PV market maturation, these pricing differentials could be significantly reduced through the development of a mature supply chain, distribution channels, and support services aimed at small, medium, and large companies. Our analysis assumes that, between 2017 and 2030, the market matures such that small, medium, and large installers can procure modules and other components at or near the spot market prices modeled in Woodhouse et al. (2016). This significantly reduces supply chain costs.

4.1.2 Business Model Integration

Currently, most solar companies operate independently from roofing companies and homebuilders, and they often do not coordinate with these traditionally separate businesses. However, some solar companies have begun to collaborate with roofing companies and/or homebuilders to offer PV to prospective customers. For example, SunPower, a PV manufacturer and installer, currently partners with 10 of the 13 largest homebuilders in California to deploy PV on new construction (SunPower 2017). In addition, some roofing companies have begun to integrate PV into their product offerings and businesses more broadly (Solar Power World 2017). Business model integration is less common in the housing industry, but this market segment is quickly evolving. For example, Lennar—the second-largest U.S. housing company—deploys PV on its new homes via its subsidiary SunStreet (Professional Builder 2016, Lennar 2017).

Increased business model integration can offer cost savings over a PV-only approach, including lower customer-acquisition costs, labor time, and overhead expenses. For example, PV can be integrated into existing sales and marketing programs from roofing and housing companies, with reduced added costs. Similarly, overhead expenses and installation labor costs could be reduced by eliminating duplicate back office expenses and integrating installation crews.

4.1.3 Product Innovation

Product innovation could take a variety of forms, such as reduced PV racking and mounting, preassembled PV, and low-cost PV roofing tiles. An integrated PV and roofing product, in particular, could yield significant cost savings, especially if the roof and PV system could be shipped and installed in unison. Although integrated products have low market share today, it is plausible that they could reach the mass market by 2030. For example, several companies have recently introduced or are developing integrated PV products (CertainTeed 2017, GAF 2017, Tesla 2017). Product innovation along these lines could influence the labor, supply chain, and structural BOS cost categories.

Our analysis is limited to standalone PV and does not examine product innovation related to PV plus storage. However, there is a growing interest among homeowners in bundled PV systems that include dispatchable load, batteries, and electric vehicles. Previous NREL analysis shows that bundled PV product offerings allow homeowners to increase PV self-consumption and realize greater value from PV generation by temporally shifting customer load under the PV production curve (O'Shaughnessy et al. 2017). Given the cost declines and the potential benefits of PV plus storage solutions, by 2030 solar homebuilders and roofing companies are likely to expand their offerings beyond standalone PV systems to include storage as well. Early signs of this trend can be seen in the United States, with limited examples of battery manufacturers announcing partnerships with homebuilders to install batteries alongside PV on new construction (Tech Home Builder 2017).

4.1.4 Economies of Scale

Economies of scale are likely to be most accessible to the new housing market, because the cost of individual systems could be reduced by spreading fixed costs across multiple installations. Homebuilders often construct an entire subdivision (averaging 60 housing units), so a combined, or closely related homebuilder/PV installer could achieve cost savings by installing multiple PV systems simultaneously.[6] For example, combining installations could reduce labor costs by requiring the work crew to go to a subdivision only once to complete multiple installations. The overall benefit of economies of scale varies by the quantity of PV systems installed in a particular area, but the key cost categories affected include labor, sales and marketing, and PII costs. Achieving economies of scale in the roof replacement market is more difficult because, with the exception of major storms, rarely does an entire neighborhood require roof replacement at the same time.

4.2 Modeled Cost-Reduction Pathways

Our four modeled pathways explore the impact the cost-reduction opportunities from Section 4.1 could have on residential PV system costs compared with the Q1 2017 benchmark. For each market (roof replacement and new construction), a less-aggressive pathway represents savings due to an incremental shift from current market practices, and a visionary pathway represents savings due to a more dramatic shift. Table 2 characterizes each of the four modeled pathways

[6] The average number of housing units in a subdivision is from a 2014 National Association of Home Builders survey (Emrath 2014).

by market and magnitude of cost reductions realized (i.e., low and high). The remainder of this section discusses the pathways in more detail.

Table 2. Four Modeled Pathways by Market and Magnitude of Cost Reductions

	Pathway			
	Roof Replacement Market		New Construction Market	
Cost-Reduction Opportunity	Less Aggressive	Visionary	Less Aggressive	Visionary
Market Maturation	High	High	High	High
Business Model Integration	Low	High	Low	High
Product Innovation	Low	High	Low	High
Economies of Scale	NA	NA	Low	High

4.2.1 Roof Replacement Market

In the roof replacement market, the less-aggressive pathway models a solar company that maintains its own separate business but loosely partners with a roofing company. These two separate companies may share business leads and office space, but they are not fully integrated into a single company. In addition, the solar company continues to install traditional racked and mounted rooftop PV. Finally, this pathway does not yield a benefit from economies of scale, because PV installed during roof replacement is typically on a project-by-project basis.

In contrast, the visionary pathway represents a company that realizes the available cost-reduction opportunities more fully. A completely integrated roofing and solar company incorporates a low-cost integrated PV and roofing product (a low-cost roofing tile or some other innovative product) into all roof offerings. As with the less-aggressive pathway, economies of scale provide no savings in this pathway.

4.2.2 New Construction Market

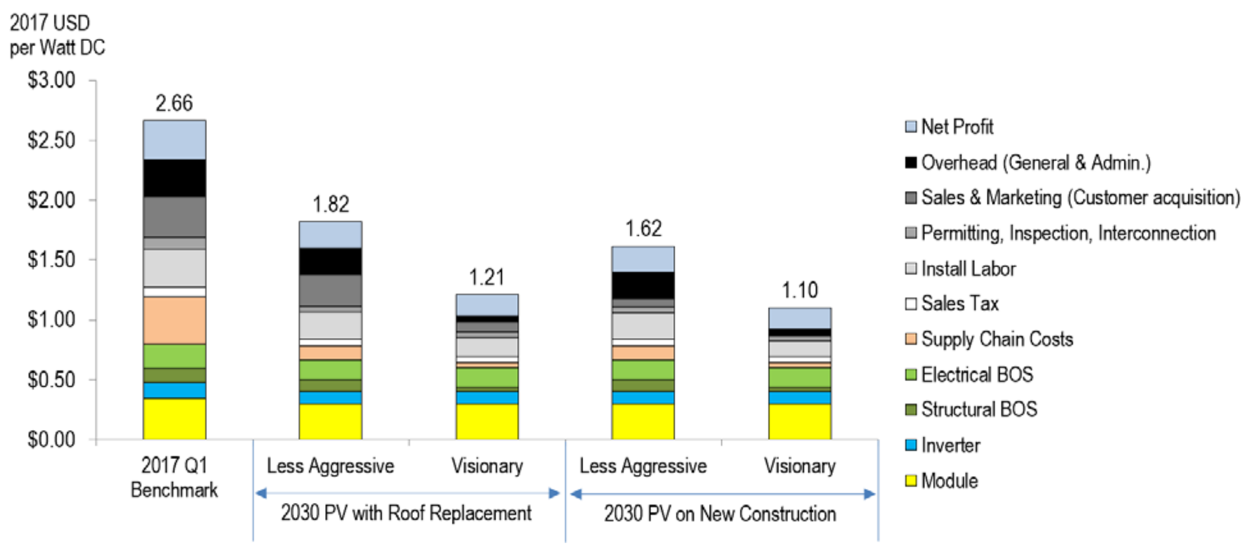
In the new construction market, the less-aggressive pathway is similar to its counterpart in the roof replacement market. The PV installer is only loosely affiliated with a homebuilder and may share office space with the homebuilder or roofing company (when the homebuilder subcontracts the roofing portion of new homes). The PV installer may also establish a formal partnership with a homebuilder, but it is not fully integrated into the construction process/business. The PV installer continues to install a traditional racked and mounted PV product and realizes some economies of scale; we assume the installer can leverage its partnerships with the housing industry to install PV on at least 25% of homes in a typical subdivision (i.e., 60 housing units, per Emrath 2014).

The visionary pathway, in contrast, assumes PV is fully integrated with the home design-build process from the start. It also assumes use of a low-cost integrated PV and roofing product as well as significant economies of scale due to installing PV on all new homes within a subdivision.

5 Cost-Reduction Results by Pathway

Figure 2 shows installed residential PV system prices for each of our modeled pathways in 2030, which all provide significant savings over the Q1 2017 benchmark (see Appendix B for detailed cost breakdowns and assumptions). Savings are largest in the supply chain, sales and marketing, overhead, and installation labor cost categories. Much of the supply chain savings result from the assumed market maturation that eliminates module price premiums related to historical inventory and small-scale procurement (potential savings of $0.27/Wdc); these savings are consistent across each of the pathways. The remaining three cost-reduction opportunities (business model integration, product innovation, and economies of scale) influence the PV system prices in each modeled pathway differently.

Because the two visionary pathways provide substantially larger cost savings compared with their less-aggressive counterparts, we present detailed cost-modeling results for these two pathways in Sections 5.1 and 5.2.



USD = U.S. dollars

Figure 2. Modeled installed residential PV system prices at time of roof replacement and new construction in 2030, compared with a weighted average of the Q1 2017 benchmark

5.1 Roof Replacement Market

The 2030 residential installed PV system price in our roof replacement visionary pathway is 55% lower than the Q1 2017 benchmark system price. Figure 3 breaks out the savings by cost category. The greatest savings are derived from the supply chain, sales and marketing, overhead, and installation labor categories.

Most supply chain efficiencies arise from market maturation (see Section 4.1.1). However, additional supply chain savings are realized under the visionary pathway relative to the less-aggressive pathway, because PV is integrated into the roofing material in the visionary pathway. This product integration would allow the PV and roofing material to be shipped together, thereby eliminating additional shipping costs. In contrast, the less-aggressive pathway assumes that companies continue to install traditional racked and mounted PV that is shipped and installed separately from the roof.

The full integration of a PV installer with a roofing company offers a significant sales and marketing benefit. Individuals invest in retrofitted PV systems voluntarily, but they typically replace their roofs owing to a specific requirement. Therefore, prospective customers may be more inclined to respond positively to PV marketing that is incorporated with a roof purchase, compared with the marketing of PV alone. At the same time, PV marketing could be integrated into existing roofing customer outreach, marketing, and advertising efforts at little or no additional cost. As a result, in the visionary pathway the fully integrated firm has a single sales and marketing budget to sell an integrated PV roofing product, which eliminates most customer acquisition costs (except for system design). In the less-aggressive pathway, we assume a solar company only loosely partners with a roofing company by, for example, sharing customer leads. In return for successful leads, the partner might receive a sales commission.[7] The savings achieved through this approach are substantially lower than the savings in the visionary case.

Similarly, fully integrating a PV installer with a roofing company yields significant overhead savings. A standalone solar company incurs typical overhead costs such as rent, office expenses, professional services, and software/information technology. Because the visionary pathway models an integrated solar and roofing business, these costs would be significantly reduced. Nevertheless, some additional costs would be associated with integration including acquiring PV or roofing expertise. In our model, we account for the costs of a roofing company acquiring PV expertise in the overhead category.

Installation labor costs are also reduced, owing to business model and product integration. Most conventional, racked and mounted rooftop PV systems can be installed by the same class of labor already employed by a roofing company,[8] and we assume that same labor class can be employed to install an integrated PV and roofing product. Combining roofing and PV installation activities creates synergies and logistic efficiencies that reduce truck rolls, crew-hours spent on site, and other direct transportation costs, such as fuel. The use of an integrated PV and roofing product in the visionary pathway also eliminates the labor required for racking and mounting installation, which provides additional labor cost savings over the less-aggressive pathway.

The roof replacement visionary pathway also benefits from savings in other cost categories. For example, the PII cost is reduced because we assume the PV permit cost declines to a standard $200 per system. Structural BOS savings are realized owing to the elimination of racking and mounting, in favor of the integrated product.

[7] Interview findings suggest a broad range of typical sales commissions, from $0.25/W to $1/W, in the current market, depending on the geographic region and pricing structure. For this analysis, we assume the commission is less than the cost of customer acquisition the solar company would otherwise incur working independently.

[8] Interviewees noted that, with appropriate training, many roofing installation crews today retain the level of expertise required to install the components of a PV system that are above the roof (e.g., racking, mounting, modules). However, most roofing companies would likely need to subcontract, or hire, an electrician to install PV system components such as electrical wiring and conduit.

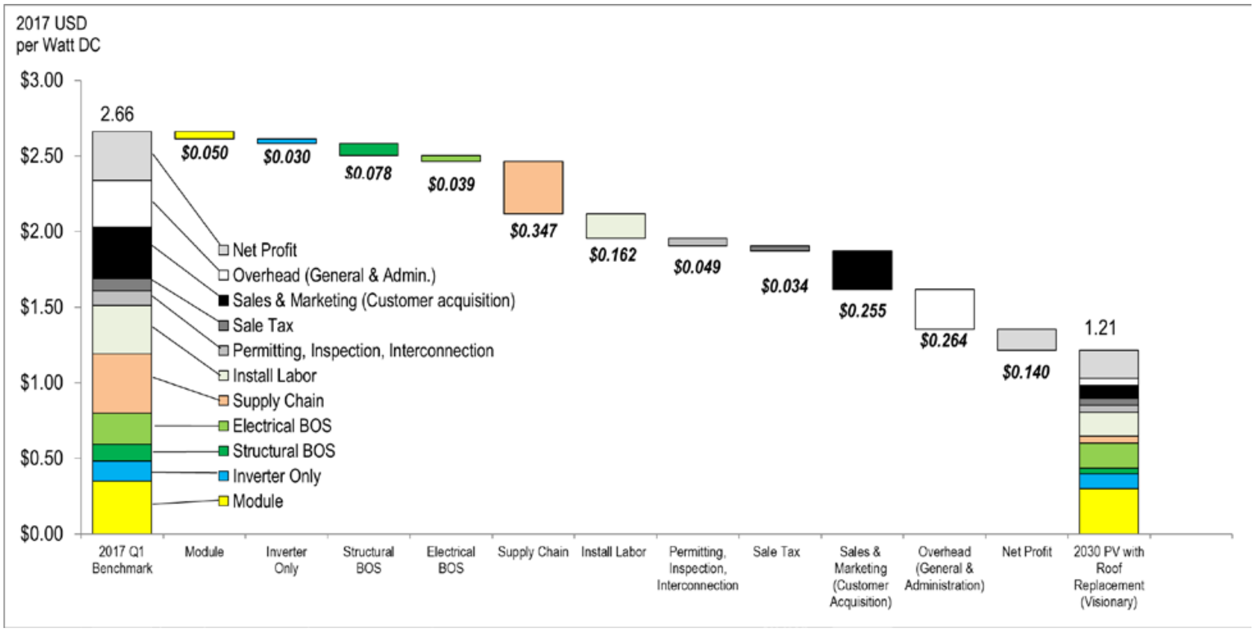


Figure 3. Cost reductions achieved by the roof replacement visionary pathway in 2030

5.2 New Construction Market

The 2030 residential installed PV system price in our new construction visionary pathway is 59% lower than the Q1 2017 benchmark system price (Figure 4), suggesting that installing PV on new homes could yield greater cost savings than installing it during roof replacement. The supply chain savings are the same for the two visionary pathways,[9] but the new construction visionary pathway achieves greater sales and marketing, installation labor, and PII savings, in part by leveraging economies of scale.

Sales and marketing costs are reduced in the new construction visionary pathway, because installing PV on every new home in a development eliminates customer acquisition costs that are currently typical for a retrofitted PV system, such as sales calls, site visits, customer outreach, and bid/pro-forma preparation. The roof replacement visionary pathway provides similar savings. However, installing PV on new homes provides additional savings via design and engineering standardization. Including standard PV system designs and sizes for each home floor plan reduces upfront engineering and design costs that would be incurred when completing a retrofitted PV installation of any kind.

Coordination and collaboration across construction and PV installation crews provides labor savings in both visionary pathways. However, the labor savings in the new construction pathway are greater, owing to economies of scale and the ability of PV installation crews to move readily across multiple co-located housing units.

PII savings are also greater in the new construction visionary pathway compared with the roof replacement visionary pathway, because integrating PV into the building permitting process

[9] Supply chain savings are the same in both visionary pathways because both pathways benefit from market maturation, as outlined in Section 4.1.1, and both incorporate installation of an integrated PV and roofing product.

required for the entire subdivision reduces PII costs per system. In addition, completing multiple new construction PV permits in succession results in savings associated with economies of scale.

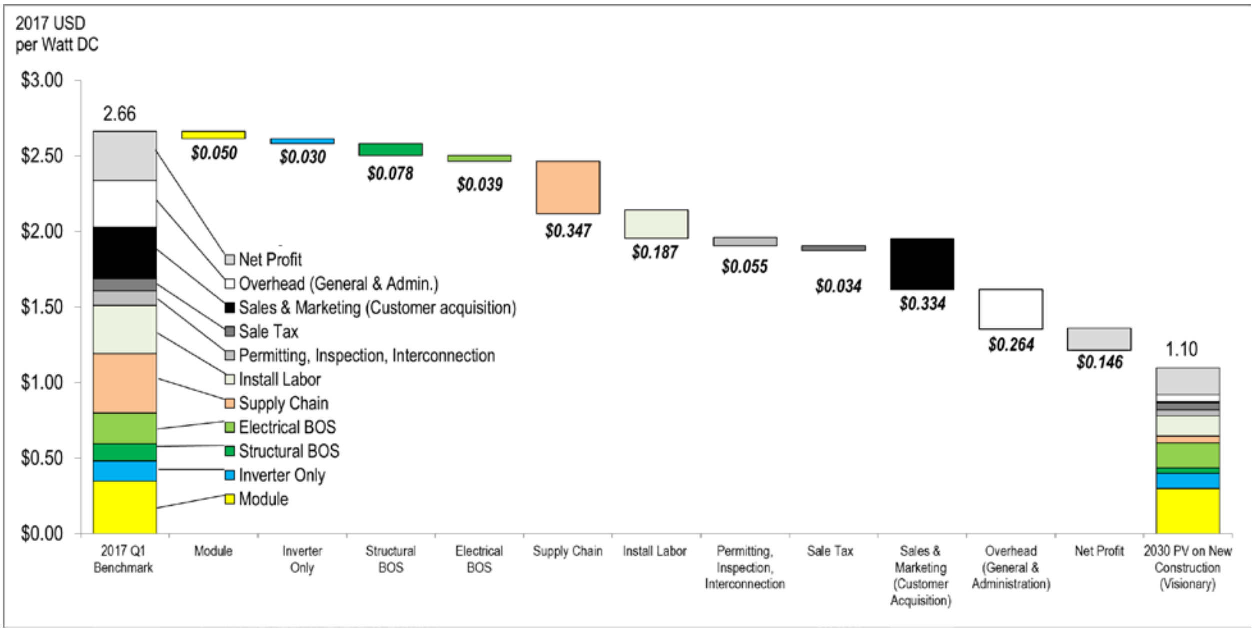


Figure 4. Cost reductions achieved by the new construction visionary pathway in 2030

5.3 Achieving the SETO 2030 LCOE Target

Installed-system prices are a key input for calculating residential PV's LCOE. Other parameters—such as lower operations and maintenance (O&M) costs, more favorable financing terms, and improved PV module performance—are also expected to contribute to declining LCOE through 2030 (Woodhouse et al. 2016). Here we combine our system price results with the other expected improvements to determine whether the SETO 2030 LCOE target can be achieved via our modeled pathways. We model an LCOE for the Q1 2017 benchmark based on the assumptions in Fu et al. (2017), and we model LCOEs for our four pathways based on our modeled system prices and key assumptions from Woodhouse et al. (2016) (Table 3).

As Figure 5 shows, the less-aggressive pathways could progress about 70%–80% toward the SETO 2030 LCOE target of 5 ¢/kWh. In contrast, the new construction visionary pathway achieves the target, and the roof replacement visionary pathway is slightly higher. Thus, our analysis suggests that moving toward a fully integrated roofing product and a fully integrated business model may be critical to achieving the SETO 2030 residential PV target.

Table 3. Assumptions for Calculating Residential PV LCOE

LCOE Cost Input (2017 USD/Wdc)	Q1 2017 Benchmark	2030 Pathways
Installed cost ($/W)	$2.66	Varies by pathway
Annual degradation (%)	0.75%	0.20%
Inverter replacement price ($/W)	$0.13	$0.10
Inverter lifetime (years)	15	30
O&M expenses ($/kw-year)	$21	$7
Pre-inverter derate (%)	90.50%	90.50%
Inverter efficiency (%)	98.00%	98.00%
System size (kWdc)	5.7	5.7
Inverter loading ratio	1.15	1.15
Real discount rate	6.9%	3.4%
Inflation rate	2.5%	2.5%
Debt interest rate	4.80%	4.80%
Debt fraction	40%	0%
Analysis period (years)	30	30

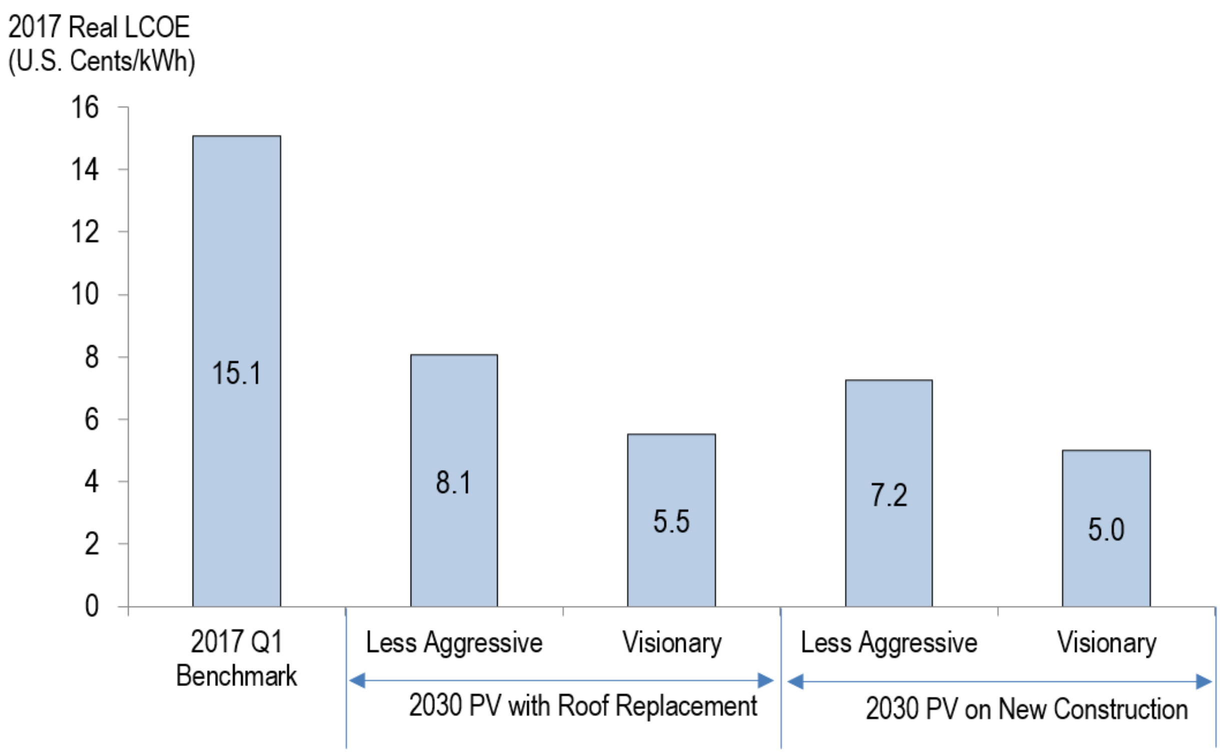


Figure 5. Modeled residential PV LCOE at time of roof replacement and new construction in 2030, compared with the LCOE for a weighted average of the Q1 2017 benchmark

In addition, reducing installed-system costs—particularly soft costs—likely will be critical to achieving the SETO 2030 target in either market. Figure 6 (roof replacement visionary pathway) and Figure 7 (new construction visionary pathway) compare the LCOE impacts of installed-system cost reductions with the impacts of improvements in other parameters. In both pathways, installed-system soft cost reductions account for roughly 65% of the savings in 2030. None of the other individual parameters account for more than 9% of the LCOE reductions.

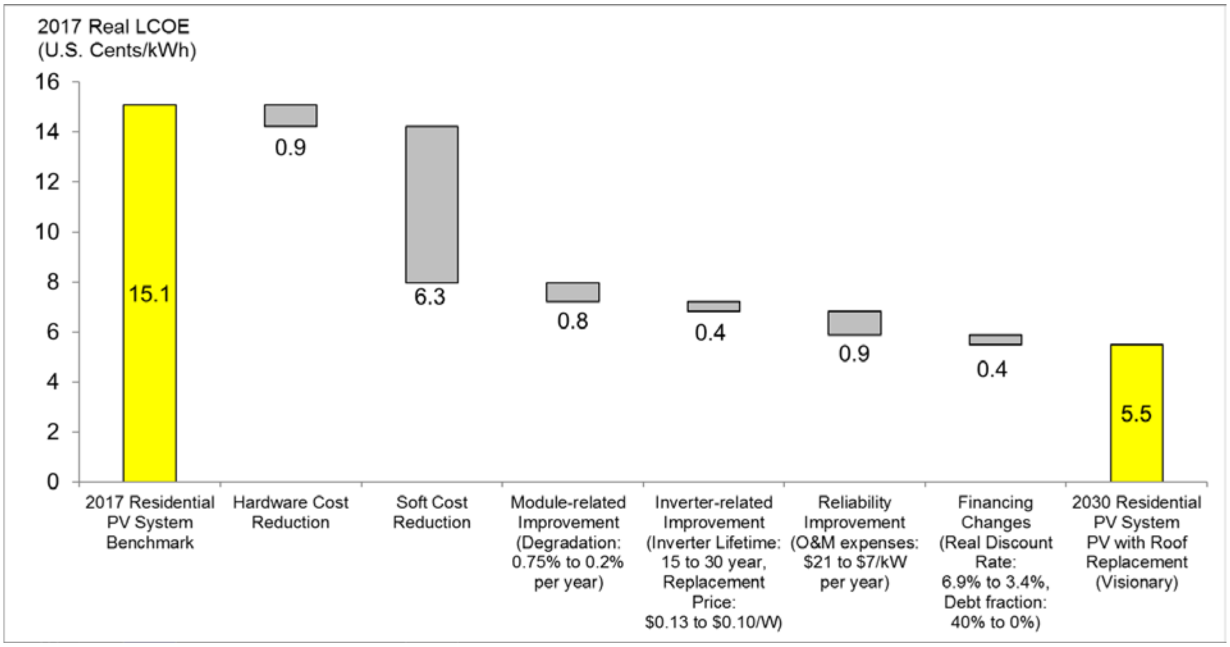


Figure 6. Modeled residential PV LCOE reductions for the roof replacement market visionary pathway in 2030, compared with the Q1 2017 benchmark

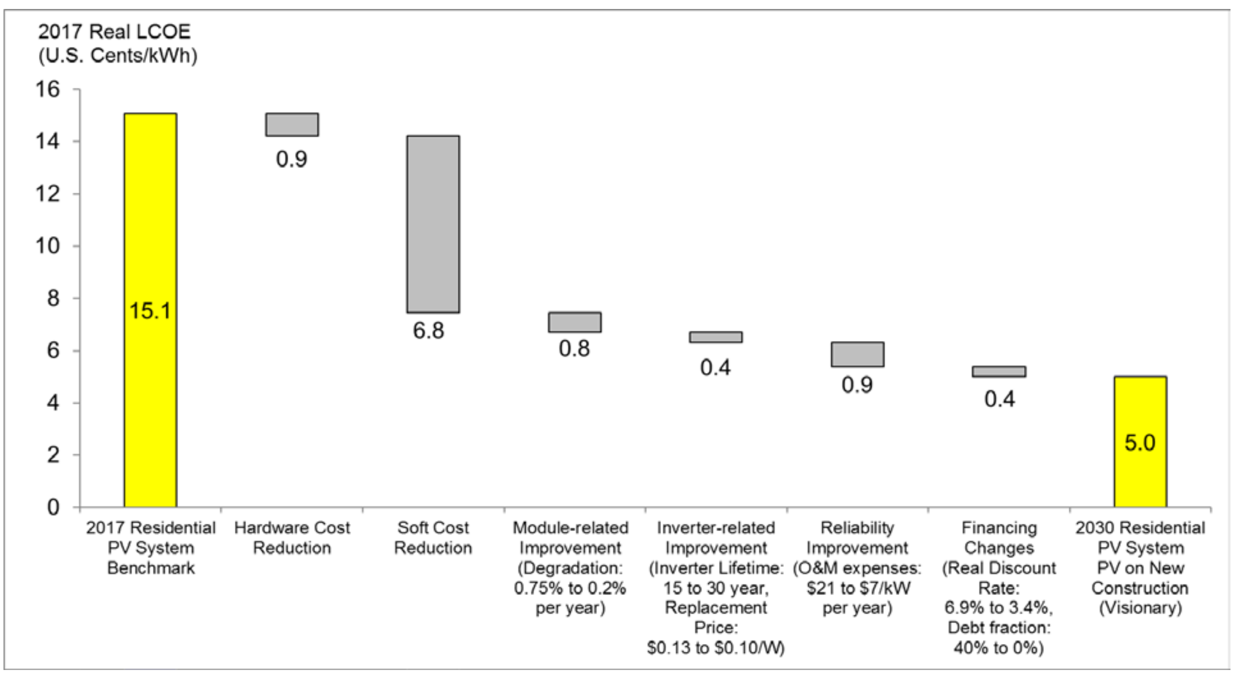


Figure 7. Modeled residential PV LCOE reductions for the new home construction market visionary pathway in 2030, compared with the Q1 2017 benchmark

6 Barriers and Considerations Related to Achieving the SETO 2030 Targets

Although we envision pathways toward ultra-low-cost residential PV in Section 5, our interviewees identified barriers and considerations that must be addressed to achieve these pathways. Here we examine these barriers and considerations in terms of the key cost-reduction opportunities. For two of these opportunities—market maturation and product innovation—the barriers and considerations are consistent across the roof replacement and new construction markets. For the other two opportunities—business model integration and economies of scale—barriers and considerations may differ between the markets.

6.1 Market Maturation

A significant portion of the supply chain cost reductions identified in our analysis is due to market maturation and a resulting narrowing of the gap between spot prices and wholesale prices. In part, this gap is an artifact of rapidly changing prices in a market with significant historical inventories and multiple transactions prior to the end user. As the U.S. PV market matures, we expect installers will be able to procure modules and other components more efficiently, thereby eliminating additional supply chain costs.

Interviewees suggested that the PV industry may reach maturity, as other commodity industries have, through a mix of consolidation and innovation in supply chain service. Some market consolidation is underway, and interviewees believed this trend will continue through 2030, particularly for equipment providers. At the same time, interviewees suggested the development of a diverse set of supply chain service providers that support PV installers will drive down procurement costs further, while increasing PV's value proposition. Interviewees pointed to existing service providers that partner with installers to reduce customer acquisition costs as a model for what is possible. In addition, various third-party service providers seeded by the DOE SETO Incubator Program (DOE 2017) already exist in the market.

If the PV industry reaches maturity, its practices could come to resemble those in other trades, with a robust installer market supported by more regional product dealer and service providers. However, realizing this future likely will require investment in developing new services and bringing them to market at sufficient scale to ensure profit and mass market appeal and to mitigate the procurement disadvantages of smaller purchasers. Currently, it is unclear whether the industry will mature enough to enable a wide variety of installers to procure modules at comparatively low markups. If the required maturation does not occur, the deep supply chain cost reductions we assume across all four pathways may not be achieved.

6.2 Product Innovation

Our two visionary pathways assume a low-cost integrated PV and roofing product is available by 2030, which would significantly reduce supply chain, installation labor, and permitting costs as the PV and roofing materials are shipped, installed, and permitted in unison. Whether integrated PV products can achieve lower costs and greater market share is uncertain at this time. If such a low-cost product does not materialize by 2030, our cost-reduction pathways would change.

Research and development of integrated PV products has been ongoing for years (James et al. 2011), and today there is renewed interest in integrated PV as new products come to market. Interviewees noted that early technology adopters are being drawn to new, integrated PV roofing materials at a price premium for the aesthetic value they provide. However, although many non-cost considerations affect the consumer decision-making process, integrated products must also be low-cost to appeal to a broad market.

Innovation will be required to develop low-cost integrated PV products. Interviewees noted that these custom products currently are produced on a smaller scale, require manufacturing process changes, and require more skill and time to install—all of which add costs. The lower efficiency of current integrated products also makes these products more expensive than conventional PV modules, because more integrated product is required to generate an equivalent amount of electricity. Robust design innovation that addresses these issues likely will be critical if integrated products are to capture significant market share through 2030.

6.3 Business Model Integration

Across both visionary pathways, business model integration is assumed to provide significant sales and marketing, overhead, labor, and PII cost savings that result in lower installed PV system prices. However, business model integration presents unique challenges for PV installed at the time of roof replacement and PV installed on new home construction.

6.3.1 Roof Replacement Market

Interviewees noted that the business models of solar and roofing companies are well aligned and that collaboration between these types of companies likely will increase. However, the need to have experienced solar sales professionals on staff can pose a barrier to roofing companies that want to sell PV directly to consumers. Several interviewees noted that the expertise required to sell PV effectively is significantly different from the expertise required to sell roofs. For example, solar sales professionals may be trained in residential utility rate structures and consumer load profiles, whereas roofers may not be trained in these areas. Therefore, roofing companies must train existing sales staff, or hire solar sales professionals, to sell PV and roofing products together effectively. At the same time, incorporating PV into a roof replacement may cost more than a roof replacement alone. Therefore, PV sales are not guaranteed, despite these investments.

Interviewees also suggested that improved PII processes are needed for solar-roofing companies to realize the full cost savings of business model integration. For example, under most authorities having jurisdiction (AHJs), a new roof and accompanying PV installation are treated as two individual projects for the purposes of permitting and inspection (even for integrated products). AHJs commonly require that, before commencement of PV installation, all permitting and inspection requirements for the new roof be completed, resulting in two distinct permitting packages and inspections. Combining the permitting and inspection processes for the new roof and PV installation would enable more timely and cost-efficient project completion. In addition, the lack of standardization in PV permitting, interconnection requirements, and fees across more than 18,000 AHJs and 3,000 utilities impedes installers' ability to deploy PV rapidly across numerous jurisdictions and utility territories (Grow Solar 2017, APPA 2017). Some states, including Vermont and Rhode Island, have adopted standardized PV permitting processes.

Others, such as New York and California, have directed AHJs to enact model standards. Despite this state-level progress, interviewees suggested that roofing companies may consider the lack of PV PII standardization as a financial risk, thereby deterring the expansion of product offerings to include PV.

6.3.2 New Construction Market

For solar companies that install PV on new housing developments, the target customer is the homebuilder, rather than the end user. This can result in significant sales and marketing savings over current business practices, because homebuilders likely will retain the same solar contractor across multiple developments. To date, most homebuilders do not incorporate PV into all new housing developments. Interviewees suggested that increased business model integration could be spurred by consumer interest, positing that, as homebuyers become familiar with PV's benefits, market demand for PV on new construction will increase. The effectiveness of this approach may be limited, however, because PV might compete with other home upgrades that provide higher revenue to homebuilders.

Interviewees suggested that favorable policy could enhance customer demand and foster more business model integration, highlighting various policy options that could achieve this goal. One common example was California's amended energy efficiency regulations under Title 24, which requires every new home be built to net-zero energy standards by 2020. Effective January 1, 2017, this amendment provided a compliance credit for PV that homebuilders can use to meet Title 24 net-zero energy requirements. Interviewees cited California's Title 24 amendment as a catalyst for PV on new construction, because PV can be more cost-effective than certain energy efficiency measures.

The presence of favorable policy alone, however, is unlikely to capture the full savings potential of business model integration. In California, when homebuilders incorporate PV into new construction as a Title 24 compliance measure, the PV can be included in the master building permit. Interviewees cited PII challenges with this approach. In this scenario, the master building permit serves as an umbrella permit for the entire house, so delays in PV PII can slow construction of the entire project. Similarly, changes made to the PV system design after the master building permit has been submitted would require revision and resubmittal of the entire permitting package. Interviewees suggested that allowing more flexibility for PV systems in the master building permit could address these concerns.

In addition, interviewees noted that solar partners often are not involved in the design of housing developments, which can impede the solar and new construction industries from realizing the full potential of collaboration. For example, when the PV installer is excluded from the housing development planning process, it has limited ability to co-optimize system design and roof layout, or take advantage of streamlined wiring and conduit with PV-ready housing designs. As PV becomes more common on new housing developments and consumers request maximum solar benefits, builders may be more inclined to consider solar exposure in building designs.

Finally, in the new construction market, PV engineers must design and size systems without the benefit of homeowner electricity-use data, which could result in standard system designs that are smaller than would otherwise be installed for a residential retrofit.[10] These smaller system sizes may not maximize consumer benefits, but they may enable PV installers to meet strict building construction and permitting timelines. Interviewees suggested that the development and widespread use of software to model plug loads may help engineers size systems more effectively.[11] This and other innovations in the new construction market will likely be necessary to capture all of the cost savings associated with business model integration.

6.4 Economies of Scale

Although our pathways consider cost reductions associated with economies of scale only for the new construction market, the roof replacement market might see some benefits from this approach by 2030. For example, some interviewees suggested that a company could offer customers the option to defer a PV installation and roof replacement for several weeks at a reduced price to enable the pooling of customers in a particular area, thus maximizing the efficiency of crew logistics and truck rolls. However, many individuals requiring roof maintenance may not be able to wait for roof replacement, which limits this option.

In the new construction market, the modeled cost savings from economies of scale are highly uncertain. Alternative business models, construction timelines, project sizes, and workforce management may diminish or enhance our projected cost savings. Furthermore, company size can greatly influence a homebuilder's ability to maximize the benefits of economies of scale. For example, companies that construct fewer than 20 homes annually are unlikely to achieve the same level of process and pricing efficiencies as a company that builds hundreds of homes each year. There may also be increased costs associated with permitting challenges and delays when adopting PV on multiple properties, which would impact modeled savings. Conversely, economies of scale could influence more cost categories than installation labor, sales and marketing, and PII costs as modeled in this analysis (see Appendix B). Therefore, although the industry is likely to experience some benefit from economies of scale, the scope and timeline of these savings are unclear.

[10] Interviewees cited PV system sizes of 2kW–3 kW as common for new housing construction, smaller than NREL's assumed average U.S. residential retrofit size of 5.7 kW.

[11] Future home energy demand may be influenced by increasing energy efficiency and electrification. Given the uncertainty surrounding these countervailing trends, optimizing PV systems according to a standard size will likely pose a challenge through 2030.

7 Conclusion

We project that 3.3 million residential roofs will be replaced or built each year in the continental United States from 2017–2030, representing a significant market opportunity for residential rooftop PV installers. These two market segments also present considerable rooftop PV cost-reduction opportunities, including four key opportunities that we analyze: market maturation, product innovation, business model integration, and economies of scale.

We apply various combinations of these cost-reduction opportunities to model four pathways to low-cost residential PV in 2030: less-aggressive and visionary pathways in the roof replacement market, and less-aggressive and visionary pathways in the new home construction market. We find that the two visionary pathways—which maximize the savings potential from the four cost-reduction opportunities—could meet or nearly meet the SETO 2030 residential PV target. Specifically, the new construction visionary pathway achieves the 5 ¢/kWh LCOE target, and the roof replacement visionary pathway almost achieves it.

Our analysis has two key implications. First, because installed-system soft cost reductions account for about 65% of the LCOE reductions in 2030 for both visionary pathways, residential PV stakeholders may need to emphasize these soft cost reductions to achieve the 2030 target. Second, capturing these savings will likely require considerable innovation in the technologies and business practices employed by the PV industry.

There are various challenges to achieving the necessary innovations. For example, business model integration, particularly across solar and roofing companies, is critical to reducing the significant sales, marketing, labor, and overhead costs associated with the current PV retrofit business model. This type of business model integration will likely require increased education and cross-training for PV installers, roofers, and homebuilders. At the same time, homebuilders, PV installers, and roofing companies will likely require clear examples of the benefits of business model integration before embracing it widely.

Extensive use of fully integrated PV and roofing products is also crucial to our modeled pathways. However, although integrated products have been, or are being developed, significant investments in research, development, time, and effort will be required to produce the type of low-cost integrated product envisioned in our analysis.

Finally, achieving economies of scale throughout the PV supply-installation chain is important for achieving our pathways. Additional research is needed to clarify the cost savings that economies of scale could provide, especially because of the considerable PII hurdles that must be addressed to realize these benefits.

References

APPA (American Public Power Association). 2017. "Stats and Facts." Accessed December 2017. https://www.publicpower.org/public-power/stats-and-facts.

Ardani, K., G. Barbose, R. Margolis, R. Wiser, D. Feldman, and S. Ong. 2012. *Benchmarking Non-Hardware Balance of System (Soft) Costs for U.S. Photovoltaic Systems Using a Data Driven Analysis from PV Installer Survey Results*. NREL/TP-7A20-56806. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy13osti/56806.pdf.

Ardani, K., E. O'Shaughnessy, R. Fu, C. McClurg, J. Huneycutt, and R. Margolis. 2017. *Installed Cost Benchmarks and Deployment Barriers for Residential Solar Photovoltaics with Energy Storage: Q1 2016*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-67474. https://www.nrel.gov/docs/fy17osti/67474.pdf.

BNEF (Bloomberg New Energy Finance). 2017. *Bloomberg New Energy Finance PV Module Maker Tiering System*. New York: BNEF. https://data.bloomberglp.com/bnef/sites/4/2012/12/bnef_2012-12-03_PVModuleTiering.pdf.

CertainTeed. 2017. "Apollo II." Accessed December 2017. https://www.certainteed.com/solar/products/apollo-ii/.

Chung, D., C. Davidson, R. Fu, K. Ardani, and R. Margolis. 2015. *U.S. Photovoltaic Prices and Cost Breakdowns: Q1 2015 Benchmarks for Residential, Commercial, and Utility-Scale Systems*. NREL/TP-6A20-64746. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy15osti/64746.pdf.

DOE (U.S. Department of Energy). 2016. *The SunShot Initiative's 2030 Goal: 3¢ per Kilowatt Hour for Solar Electricity*. DOE/EE-1501. Washington, DC: DOE. https://energy.gov/sites/prod/files/2016/12/f34/SunShot%202030%20Fact%20Sheet-12_16.pdf.

DOE (U.S. Department of Energy). 2017. "SunShot Incubator Program." Accessed December 2017. https://energy.gov/eere/sunshot/sunshot-incubator-program.

EIA (U.S. Energy Information Administration). 2015. *Annual Energy Outlook 2015*. Washington, DC: EIA. https://www.eia.gov/outlooks/archive/aeo15/.

EIA (U.S. Energy Information Administration). 2017a. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2017*. Washington, DC: EIA. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

EIA (U.S. Energy Information Administration). 2017b. "2015 RECS Survey Data." Accessed December 2017. https://www.eia.gov/consumption/residential/data/2015/.

Emrath, P. 2014. *Typical American Subdivisions*. Washington, DC: National Association of Home Builders. https://www.nahb.org/-/media/Sites/NAHB/SupportingFiles/8/Typ/TypicalAmericanSubdivisionFINAL_20140902080612.ashx?la=en&hash=A722B42C2C0FBB51BF30DCCD78C458EA6B179FE0.

Feldman, D., and M. Bolinger. 2016. *On the Path to SunShot: Emerging Opportunities and Challenges in Financing Solar*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65638. http://www.nrel.gov/docs/fy16osti/65638.pdf.

Fu, R., D. Chung, T. Lowder, D. Feldman, K. Ardani, and R. Margolis. 2016. *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2016*. NREL/TP-6A20-66532. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/66532.pdf.

Fu, R., D. Feldman, R. Margolis, M. Woodhouse, and K. Ardani. 2017. *U.S. Solar Photovoltaics System Cost Benchmark: Q1 2017.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-68925. https://www.nrel.gov/docs/fy17osti/68925.pdf.

GAF. 2017. “DecoTech Roof-Integrated Solar System.” Accessed December 2017. https://www.gaf.com/roofing/residential/solar.

Gagnon, P., R. Margolis, J. Melius, C. Phillips, and R. Elmore. 2016. *Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment*. NREL/TP-6A20-65298. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy16osti/65298.pdf.

Goodrich, A., T. James, and M. Woodhouse. 2012. *Residential, Commercial, and Utility-Scale Photovoltaic System Prices in the United States: Current Drivers and Cost Reduction Opportunities*. NREL/TP-6A20-53347. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy12osti/53347.pdf.

Grow Solar. 2017. “Permitting.” Accessed December 2017. http://www.growsolar.org/permitting/.

GTM and SEIA (Greentech Media Research and Solar Energy Industries Association). 2016. *U.S. Solar Markets Insights.* Washington, DC: SEIA. https://www.seia.org/research-resources/solar-market-insight-report-2016-year-review.

InterNACHI (International Association of Certified Home Inspectors). 2017. “InterNACHI's Standard Estimated Life Expectancy Chart for Homes.” Accessed December 2017. https://www.nachi.org/life-expectancy.htm.

James, T., A. Goodrich, M. Woodhouse, R. Margolis, and S. Ong. 2011. *Building-Integrated Photovoltaics (BIPV) in the Residential Sector: An Analysis of Installed Rooftop System Prices*. NREL/TP-6A20-53103. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy12osti/53103.pdf

Lennar. 2017. “New Home Solar Systems.” Accessed December 2017. https://www.lennar.com/mylennar/resource-center/article/benefits-of-solar.

NREL (National Renewable Energy Laboratory). 2017. “Annual Technology Baseline and Standard Scenarios.” Accessed December 2017. http://www.nrel.gov/analysis/data_tech_baseline.html.

O'Shaughnessy, E., K. Ardani, D. Cutler, and R. Margolis. 2017. *Solar Plus: A Holistic Approach to Distributed Solar PV*. NREL/TP-6A20-68497. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy17osti/68371.pdf.

Professional Builder. 2016. "2016 Housing Giants Rankings." *Professional Builder*, May 4, 2016. https://www.probuilder.com/2016-housing-giants-rankings.

Shiao, M.J., C. Honeyman, T. Heggarty, J. Jones, N. Litvak, S. Moskowitz, B. Attia, B. Gallagher, A. Mond, M. Parikh, A. Perea, C. Smith, and T. Zin. 2017. *Q1 2017 Solar Executive Briefing*. Boston: Greentech Media Research.

Solar Power World. 2017. "2017 Top Solar Rooftop Contractors." Accessed December 2017. https://www.solarpowerworldonline.com/2017-top-solar-rooftop-contractors/.

SunPower. 2017. *Top New Home Builders Choose SunPower to Advance California's Net Zero Compliance Goals Before 2020: SunPower Installs Solar at 1,000th New Home Community*. Press release, June 27, 2017. http://newsroom.sunpower.com/2017-06-27-Top-New-Home-Builders-Choose-SunPower-to-Advance-Californias-Net-Zero-Compliance-Goals-Before-2020.

Tech Home Builder. "Mandalay Homes and sonnen Partner for World-Class Community." *Tech Home Builder*, November 2, 2017. http://techomebuilder.com/emagazine-articles-1/mandalay-homes-and-sonnen-partner-for-world-class-community.

Tesla. 2017. "Solar Roof." Accessed December 2017. https://www.tesla.com/solarroof.

Woodhouse, M., R. Jones-Albertus, D. Feldman, R. Fu, K. Horowitz, D. Chung, D. Jordan, and S. Kurtz. 2016. *On the Path to SunShot: The Role of Advancements in Solar Photovoltaic Efficiency, Reliability, and Costs*. NREL/TP-6A20-65872. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/65872.pdf.

Appendix A: Quantifying Residential PV Potential from 2017–2030

The technical potential for residential rooftop PV from 2017–2030 in the rooftop replacement and new construction markets will be influenced by a wide variety of factors, such as population growth and consumer decisions. Our analysis is meant to generate plausible estimates of PV potential for the two segments by state, but we acknowledge the uncertainties related to market development over the analysis period.

Determining the technical potential of the roof replacement market is the most challenging owing to the impacts of roofing materials and climate on roof replacement timelines. For example, asphalt and composite shingles have an average lifetime of 25 years, whereas a properly maintained ceramic tile roof may last 70 years in a dryer climate, or 35 years in a wetter climate, before needing substantial maintenance (Table 4).

As a result, quantifying rooftop PV potential in this segment requires attention to the age of the home, its roofing material, and its location. The U.S. Energy Information Administration (EIA 2017b) tracks the type and age of residential housing stock by census region in the 2015 Residential Energy Consumption Survey (RECS). The focus of this analysis is on the single-family detached home market, which represents 73.9 million homes or about 63% of residential buildings in the United States (EIA 2017b). RECS tracks the age of this housing stock by census sub-region and decade from 1950–2015. These data are disaggregated into yearly builds using a time-series approach. There are 20.8 million homes, or about 28% of single-family detached housing, built before 1950. To incorporate this housing stock into our analysis, we assume that all these older houses were built between 1940 and 1949; much of this housing was likely built earlier than 1940, but this assumption enables us to consider older homes in our analysis of roof replacement schedules.

RECS tracks the market penetration of certain residential roofing materials by census region, and we use these data and the age of housing stock to estimate roof replacement schedules. Overall, shingles (composite or asphalt) are the most common residential roofing material used in the United States, followed by metal, wood, and ceramic or clay tiles (Figure 8). The percentage of the market captured by each roofing material varies regionally, and this variation relates to the impact different climates can have on roofing materials. For example, in very hot and dry climates, clay tiles perform better and can last much longer than asphalt or composition shingles. Thus, although ceramic or clay tiles cost more than traditional shingles do, they capture a larger market share in the West than in other regions (Figure 8).

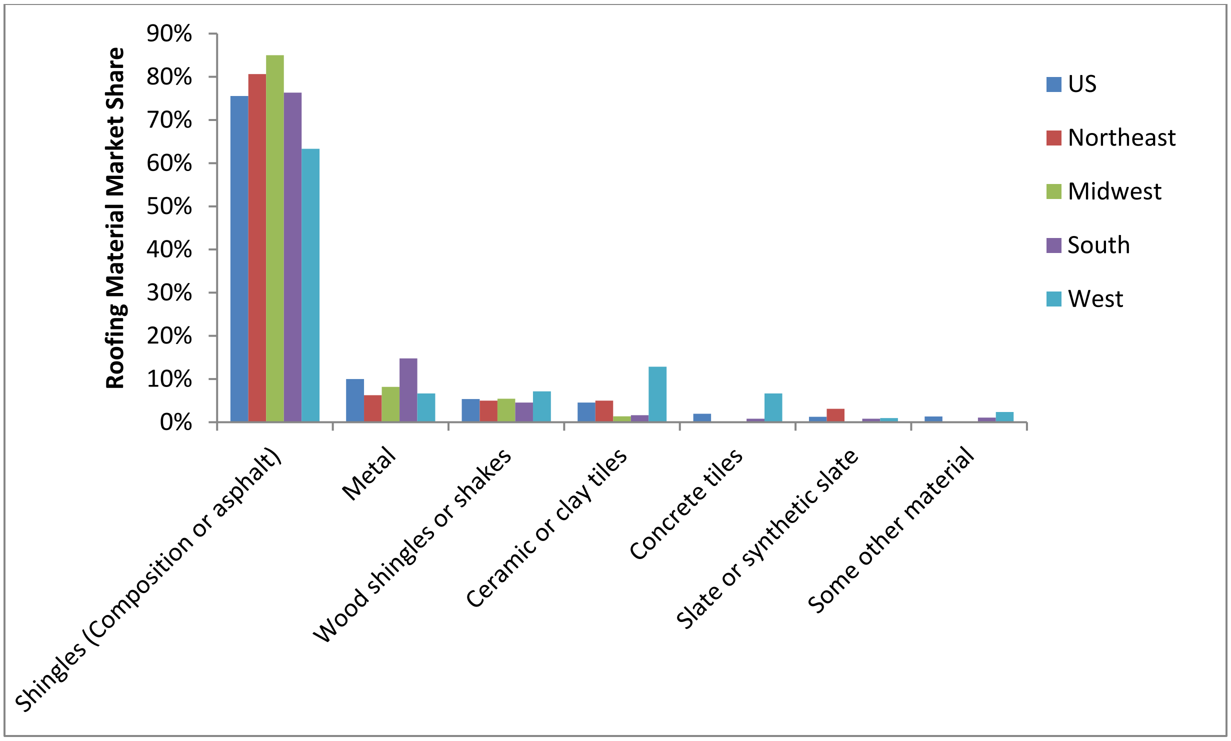


Figure 8. Residential roofing material market penetration nationally and by census region, 2015 (adapted from EIA 2017b)

Although RECS tracks roofing material penetrations regionally, it does not break out roofing material by housing type (single-family homes vs. apartment buildings, etc.). Thus, we apply the regional roofing material market penetrations (as reflected in Figure 8) proportionally to all single-family detached homes by state. In addition, RECS does not track roofing material penetrations based on building stock age. Finally, EIA does not have historical data on roofing material composition prior to 2009. This is problematic because roofing material composition and lifetimes have evolved over time, which can impact when existing homes are likely to require roof replacement. Nevertheless, to provide an estimated timetable for roof replacement, we assume that every home has had the same roofing material composition reflected in the 2015 RECS survey throughout its life. We then assume each roof is replaced in accordance with the current roofing material lifetimes listed in Table 4, which are based on InterNACHI (2017) and interviewee input.

Table 4. Vetted Estimates of Roofing Material Lifetimes by Type and, in Some Instances, Region

Roofing Material	Vetted Lifetime (years)	Regional Variation
Shingles (Asphalt or Composition)	25	
Metal	60	
Wood	25	
Ceramic or Clay	35 or 70	In wet climates (Northeast, South, and Midwest), underlayment likely needs to be replaced about every 35 years; in dryer climates (West), 70 years.
Concrete	35 or 70	In wet climates (Northeast, South, and Midwest), underlayment likely needs to be replaced about every 35 years; in dryer climates (West), 70 years.
Slate	100+	
Synthetic Slate	70	
Other Material*	25	

* "Other material" roof lifetimes can vary by region. For this analysis, roofs on all homes with this material are assumed to last 25 years. In general, roofing lifetimes can vary significantly based on installation quality, material quality, proper maintenance, climate, and homeowner decision-making.

We use this method to estimate a roof replacement schedule for each single-family detached home by state. Not all existing homes are suitable for PV owing to shading or lack of sufficient roof space, among other barriers. Gagnon et al. (2016) estimate the percentage of unsuitable homes by state, and we remove these homes from our analysis accordingly. We then tally the remaining homes expected to require a roof replacement from 2017–2030 and average them to provide an annual estimate by state.

We apply two approaches to translate roof replacements into residential PV technical potential by state. The first is the most aggressive and assumes that each roof replacement maximizes PV deployment; for this we use the estimates of maximum residential PV potential by state made by Gagnon et al. (2016). Although maximizing PV capacity and thus generation may become more common in the future, today residential PV system sizes are smaller, at about 5 kW. Therefore, we include a second estimate based on this smaller system size to offer a more conservative estimate of PV potential. We average the estimated potential capacities across the study period to calculate an annual average market potential in GW. To estimate generation, we apply average PV capacity factors by state.

Because our analysis makes several important assumptions that likely do not reflect the true roof replacement market, the results should only be considered a rough approximation. Table 5 shows our key assumptions for the roof replacement market by state.

Table 5. Key Assumptions for the Roof Replacement Market by State (2017–2030)

State	Potential Retrofits	PV Suitability	Suitable Retrofits	Annual Average Retrofits	Annual Capacity (GW) Conservative	Annual Capacity (GW) Aggressive
AK*						
AL	608,912	83%	507,630	36,259	0.18	0.36
AR	341,961	83%	284,902	20,350	0.10	0.20
AZ	738,185	81%	599,087	42,792	0.21	0.42
CA	3,862,123	88%	3,391,722	242,266	1.21	2.44
CO	691,011	74%	510,763	36,483	0.18	0.27
CT	466,030	75%	350,999	25,071	0.13	0.23
DC	79,004	81%	63,699	4,550	0.02	0.04
DE	110,424	79%	86,936	6,210	0.03	0.06
FL	2,390,697	91%	2,174,105	155,293	0.78	1.69
GA	1,195,830	80%	956,628	68,331	0.34	0.64
HI*						
IA	510,506	82%	419,613	29,972	0.15	0.28
ID	209,919	74%	154,377	11,027	0.06	0.10
IL	2,005,142	83%	1,655,400	118,243	0.59	1.09
IN	1,038,954	83%	859,804	61,415	0.31	0.59
KS	473,472	83%	393,260	28,090	0.14	0.26
KY	555,533	80%	445,691	31,835	0.16	0.29
LA	535,747	89%	477,248	34,089	0.17	0.36
MA	887,611	73%	648,125	46,295	0.23	0.47
MD	697,807	82%	570,428	40,745	0.20	0.36
ME	173,499	73%	126,369	9,026	0.05	0.10
MI	1,555,098	79%	1,225,989	87,571	0.44	0.80
MN	898,962	76%	682,085	48,720	0.24	0.41
MO	992,286	83%	823,450	58,818	0.29	0.54
MS	374,205	85%	317,710	22,694	0.11	0.22
MT	130,022	72%	94,250	6,732	0.03	0.07
NC	1,176,857	80%	946,927	67,638	0.34	0.64
ND	123,438	75%	92,841	6,632	0.03	0.07
NE	310,587	82%	254,375	18,170	0.09	0.16
NH	173,931	73%	126,429	9,031	0.05	0.10
NJ	979,361	78%	762,692	54,478	0.27	0.49

NM	221,636	84%	186,465	13,319	0.07	0.13
NV	313,127	73%	228,637	16,331	0.08	0.12
NY	2,161,981	79%	1,714,884	122,492	0.61	1.17
OH	1,819,193	81%	1,472,236	105,160	0.53	0.95
OK	448,993	87%	392,149	28,011	0.14	0.29
OR	402,789	80%	322,603	23,043	0.12	0.23
PA	1,399,790	80%	1,125,999	80,429	0.40	0.78
RI	137,658	77%	106,555	7,611	0.04	0.06
SC	575,406	83%	477,911	34,137	0.17	0.33
SD	140,945	81%	113,771	8,127	0.04	0.08
TN	832,766	81%	675,044	48,217	0.24	0.47
TX	3,188,461	89%	2,852,544	203,753	1.02	2.04
UT	380,544	72%	275,728	19,695	0.10	0.18
VA	975,628	80%	776,724	55,480	0.28	0.51
VT	81,388	74%	60,446	4,318	0.02	0.05
WA	717,125	75%	535,318	38,237	0.19	0.38
WI	905,136	79%	719,496	51,393	0.26	0.48
WV	212,377	76%	160,544	11,467	0.06	0.11
WY	73,023	79%	57,610	4,115	0.02	0.04
Total	39,275,078		32,258,199	2,304,157	11.52	22.13

* Alaska and Hawaii are not included in this analysis, because there were insufficient data to determine PV capacity potential in the Gagnon et al. (2016) data set.

Estimating the PV potential for the new construction market relies on a different methodology. EIA (2015) models new single-family detached housing builds by census region across five scenarios in the 2015 Annual Energy Outlook. Of the five scenarios, the reference case is considered the base case, and we use this case to determine the total new, single-family detached homes built across each state.[12]

As we do for the roof replacement market, we assume that not all new homes will be suitable for PV,[13] and we use the same suitability rates for the existing housing market to determine PV potential through 2030. We sum the total suitable homes by state and average them to calculate yearly builds. Then we apply the same capacity and generation methods used in the roof replacement analysis. Table 6 shows our key assumptions for the new construction market by state.

[12] The Annual Energy Outlook reference case data were disaggregated to each state using the University of Virginia's state population projections http://demographics.coopercenter.org/national-population-projections/, and then the growth was projected through 2030 using a time-series approach.

[13] It is possible that all new homes could be designed to maximize PV access, thereby increasing the market estimate for this sector.

Table 6. Key Assumptions for the New Construction Market by State (2017–2030)

State	New Homes	PV Suitability (%)	Suitable Homes	Annual Average Builds	Annual Capacity (GW) Conservative	Annual Capacity (GW) Aggressive
AK*						
AL	294,539	83%	245,547	17,539	0.09	0.17
AR	255,608	83%	212,958	15,211	0.08	0.15
AZ	505,167	81%	409,977	29,284	0.15	0.29
CA	1,358,154	88%	1,192,733	85,195	0.43	0.86
CO	378,232	74%	279,571	19,969	0.10	0.15
CT	117,358	75%	88,390	6,314	0.03	0.06
DC	37,286	81%	30,062	2,147	0.01	0.02
DE	64,885	79%	51,084	3,649	0.02	0.04
FL	1,428,220	91%	1,298,827	92,773	0.46	1.01
GA	724,527	80%	579,600	41,400	0.21	0.39
HI*						
IA	143,830	82%	118,222	8,444	0.04	0.08
ID	116,789	74%	85,888	6,135	0.03	0.06
IL	394,359	83%	325,574	23,255	0.12	0.21
IN	202,878	83%	167,895	11,992	0.06	0.11
KS	141,906	83%	117,866	8,419	0.04	0.08
KY	264,373	80%	212,100	15,150	0.08	0.14
LA	375,928	89%	334,880	23,920	0.12	0.25
MA	214,412	73%	156,562	11,183	0.06	0.11
MD	406,993	82%	332,700	23,764	0.12	0.21
ME	44,019	73%	32,062	2,290	0.01	0.02
MI	297,961	79%	234,902	16,779	0.08	0.15
MN	270,072	76%	204,917	14,637	0.07	0.12
MO	298,758	83%	247,924	17,709	0.09	0.16
MS	180,362	85%	153,132	10,938	0.05	0.11
MT	68,828	72%	49,892	3,564	0.02	0.03
NC	700,127	80%	563,339	40,239	0.20	0.38
ND	31,571	75%	23,745	1,696	0.01	0.02
NE	89,718	82%	73,480	5,249	0.03	0.05
NH	46,194	73%	33,578	2,398	0.01	0.03
NJ	205,013	78%	159,657	11,404	0.06	0.10

NM	151,803	84%	127,714	9,122	0.05	0.09
NV	222,332	73%	162,341	11,596	0.06	0.09
NY	439,413	79%	348,542	24,896	0.12	0.24
OH	347,958	81%	281,596	20,114	0.10	0.18
OK	326,080	87%	284,797	20,343	0.10	0.21
OR	137,101	80%	109,808	7,843	0.04	0.08
PA	284,704	80%	229,018	16,358	0.08	0.16
RI	34,138	77%	26,425	1,888	0.01	0.02
SC	332,674	83%	276,307	19,736	0.10	0.19
SD	40,175	81%	32,429	2,316	0.01	0.02
TN	405,016	81%	328,308	23,451	0.12	0.23
TX	2,385,145	89%	2,133,861	152,419	0.76	1.53
UT	211,120	72%	152,969	10,926	0.05	0.10
VA	576,842	80%	459,239	32,803	0.16	0.30
VT	20,978	74%	15,580	1,113	0.01	0.01
WA	246,959	75%	184,349	13,168	0.07	0.13
WI	179,334	79%	142,553	10,182	0.05	0.09
WV	115,236	76%	87,111	6,222	0.03	0.06
WY	38,660	79%	30,500	2,179	0.01	0.02
Total	16,228,560		13,430,512	959,322	4.80	9.31

* Alaska and Hawaii are not included in this analysis, because there were insufficient data to determine PV capacity potential in the Gagnon et al. (2016) data set.

Appendix B: Detailed Cost Modeling Results and Assumptions

To understand the opportunity for achieving ultra-low PV system costs by 2030, we model four cost-reduction pathways. Each pathway was developed by adjusting system cost inputs based on the four key cost-reduction opportunities. Table 7 compares the system costs for each of the four modeled pathways in relation to the Q1 2017 benchmark.

Three of the 11 categories are not impacted by the cost-reduction pathways referenced in this study, including module, inverter, and electrical BOS. Nevertheless, we model savings from the Q1 2017 benchmark in 2030 for each of these categories. The cost savings for hardware (i.e., module and inverter price reductions) are driven by expected savings from technology advances through 2030 as outlined in Woodhouse et al. (2016). Electrical BOS is also reduced 15% to represent assumed incremental savings in wiring and electrical equipment needed for PV through 2030.

Six of the 11 categories are influenced directly by the cost-reduction opportunities envisioned in this report, and the key assumptions behind these modeled savings are discussed in turn here. Structural BOS costs for both less-aggressive pathways see a 10% reduction from current costs due to incremental improvements in racking. In contrast, the visionary pathways see a 64% reduction in these costs, because racking costs are eliminated with use of an integrated product.

Supply chain costs are reduced by 69% in both less-aggressive scenarios due to eliminating module price and inventory markups. The visionary pathways provide additional savings totaling 87% lower than the Q1 2017 benchmark due to removing shipping costs associated with PV, which are expected to be absorbed by shipping an integrated roofing and PV product.

Direct labor installation costs are reduced by 28%–59% from the Q1 2017 benchmark. The lower end of the savings spectrum is based on incremental installation labor savings paired with collaboration between roofing and PV contractors. The higher end assumes that a PV division is integrated with a homebuilder, enabling one team to install PV and roofs on new construction, with additional savings from economies of scale.

PII cost savings for the roof replacement market result from streamlining permitting fees from $400 in the Q1 2017 Benchmark to $200 in 2030. Economies of scale savings further reduce PII costs for both pathways in the new construction market; these two pathways see slight variation in savings resulting from the assumption that, in the visionary case, a company installs PV on all new homes and thereby maximizes economies of scale, whereas, in the less-aggressive case, a company distributes PII costs across fewer installations. Even so, this savings is so small it is lost in rounding.

The sales and marketing category is most heavily influenced by the business model integration opportunity. In the roof replacement market, the less-aggressive pathway represents a scenario in which a solar company partners with a roofing company to conduct some sales and marketing. For the visionary pathway, the expectation is that all sales and marketing costs are integrated with an existing marketing budget from the roofing company. The new construction market is generally similar. In the less-aggressive pathway, savings are associated with a solar company partnering with a homebuilder. In the visionary pathway, PV is integrated, or closely aligned with, a homebuilder's core business. However, the sales and marketing costs for both new construction pathways are lower than the costs for both roof replacement pathways, because the new construction market pathways benefit from reduced design costs due to PV installers having upfront involvement in new home design. The cost variation between the two new construction pathways reflects the higher economies of scale benefit in the visionary pathway compared with the less-aggressive pathway.

The overhead category is predominantly influenced by business model integration. The two less-aggressive pathways leverage the benefit of partnerships with roofing companies as well as incremental cost savings. The two visionary pathways realize the largest overhead savings, because PV is integrated into or closely aligned with a roofing or housing company, requiring little additional overhead.

Finally, the sales tax and profit categories vary by pathway. These values are fixed percentages of the previous cost categories. Thus, this variation results from the method employed as opposed to any direct impact from the cost-reduction pathways.

Table 7. Comparison of Modeled Costs by Category and Pathway in $/Wdc (Percentage Reduction from Q1 2017 Benchmark)

Cost Category	Q1 2017 Benchmark	Roof Replacement Market		New Construction Market	
		Less Aggressive	Visionary	Less Aggressive	Visionary
Module price	$0.35	$0.30 (-14%)	$0.30 (-14%)	$0.30 (-14%)	$0.30 (-14%)
Inverter price	$0.13	$0.10 (-23%)	$0.10 (-23%)	$0.10 (-23%)	$0.10 (-23%)
Structural BOS	$0.11	$0.10 (-10%)	$0.04 (-64%)	$0.10 (-10%)	$0.04 (-64%)
Electrical BOS	$0.20	$0.17 (-15%)	$0.17 (-15%)	$0.17 (-15%)	$0.17 (-15%)
Supply chain costs	$0.39	$0.12 (-69%)	$0.05 (-87%)	$0.12 (-69%)	$0.05 (-87%)
Sales tax	$0.08	$0.06 (-25%)	$0.05 (-38%)	$0.06 (-25%)	$0.05 (-38%)
Direct installation labor	$0.32	$0.23 (-28%)	$0.16 (-50%)	$0.22 (-31%)	$0.13 (-59%)
Permitting, inspection, and interconnection (PII)	$0.10	$0.05 (-50%)	$0.05 (-50%)	$0.04 (-60%)	$0.04 (-60%)
Sales & marketing (customer acquisition)	$0.34	$0.26 (-24%)	$0.09 (-74%)	$0.07 (-79%)	$0.01 (-97%)
Overhead (general & administrative)	$0.31	$0.22 (-29%)	$0.04 (-87%)	$0.22 (-29%)	$0.04 (-87%)
Profit (%)	$0.32	$0.22 (-31%)	$0.18 (-44%)	$0.22 (-31%)	$0.18 (-44%)
Total	$2.66	$1.82 (-32%)	$1.21 (-55%)	$1.62 (-39%)	$1.10 (-59%)