Achieving Low-Cost Solar PV:

Industry Workshop Recommendations for Near-Term Balance of System Cost Reductions

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This Report

Solar photovoltaic (PV) electricity offers enormous potential to contribute to a low-carbon electrical system. However, costs must drop to fundamentally lower levels if this technology is to play a significant role in meeting U.S. energy needs.

"Balance of system" (BoS) costs (all costs except the PV module) currently account for about half the installed cost of a commercial or utility PV system. Module price declines without corresponding reductions in BoS costs will hamper system cost competitiveness and adoption.

This report summarizes near-term cost-reduction recommendations that emerged from Rocky Mountain Institute's *Solar PV Balance of System Design Charrette*,[1] an industry-wide event organized in June 2010.[2] It focuses on BoS costs for rigid, rectangular modules installed in commercial and utility systems up to 20 MW capacity. The design strategies and recommendations in this report lay the foundations for near-term cost reductions of ~50% over current best practices. These reductions exceed current trajectories, and if implemented, can enable greater solar PV adoption.

We hope this report will prove useful to a wide range of solar industry stakeholders and interested observers. In particular, our recommendations are targeted at equipment manufacturers, PV system installers, project developers, financiers, government program administrators, and potential new entrants.

Beyond the near-term focus of this report, many diverse and potentially "game-changing" PV cells and module technologies are being developed and/or launched. Some of these could prompt drastic cost reduction, but even if those technologies succeed, their ability to scale quickly is unknown so the country cannot wait for a technological breakthrough.

Finally, it is important to recognize that solar PV is only one piece of a low-carbon energy system, which must include a portfolio of efficiency and clean technologies.

[1] A charrette is an intensive, transdisciplinary, roundtable design workshop with ambitious deliverables and strong systems integration. Over a three-day period, the Solar PV BoS charrette identified and analyzed cost reduction strategies through a combination of breakout groups focused on specific issues (rooftop installation, ground-mounted installation, electrical components and interconnection, business processes) and plenary sessions focused on feedback and integration.

[2] Some of the recommendations emerged after the charrette, through discussions with participants and other contributors.

Acknowledgements and Contributors

The Solar PV BoS Design Charrette would not have been possible without the generous support of the following partners:

Fred and Alice Stanback

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In addition, we would like to thank the charrette participants, RMI staff and partners, and other contributors to this project.[3]

[3] A full list of contributors and attendees can be found in Appendix A.

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Executive Summary

Near-term *balance of system* (BoS) cost-reduction recommendations developed at Rocky Mountain Institute's *Solar PV Balance of System Design Charrette*[4] indicate that an improvement of ~50 percent over current best practices is readily achievable. Implementing these recommendations would decrease **total BoS costs to $0.60–0.90/watt for large rooftop and ground-mounted systems**, and offers a pathway to bring photovoltaic electricity into the conventional electricity price range.

PV Adoption is Hindered by High "Balance of System" (BoS) Costs

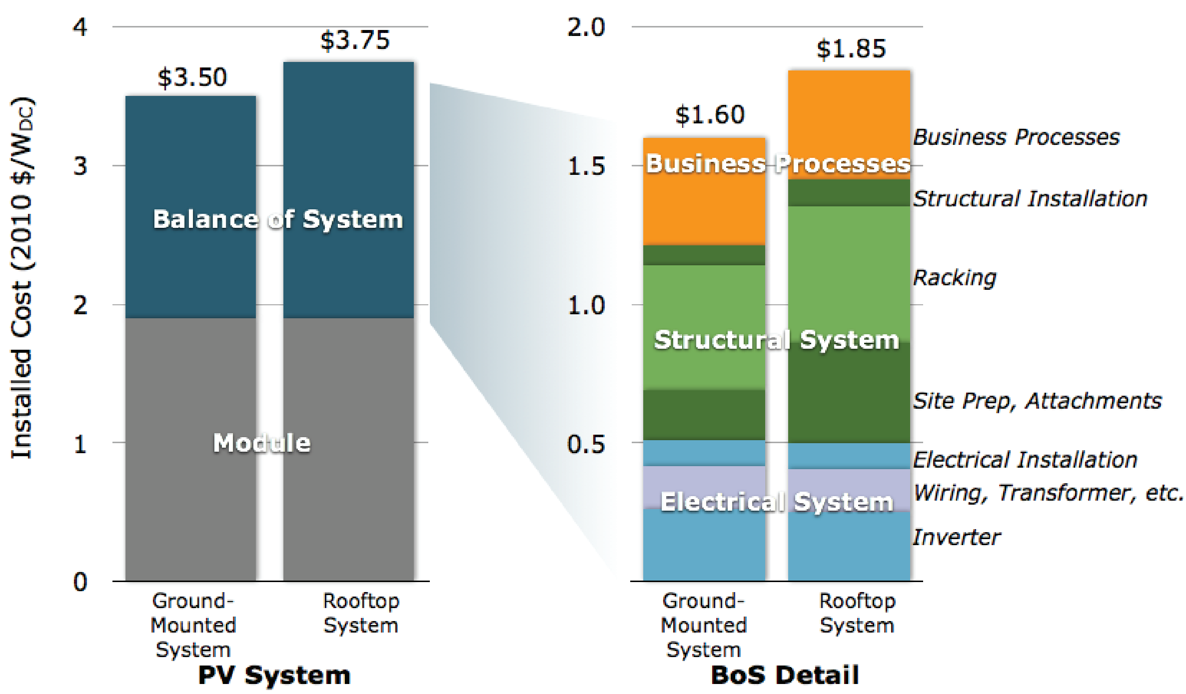
In the context of numerous global challenges—including climate change, volatile fuel prices, energy infrastructure insecurity, and rising energy costs—solar photovoltaic (PV) technologies have made great strides during the past fifty years from their origins in special applications like satellites and off-the-grid systems. However, they have not yet been widely adopted for electrical generation. One of the main reasons is cost. Although solar PV has reached grid parity in select markets, significant reductions are still required to make it a true "game-changer."

Technology development and economies of scale have helped manufacturers of both crystalline silicon and thin film (such as CdTe) PV modules create aggressive yet credible cost-reduction roadmaps.[5] These trends make BoS costs—which account for approximately half of typical commercial and utility project costs—ever more significant. In addition, BoS cost-reduction opportunities are fragmented—usually not road-mapped or coordinated—and, therefore, progress is unlikely to be as aggressive as it is for modules.

In this report, "balance of system" refers to all of the up-front costs associated with a PV system *except the module:* mounting and racking components, inverters, wiring, installation labor, financing and contractual costs, permitting, and interconnection, among others.

Figure 1, below, shows a cost breakdown for a conventional commercial or utility PV system installed in 2010, based on research with industry players. Balance of system costs include the electrical system, the structural system, and enabling business processes.

Figure 1. Cost Breakdown of Conventional U.S. PV Systems ca. 2010[6]



[4] See Footnote 1.

[5] As shown in Figure 1, current best-practice costs for PV systems are in the vicinity of $3.50/W for ground-mounted systems [throughout this report, cost estimates are presented in dollars per watt of module DC rated capacity, unless stated otherwise]. In order to compete on cost without subsidies against US average retail electricity prices, a cost reduction of approximately 50 percent is required. Additional gains are necessary to compete with wholesale power generation.

[6] This cost estimate presents costs using the $/W metric. Ultimately, PV system designs should be optimized based on the "levelized cost of electricity" (LCOE). LCOE (in $/kilowatt-hour) distributes the cost over the output of the system, and takes into account such important factors as system performance, reliability, and maintenance costs. For an analysis of LCOE, refer to Figure 4 and the main text of the report.

The Nature of the BoS Industry Poses Challenges to Cost Reduction

Achieving significant BoS cost reductions with large PV systems is particularly challenging because the installation process requires contributions from many players, including developers, installers, suppliers, regulators, utilities, and building owners. The BoS industry is more fragmented than the module manufacturing industry and has to accommodate widely varying sites, regulatory systems, and customer demands. Within this context, several important considerations for BoS cost-reduction strategies emerged at the charrette:

- **Each PV system has unique characteristics and must be individually designed**—differences between sites, regions, and design objectives mean that a one-size-fits-all approach to PV development is impractical and would produce sub-optimized PV systems. As the PV industry grows, high volume approaches must balance standardization and customizability.
- **There is no silver bullet design solution—**since BoS costs are dispersed across several categories, ranging from structural support to electrical connection to financing, transformational cost reductions will come from many relatively small improvements. In order to coordinate and prioritize these opportunities, integrated analysis tools and cross-value-chain collaboration efforts are needed.
- **Many opportunities for cost reduction are available—**despite recent progress, many cost-reduction opportunities still exist related to improving technology, more appropriate regulations, better information, and economies of skill and scale. Industry *coopetition*[7] is essential to identify and remove barriers to widespread adoption of opportunities.

In late June 2010, Rocky Mountain Institute (RMI) organized a design charrette[8] in San Jose, California. The charrette was focused on balance of system cost-reduction opportunities for commercial and small utility PV systems. The charrette included more than 50 industry experts[9] who participated in a facilitated series of plenary sessions and working breakout groups.
During the charrette process, the participants focused on BoS design strategies that can be applied at scale in the near term (less than five years). Since rigid, rectangular modules account for more than 95 percent of the current market, charrette BoS designs were constrained to this widespread standard. In addition, the charrette addressed relatively large systems (rooftop systems larger than 250 kW and ground-mounted systems in the 1–20 MW range).[10]

A Systems Approach Encompassing Design, Processes, and Scaling Can Yield Significant Savings

As illustrated in Figure 2, the charrette focused on physical system design, enabling business processes, the scaling of the industry, and the synergies available by coordinating across boundaries. There are many links between these areas, and, in many cases, benefits achieved in one area can create positive or negative repercussions for other areas (e.g., a more reliable electrical system design reduces performance risk, thus lowering financing costs). Because of this fragmentation, these interconnections, and the absence of a "silver bullet" solution, transformational cost reduction requires a systems approach.[11]

Cumulative Cost Reduction Potential is Substantial

Charrette participants provided hundreds of ideas for cost reduction, formulated design principles, developed specific designs, and considered concrete implementation recommendations.[12] This report focuses on some of the most broadly applicable recommendations, which are also sometimes the most challenging to implement. A full list of ideas and recommendations is available upon request.

Physical System Design—Minimize Levelized Cost

Many of the most promising physical design strategies are already being considered by leading installers and component suppliers, but they have not yet been widely deployed or combined in optimal ways. Charrette participants identified several critical areas:

- **Reduce wind exposure—**reducing module exposure to wind forces enables the downsizing of structural components. Strategies include module spacing, site layout, spoiling and deflection

[7] *Coopetition* can be defined as "cooperation for mutual benefit in a competitive environment".

[8] See footnote 1.

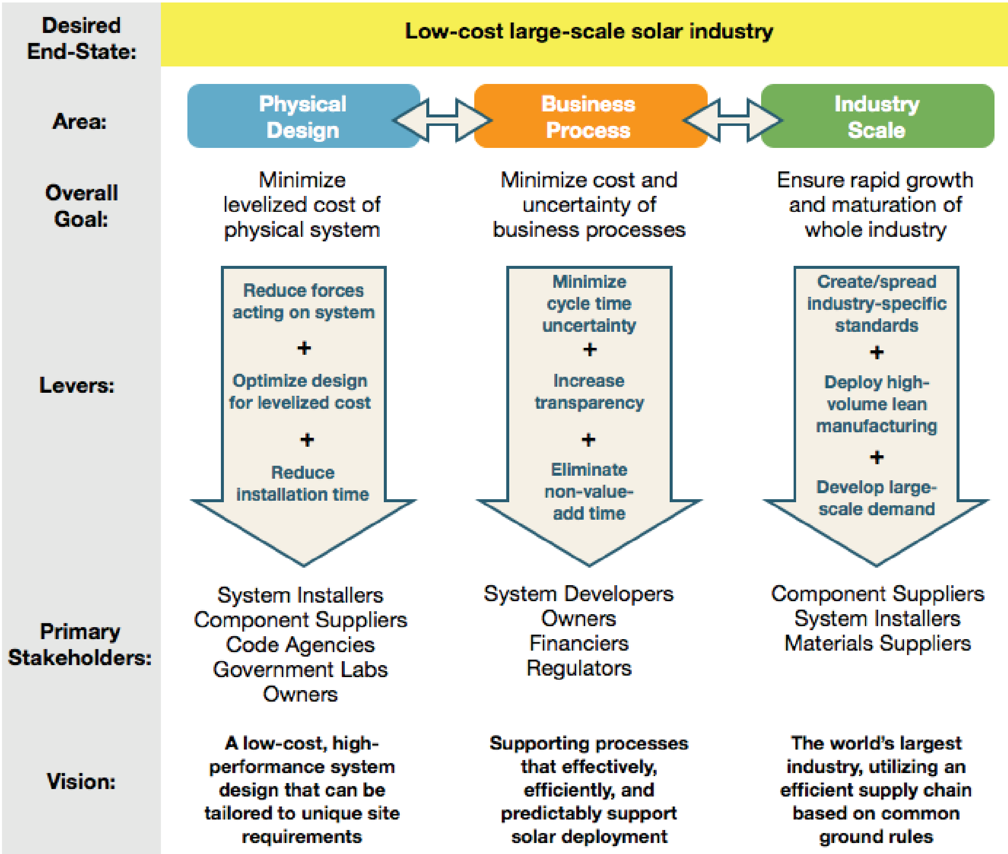
[9] Attendees included PV installers, PV system designers, PV component manufacturers, utilities, system owners, auto industry engineers, design experts, lean manufacturing experts, process experts, PV module manufacturers, and numerous other backgrounds.

[10] Though innovative module design solutions, approaches for smaller systems and the role of subsidies are clearly important, they are outside the scope of these recommendations.

[11] A systems approach spans the entire value chain and players, and considers improvements for one component or process in light of their impacts on or synergies with other elements of the system.

[12] The design strategies and recommendations presented in this report reflect discussions and findings from the charrette supplemented by RMI research. Charrette participants and other experts have contributed to these views, but their input does not imply endorsement.

Figure 2. A Systems Approach to PV BoS Cost Reduction



technologies, and more advanced design concepts with flexible structures. For a typical ground-mounted system, efficient wind design (with enabling regulations) is estimated to reduce the wind forces on modules by 30 percent or more, potentially leading to corresponding reductions in structural system cost. These strategies have not seen widespread industry deployment, partially due to challenges associated with the application of the ASCE-7 structural standard.

- **Use module for structure**—there are opportunities to use rigid glass modules as part of the structural system, enabling the downsizing of racking systems for rooftop and ground-mounted systems. Close collaboration between installers, manufacturers, and certification agencies is required to achieve this goal.
- **Rethink electrical system architectures**—ongoing improvements in small inverter costs, reliability, and performance can help capture benefits associated with high-voltage power aggregation and high-frequency conversion. Both these approaches reduce the cost of the physical plant, including wires and inverters, while offering better system performance if reliability can be maintained.
- **Develop new power electronics technologies**—power electronics, most notably DC-to-AC inverter technologies, offer an opportunity for breakthrough technical design. In particular, integrating AC intelligence into each module of an array or string of modules appears to offer high potential for cost reduction. Ultimately, plug-and-play installation approaches that don't require specialized labor may be possible.
- **Minimize installation labor**—increased installation efficiency can come with innovation, experience, and scale, as designers continue to develop tool-less systems, automated equipment, and higher levels of preassembly. For ground-mounted systems, these strategies could save an estimated 30 percent of labor time and cost. For rooftops, where labor is a large share of the cost, the opportunity is even greater.

Business Processes—Reduce Cost and Uncertainty

Charrette participants considered each step in the business processes[13] that a PV project goes through, from proposal to interconnection. As the U.S. PV industry matures, there are considerable opportunities to make these processes more streamlined and less expensive while decreasing project risk. A particular focus on the following areas is important:

- **Eliminate unnecessary steps and streamline processes**—significant cost reductions can be achieved by streamlining processes throughout the project cycle. Implementing consistent regulations and reducing the uncertainty associated with approval processes can help reduce non-value-added time. A detailed process map—that identifies current cycle times and costs, as well as unneeded actions, rework, and other factors driving time, complexity, and cost—is needed. Dedicated efforts by industry organizations and customers are needed to inform this analysis and to demonstrate highly replicable processes that reduce costs while maintaining safety.
- **Reduce project "dropouts"**—every project that does not make it from proposal to completion adds overhead to successful projects. These "dropout" projects may be caused by unrealistic customer expectations, stakeholder inexperience, unforeseen permitting challenges, or a lack of capital. One way to address these issues might be a database of existing projects that developers can use to evaluate proposed projects.

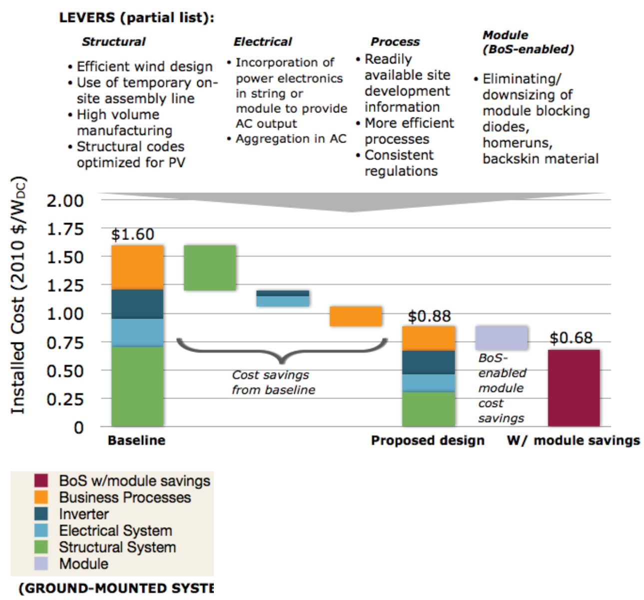
Industry Scale—Ensure Growth and Maturation

As the solar industry grows, there is great potential to adopt best practices from other large, globalized, commoditized industries. Two key areas complement each other to offer cost savings:

- **Standardize components and processes**—as the industry matures, an increased level of standardization of BoS component designs can decrease cost, labor, and permitting time. Efforts to increase standardization can draw from other industries, without overly constraining the solar PV industry's flexibility to adapt to site-specific situations or prevent innovative designs. Project integrators/systems installers collaborating with suppliers can drive increased standardization and economies of scale for components. "Coopetition" across the value chain is a strong enabler of standardization.
- **Leverage high-volume, lean manufacturing**—manufacturing volumes for many BoS components are already in the hundreds of thousands or millions of units per year. However, significant cost-saving opportunities remain because the solar industry is typically characterized by 1) use of materials designed and produced for a different industry; or 2) numerous manufacturers with relatively small market shares that produce mutually incompatible products. As the BoS industry sets standards and consolidates, increased volumes for fewer parts will become the norm, allowing lean manufacturers to decrease costs by reducing the material and labor required, invest in high volume manufacturing processes, and increase throughput. System size (up to a point) can play a key role in economies of scale.

When the many design considerations presented in this report are added into a conceptual system design, BoS costs in the range of $0.60–0.90/watt seem possible in the short term, with a broad variety of designs achieving those costs. Figure 3 shows the cost estimate for the charrette's ground-mounted design using the plant-level inverter approach, yielding a total BoS cost of $0.68/watt (after taking into account a $0.20/watt per module cost reduction).

Figure 3. Near-Term Cost Savings for Charrette Ground-Mounted System Design[14]



Recognizing that the *levelized cost of electricity* (LCOE)[15] is the most important metric, Figure 4 shows the potential effect of the design recommendations on LCOE. In addition, the figure shows the potential effect on LCOE of reducing module costs to $0.70/watt, even though strategies to achieve that goal were outside the scope of the charrette.

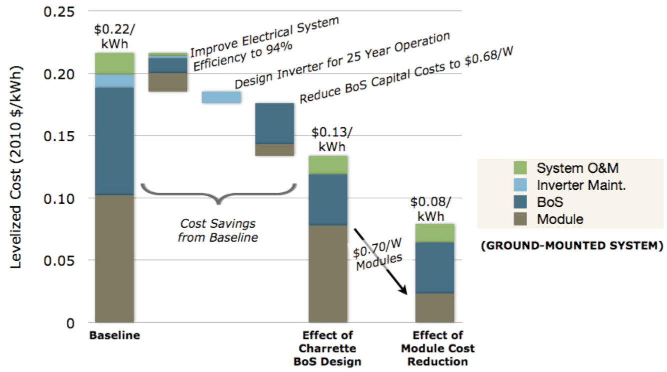
A widely scalable PV design capable of achieving costs under $0.10/kWh unsubsidized offers truly game-changing potential because it becomes cheaper than retail electricity in many U.S. markets.

[13] In this report, "Business Processes" refer to all the enabling processes associated with a PV project, including customer negotiation, contracting and financing, permitting and regulatory approvals, and utility interconnection.

[14] *Effect of Module Cost Savings*: For certain electrical system architectures, increased integration of inversion processes with module electronics is possible. Specifically designing power electronics intelligence to match module characteristics may reduce module costs by safely downsizing or eliminating blocking diodes, module home runs, and backskin material.

[15] See footnote 5.

Figure 4. Levelized Cost of Electricity Estimate for Charrette Ground-Mounted System Design



A Comprehensive Industry-Wide Effort is Needed Now

In order to realize these cost reductions, coordinated action is necessary. Specifically, Figure 5 lists high-priority activities to enable and accelerate cost-reduction efforts. Several of these activities address challenges specific to structural, electrical, or process cost-reduction ideas. A diverse, regularly collaborating group of stakeholders needs to lead and contribute to these recommendations. These measures are described in more detail in the main body of the report and in Appendix B.

In addition to the activities proposed for each focus area, a coordinated effort is required to tie together the disparate BoS cost drivers. One idea suggested at the U.S. Department of Energy (DOE)'s August 2010 *$1/W Workshop* could tie together the disparate cost drivers: a standard tool that provides an analytic view of costs across the BoS. Building on existing models, such a publicly available integrative modeling module could be used to evaluate the impacts on LCOE of specific design strategies—from module to installation—across the value chain. It would also allow designers, customers, regulators, and manufacturers to accurately analyze trade-offs between different designs, codes, incentive programs, contract structures, financing schemes, and economics in terms of system performance and impact on LCOE.

Overall, the activities described in this report will enable cost reduction and increased adoption by promoting:

- **Lifecycle cost decision making;**
- **Industry cooperation to promote standardization;**
- **An increased focus of development efforts on high-potential sites and designs;**
- **The ability of regulatory officials and financiers to evaluate projects efficiently;**
- **The ability of regulators to set subsidies at optimal levels and to sunset them judiciously;**
- **An increased consistency of regulations across utility and government jurisdictions; and**
- **The acceleration of updates to structural and electrical codes.**

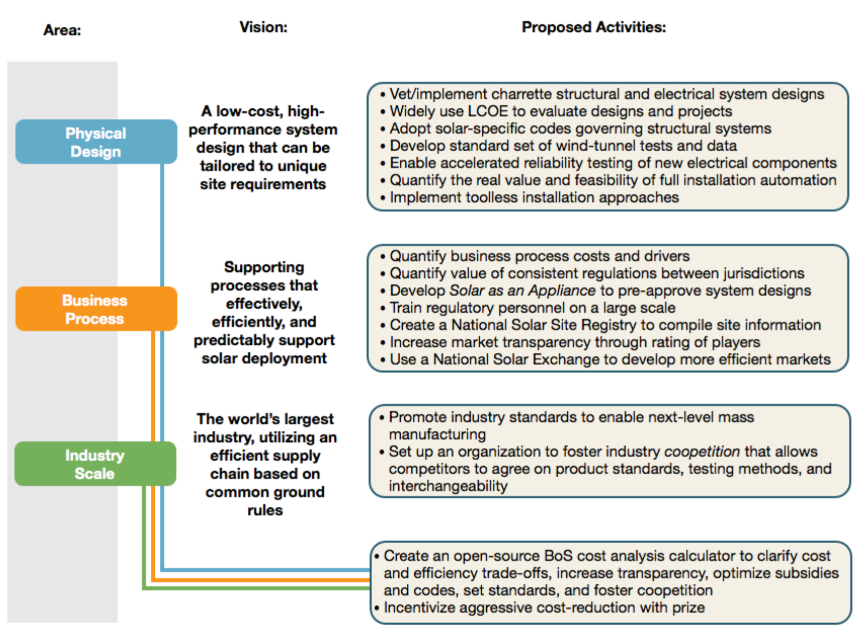
Beyond this Work: Next-Generation Systems Will Offer Additional Possibilities

The Solar PV BoS Design Charrette effort focused on conventional technologies and a less-than-five-year implementation timeframe. Significant work is required to achieve the $0.60–0.90/watt cost targets described in this report. To reduce solar PV power prices beyond these targets ($0.50/watt and below), innovative BoS approaches will be necessary.

Such approaches may include building-integrated systems, DC-electric microgrids, concentrating PV technologies, bio-based structural systems, or fundamentally different photovoltaic technologies, such as paint-on products or cells that enable the use of radically different mounting structures. BoS cost reductions will also be achieved as module efficiencies continue to improve, adding more wattage per unit area of racking and per dollar of project cost, independently of the savings described in this report.

Regardless, current BoS approaches have the potential to considerably drive down system costs and will likely remain dominant for a while.

Figure 5. Proposed Industry Activities to Support Cost-Reduction Goals



I. Introduction: The Case for PV Balance of System (BoS) Cost Reductions

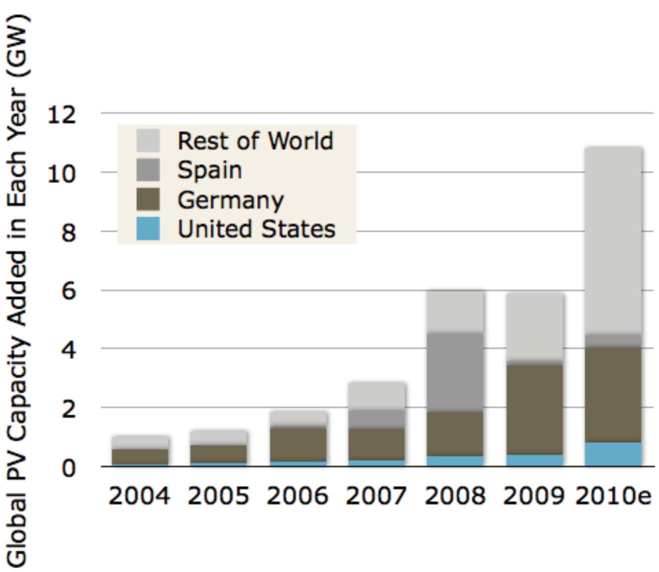
BoS Costs Constitute a Barrier to Widespread Solar PV Adoption

Solar Energy Offers a Large Opportunity

With climate change, energy insecurity, rising costs, and greater demands placing increasing stress on the electricity system, new approaches are required. As part of a portfolio of solutions that includes efficiency and a diverse set of renewables, solar energy offers tremendous potential to contribute to the low-carbon electrical system of the future. Though various types of solar energy technologies have roles to play, photovoltaics (PV) are particularly interesting due to their scalability, increasingly favorable cost structures, and performance in indirect insolation.

As seen in Figure 6, the global solar PV industry has grown substantially in recent years. However, even with more than 10 GW installed globally each year, solar power is still a small contributor to the electrical system. By comparison, 158 GW of wind power were installed globally in 2009 on power systems whose total rated capacity was 4,419 GW in 2007.[16, 17]

Figure 6. Global Solar Industry Growth Trajectory[18]



Making solar PV a large-scale contributor to our energy supplies remains difficult. The PV industry is still trying to overcome challenges posed by high costs, integration with existing electrical systems, divergent standards, emerging technologies, and competing solutions.

Widespread Adoption Requires >50% Cost Reductions

High costs remain a paramount challenge to large-scale PV adoption. Figure 7 estimates the cost-competitiveness of solar PV electricity in U.S. markets at different levels of installed costs. With current best-practice costs for commercial and utility projects around $3.50/watt, solar PV electricity is still uneconomic without subsidies in nearly all U.S. markets[19]. As described in Figure 7, a cost reduction of at least 50 percent from best practice is necessary for solar PV electricity to match average electricity rates. Additional reductions are necessary for solar PV electricity to compete directly in wholesale electricity markets.

Balance of System Costs Are an Important Issue

Figure 8 shows that the $3.50/watt baseline cost (for best-practice commercial or utility-scale ground-mounted projects) is split roughly equally between module cost and "balance of system" (BoS) costs. The intensely competitive module manufacturing industry has continually driven out costs, with leading module manufacturers implementing aggressive cost-reduction strategies.

BoS costs—currently about half the installed cost of a commercial or utility PV system—are on a less aggressive downward trajectory than module costs. BoS cost reduction is particularly difficult due to a fragmented market with myriad players, a lack of knowledge sharing, and the difficulty for value-chain players to get a long-term view of the industry's needs. Furthermore, Figure 9 shows that system efficiency[20] and O&M contributions to levelized cost of electricity ($/kWh) are strongly influenced by the BoS design.

[16] Source: "China Edges U.S. in 2009 Wind Installations." *Environmental Leader*, Feb 2010.

[17] Source: "International Energy Statistics—Total Electricity Installed Capacity." U.S. Energy Information Administration, Aug 2010.

[18] Source: "Solar Photovoltaic Industry." Deutsche Bank Global Markets Research, Feb 2010.

[19] In some cases, solar PV power may be slightly cheaper than this $3.50/W baseline, but most systems are more expensive. Large rooftop systems are slightly more expensive than ground-mounted systems; our baseline cost estimate is $3.85/W for rooftop systems, which is also representative of a best-practice project. These cost estimates present costs using the $/W metric. Ultimately, PV system designs should be optimized based on the "levelized cost of electricity" (LCOE). LCOE (in $/kilowatt-hour) distributes the costs over the output of the system, and takes into account such important factors as system performance, reliability, and maintenance costs. For an analysis of LCOE, see Figure 4 and the main text of the report.

[20] Including electric conversion and module electronics.

Figure 7. Comparison of Upfront PV-System Costs to 2010 Retail Electricity Rates[21]

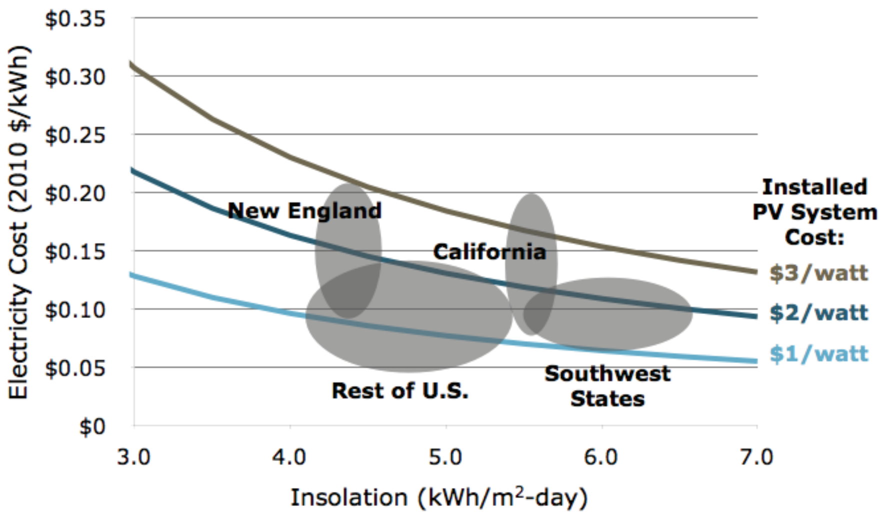


Figure 8. Cost Breakdown of Conventional PV Systems

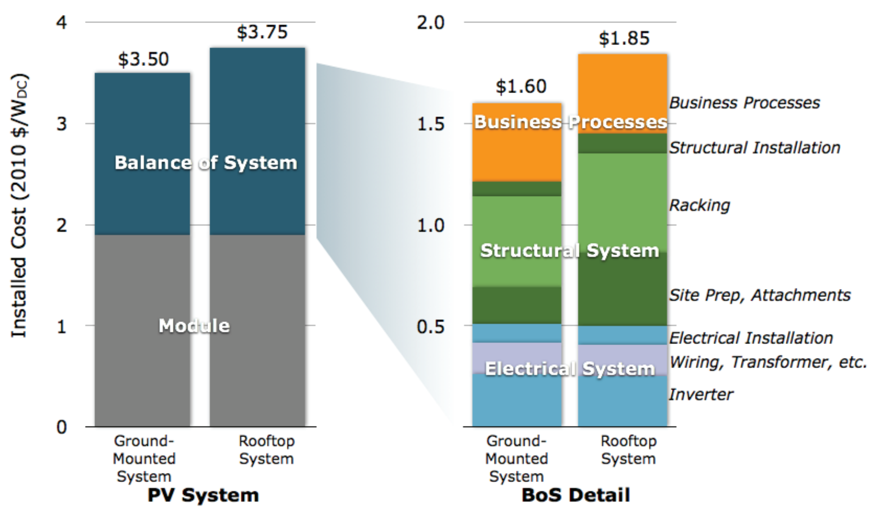
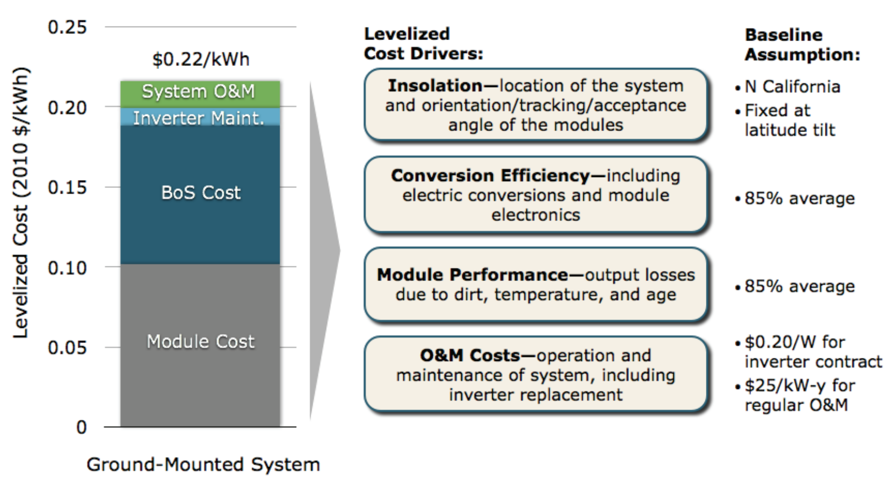


Figure 9. Levelized Cost Breakdown of Conventional PV System



[21] Source: RMI analysis of state demand, cost, and insolation data from EIA Form-826 Database.

Reduced BoS costs have long been recognized as an industry need, and significant progress has been made to develop efficient designs, streamline processes, and standardize approaches. However, best-practice BoS costs still need to come down by roughly a factor of three if solar PV electricity is to compete with grid electricity.

As PV technologies evolve (e.g., flexible panels), innovative BoS strategies may emerge in response to differing design requirements. However, with conventional rigid modules accounting for more than 95 percent of today's market, BoS solutions tailored to today's industry are needed.

The Solar BoS Design Charrette[23] Convened Prominent Industry Experts

In June 2010, RMI organized a design charrette (in San Jose, CA) focused on cost-reduction opportunities for commercial/small utility PV-systems' BoS. The charrette brought together more than 50 industry experts around a facilitated agenda of plenary sessions and working breakout groups. The charrette addressed cost challenges and emphasized collaboration and taking an end-to-end view of the industry. The group focused on technology and process solutions for conventional rigid modules on large commercial rooftops and ground-mounted systems up to 20 MW in size. The participants worked toward an aggressive goal of $0.50/watt, which is roughly aligned with a levelized cost of electricity metric of $0.04/kWh (for the BoS only, including maintenance considerations, using the assumptions listed in Figure 9). At the end of the charrette, results were presented to a committee of experts for feedback.

A "Systems Approach[22]" to BoS Cost Reduction

Key Takeaway: *The lack of a "silver bullet" technology solution for cost reduction and the many steps in the value chain suggest that an end-to-end value chain (i.e. systems) approach be pursued in order to prioritize implementation of the opportunities. A system-wide approach must encompass physical design, business processes, and the scaling of the industry.*

Numerous Opportunities Exist for BoS Cost Reduction

Charrette participants confirmed what most in the solar industry already know. The entire solar industry is still relatively immature, and **there are many opportunities for cost reduction.** These opportunities include spreading existing best practices, launching innovative ideas, and optimizing ground-mounted structural systems, rooftop structural systems, electrical systems, and business processes.

There is no "silver bullet" technology solution to the challenges of BoS cost reduction. PV-system costs are driven by racking materials, electrical systems, installation labor, and business processes—there is no single, near-term technical lever the industry can pull. In next-generation systems, high-impact solutions could take the form of building-integrated systems or new photovoltaic devices. However, such approaches are still far from being widely commercialized and adopted.

PV systems need to be individually designed. Conceptually, one way forward for the PV industry could be to adopt a completely standardized model, where a fully built standard product is sold to customers. However, a one-size-fits-all approach is not adequate—differences in climate, site topography, and sunlight obstruction necessitate at least a basic level of design optimization. To achieve economies of scale, mass customization will be required whereby common parts and approaches can be readily customized for different locations.

A Systems Approach Is Needed

With hundreds of possible design improvements and in the absence of a single scalable best-practice solution, **a systems approach** must consider improvements across the value chain. A systems approach spans the entire value chain and players, and considers improvements for one component or process in light of their impacts on or synergies with other elements of the system. In

[22] A systems approach spans the entire value chain and players, and considers improvements for one component or process in light of their impacts on or synergies with other elements of the system.
[23] See footnote 1.

PV-system design, this complex optimization problem links effects on module design, racking, and electrical system designs, process and permitting time, risk and financing, system performance, and operating costs. For example, the decision to install a tracking system must include several considerations: increased energy output, the expected increase in first cost, the increase in construction time, the impact on risk, and the likely increase in maintenance costs. Similarly, a design engineered for optimal margin of safety (to reduce structural or electrical cost) could increase permitting time and system cost.

A **levelized cost of electricity** ($/kWh over the system's useful life) **metric is necessary** to evaluate system-level trade-offs. Installed cost per watt, while commonly used to compare designs, is inadequate for system optimization. As seen in Figure 10, levelized cost is driven by several factors in addition to the broader issues of safety and scalability.

The Proposed Optimization Approach Spans Three Interlinked Focus Areas

As Figure 11 illustrates, efforts are needed in three main areas in order to make PV BoS cost-effective. This report analyzes opportunities for cost reduction in and between those areas, including recommendations on next steps.

Figure 10. Inputs to Levelized Cost of Electricity Calculation

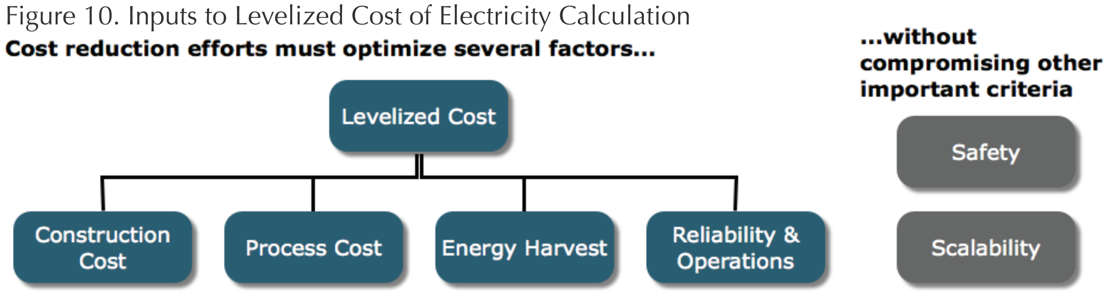
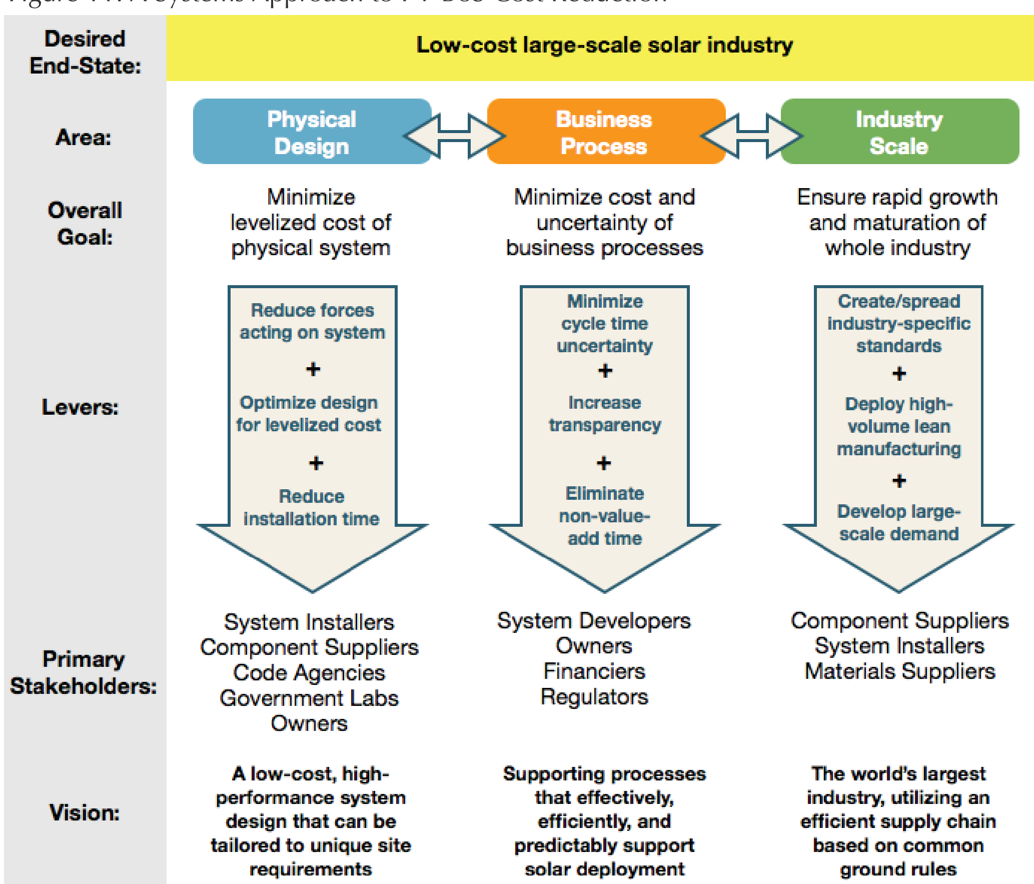


Figure 11. A Systems Approach to PV BoS Cost Reduction



II. Physical System Design: Minimize Levelized Cost

Current State and Design Objectives

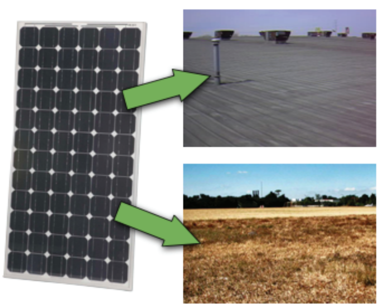
Key Takeaway: *The physical system costs (including installation labor) account for roughly 75 percent of the BoS costs[24] (and roughly 35 percent of total PV-system costs).[25] Physical system costs are divided between the structural system, which holds the modules against natural forces (e.g., wind, gravity, etc.) over the life of the system, and the electrical system, which aggregates power from the modules and connects it to the grid.*

The physical system design and construction, including manufacturing or purchasing components, preparing the site, and installing and connecting the system, drives the majority of PV balance of system costs. As seen above in Figure 8, these costs include the labor and components (including racking, wiring, foundations, and inverters) associated with the structural and electrical systems.

Though structural and electrical systems' costs are similar, the electrical costs are dominated by the inverter, which accounts for about half the electrical system cost. On the other hand, structural costs are highly variable depending on the site and structural design. In general, site preparation (including grading, foundations, and/or roof penetrations) and structural components drive structural costs; labor costs can also be important, depending on markets and installation types.

The structural system supports the module throughout its useful life by resisting natural forces and discouraging theft, in addition to maximizing solar exposure. As seen in Figure 12, the structural system design must address interrelated criteria.

Figure 12. Structural System Design Objectives



Design Objectives for Structural System

- Minimize cost—$/W and $/kWh
- Maximize solar exposure and module performance
- Resist forces—downward (gravity, snow), uplift and lateral (wind)
- Maximize lifespan/reliability—as long as the module: 25 years
- Ensure safety—for installers and O&M staff)
- Support scalability (installability, supply chain, sustainability): thousands of systems, tens of millions of modules per year

Figure 13. Common Structural Designs

	Foundations/attachment	Ballasted	Tracking
Ground-mounted	 **Description:** Mounting system attached to concrete foundation	 **Description:** Mounting system relies on the weight of the array, racking system and additional material	 **Description:** A device continuously orients the module toward the sun to increase its effectiveness
Rooftop	 **Description:** Mounting system penetrates roof surface and attaches to building framing	 **Description:** Mounting system relies on the weight of the array, racking system, and additional material	 **Description:** Same as above, but due to weight and space restrictions, tracking devices on rooftop are relatively rare

[24] $1.60/watt used at the charrette for a ground-mounted system.

[25] $3.50/watt used at the charrette for a ground-mounted system.

Figure 14. Electrical System Design Objectives

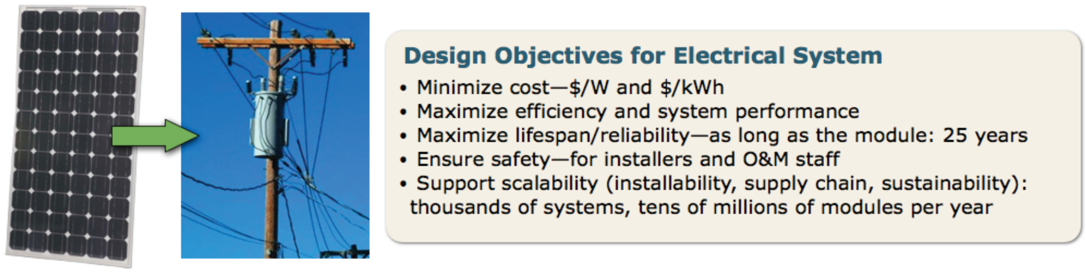
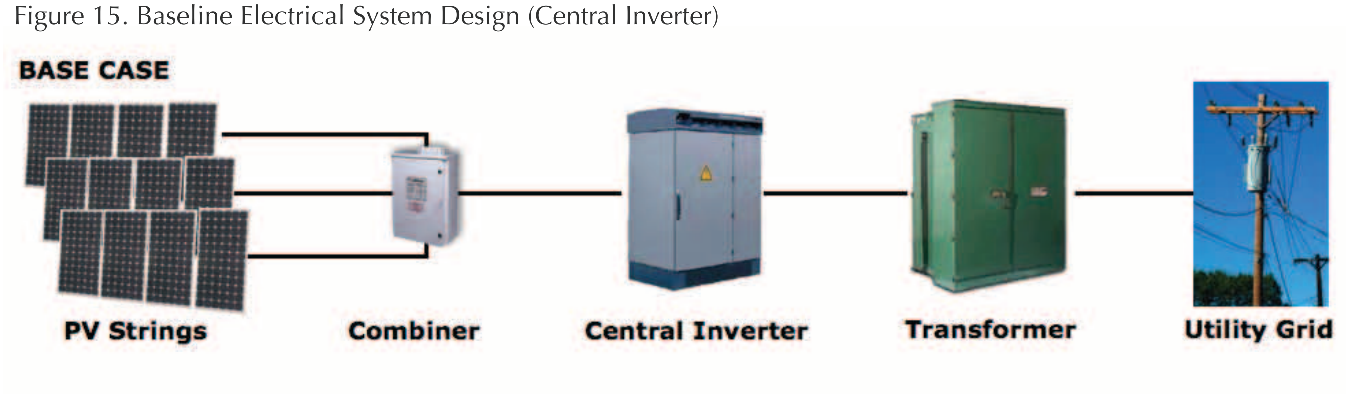


Figure 15. Baseline Electrical System Design (Central Inverter)



In response to these criteria and to the inherent differences between ground and rooftop sites, module technologies and different structural approaches are employed, as summarized in Figure 13.

The electrical system collects power from the modules and transfers it to the utility grid. To ensure overall reliability, the electrical system must also provide data and offer ease of operability to system managers. Electrical system design constraints, highlighted in Figure 14, center on ensuring the cost-effectiveness, reliability, and safety of the system.

There is a wide range of system architecture solutions that can meet these criteria. Figure 15 provides a simplified diagram of a baseline electrical system. In this configuration, power from individual modules is aggregated into DC "home runs", which deliver the power to a central inverter, where it is converted to AC power synchronized with the utility grid.

The charrette examined in detail approaches to reduce the structural and electrical components of LCOE while still meeting the design goals described above. The following subsections offer a description of how charrette participants broke down the design challenge and a summary of key insights and areas of opportunity.

Structural System Offers Potential for Improvement

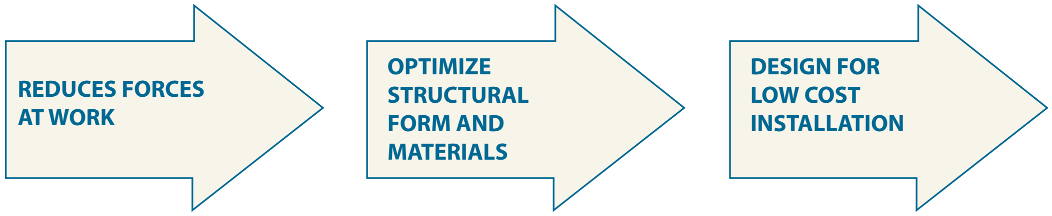
Key Takeaway: *Structural systems for rooftop and ground-mounted PV systems offer significant potential for cost reduction. Charrette participants focused on reductions driven by designs that most effectively handle wind forces and optimize labor productivity. At a conceptual design level, progress in these areas coupled with other incremental improvements could yield a 50 to 70 percent cost reduction.*

For best practice utility-scale installations, the structural system (including site prep, foundations, racking, and installation) costs roughly $0.70/watt. For rooftop systems, best-practice costs are higher, at roughly $0.95/watt.

As seen above in Figure 13, design strategies for both types of systems include ballasted, fixed ("attached"), and tracking[26] systems though rooftop structural designs pose an additional set of challenges to ground-mounted designs. Despite these differences, a common set of design principles applies across the board. The simple flow chart in Figure 16 provides a high-level strategy for structural system optimization. With the overall goal of minimizing levelized cost of electricity, an efficient design approach will:

[26] For several reasons, the charrette did not focus on tracking systems.

Figure 16. Framework for Structural System Optimization



1) reduce natural forces acting on the structure; 2) develop an efficient structural design optimized to handle the reduced load; and 3) reduce complexity for streamlined installation. To be successful, the process needs to be iterative and take into account the electrical system's design, business process implications, and scalability.

Within each of these areas, charrette participants identified strategies to push designs beyond the current state of the industry. In particular, participants highlighted specific ways to cut costs by reducing installation time and improving wind handling characteristics, as discussed in the following subsections.

Reduce Forces at Work

The first step to reducing structural cost is to minimize the forces (or the effects of those forces) that establish criteria for the physical design. In some cases, the effects of these forces can be minimized through design (e.g., a wind fence around a ground-based site could reduce the peak wind pressure). In other cases, overly conservative design criteria are dictated by codes or standards (e.g., ASCE standards do not allow wind-blocking devices to be taken into account when designing PV systems to resist gusts).

In addition to wind there are a several other forces that also influence structural design:

- Snow loads;
- Seismic forces;
- Weight of the structure; and
- Risk of theft.

Optimize Structural Form and Materials

Once the right design criteria are established, the structural designer can focus on form and materials choices. Easily deployed structural designs contribute to efficient business processes and industry growth. In particular, lightweighting can offer value by opening rooftops that may not be capable of supporting heavy structures up to solar development. Key opportunities in this category include:

- Designing lightweight systems, especially for roof tops
- Selecting the most appropriate material (e.g., steel, aluminum, plastics, or other materials);
- Maximizing the solar exposure of the modules by using tilt and/or tracking systems;
- Increasing the acceptance angle of modules with surface treatments and/or external optical devices that reflect sunlight onto each module to improve off-axis performance;
- Designing durable structures that will last as long as the modules (or longer, so the structure can be reused with new modules after 25–30 years) in a hot, bright environment.

Design for Low-Cost Installation

In keeping with the systems approach, the design cannot focus solely on components; it must also optimize installation. This is particularly important in rooftop designs where labor is a higher fraction of costs. Strategies discussed at the charrette included:

- Reduced design complexity and part count;
- Customized layout tools;
- Non-penetrating rooftop designs;
- Automated pile-drive systems;
- Tool-less assembly;
- Automated installation;
- Plug-and-play systems.

Accomplishing one or more of the goals listed above may add cost (e.g., a wind fence around the site). From a systems perspective, though, this may reduce the overall levelized cost of electricity through downsized structural components or improved system efficiency. That's why an iterative process is critical.

Many of the recommendations made at the charrette considered designs already being developed or tested. However, challenges exist in scaling up and pushing these solutions as far as possible.

Two particular areas—designs that address wind and installation labor time—warrant a more detailed analysis due to their importance in driving system costs and the fact that a single value-chain stakeholder cannot resolve them.

Opportunity 1: Efficient Design for Wind Forces

Structural engineers at the charrette estimated that if wind never blew, up to 75 percent of structural costs could be eliminated. Wind forces are a major cost driver for both rooftop and ground-mounted systems in all climate regions. While completely eliminating wind forces is unrealistic, even minor reductions in the wind load can decrease costs and increase the number of roofs available for PV.

Charrette participants estimated that a 30–35 percent reduction in wind forces is achievable for a ground-mounted system not subject to heavy snow. As shown in Figure 17, staggering the arrays, using border fencing, spacing the panels to allow the wind to pass between them, and changing code can increase this reduction. These reductions in wind forces translate into smaller structural systems and associated cost reductions. Research has shown that in some cases, a 20 percent reduction in maximum wind speed can lead to a 20 percent reduction in structural costs.[27]

In addition to the strategies highlighted above, the rooftop and ground-mounted structure groups at the charrette considered a wide range of approaches, from designs that are already used in certain applications to more fanciful ideas. Most approaches are applicable in basic concept to both rooftop and ground-mounted systems, and any given system may draw from multiple ideas. Table 1 summarizes the strategies proposed to design effectively for wind forces.

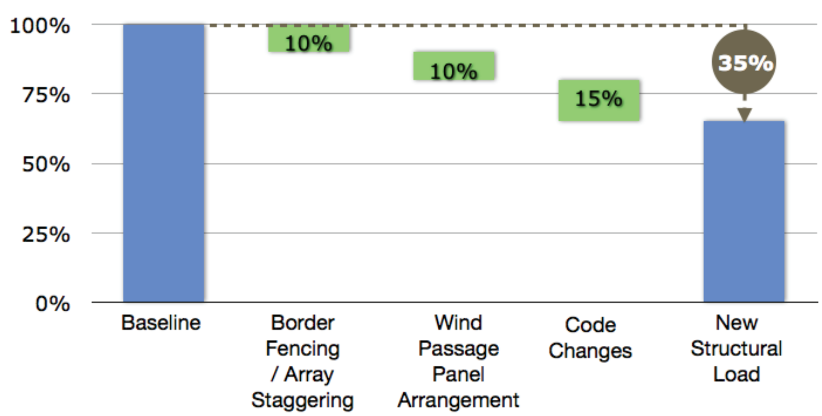
Efforts are already underway to commercialize and promote the widespread adoption of designs that draw from the approaches described in Table 1. A wide variety of approaches are applicable when non-rigid, non-rectangular modules are used—e.g., Solyndra (tube-shaped modules) and UniSolar (flexible modules affixed directly to a roof)—are examples of technologies that substantially reduce wind forces and racking costs.

Efforts to reduce wind forces will affect the entire system, and must be carefully considered. For example, reducing airflow around modules can limit cooling, which in turn can reduce module output and lifespan (a 2005 study published in the *Journal of Renewable Energy* found that reductions in wind speed could result in a reduction of power output by upwards of 10 percent).[28] Also, lowering the tilt angle reduces the angle of incidence, leading to lower power output, while specialized panel-spacing strategies can increase labor time by complicating installation procedures.

Overall, progress is required in several areas to promote the adoption of the ideas in Table 1:

- **Solar-specific codes**—current codes, in particular ASCE-7, were created for buildings and discourage full deployment of wind-reduction strategies. In many cases, ASCE-7 doesn't value the shielding effects of fences or other structures in windy conditions. This affects rooftop systems, where the parapet forms a natural wind block, as well as ground-mounted systems, where the outer rows of modules form a wind block, potentially reducing wind forces to one-third of the baseline design condition at the center of a large array.[29] Changing codes is a long-term effort, as proposed changes must be carefully vetted and risks and safety impacts analyzed. However, the impact on solar cost structures is significant, so this is an important effort.
- **Rigorous wind analysis**—Today's analytical methods—referred to as CFD (computational fluid dynamics)— are often inaccurate by up to 50

Figure 17. Estimated Wind Pressure Reduction from Charrette Design Strategies

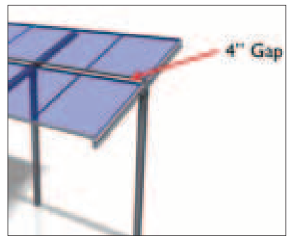
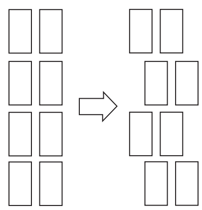
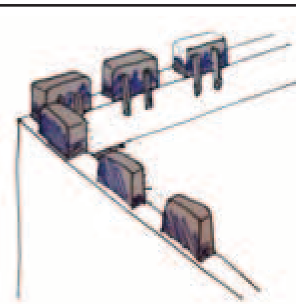
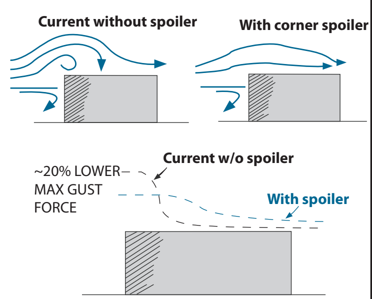


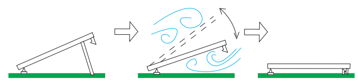
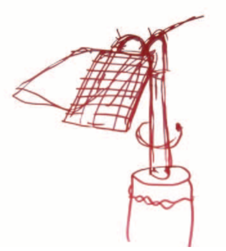
[27] McBean, Robert P. "Wind Load Effects on Flat Plate Solar Collectors." *Journal of Structural Engineering* 111.2 (1985): 343 -52.

[28] Mattei, M., G. Notton, C. Cristofari, M. Muselli, and P. Poggi. "Calculation of the Polycrystalline PV Module Temperature Using a Simple Method of Energy Balance." *Renewable Energy* 31.4 (2006): 553-67. *Elsevier*.

[29] Based on conversations at DOE "$1/W Design Workshop" August 2010.

Table 1. Summary of Wind Mitigation Techniques Presented at the Charrette

General Category	Concept	Visualization	Details
Reconsider the positioning of panels to minimize wind forces	Reduce panel angle to minimize drag forces		Flat panels are less prone to wind uplift than tilted designs. Though this strategy reduces effective wind area, it also significantly reduces electric output. Any cost savings must be weighed from a system perspective.
	Space panels to allow easier wind passage		If wind is allowed to flow through gaps in the array, wind pressures are reduced; the entire array will act less like a single large sail.
	Design system layout to optimize airflow around panels		Shift panel and/or row spacing to reduce wind lift and drag, for instance by staggering the modules as seen in the visualization.
	Optimize panel size		Develop smaller panels to reduce wind lift and drag by providing a smaller surface exposed to wind forces
Passive Control: Use auxiliary technology to reduce or redirect wind forces	Install deflectors, fences, or wind-screens to block wind		Wind barriers at the perimeter of an installation can effectively reduce wind forces on the modules. Though deflection devices add cost and time, increases may be offset by reductions in overall structural cost and complexity.
	Install spoilers to reduce turbulence experienced by panels		Spoilers on the corners of the array or mounted directly on the panel can reduce peak wind forces.
	Install micro wind turbines on rooftops to shield PVs		Placing small-scale wind turbines inboard of parapets on rooftops can generate electricity while shielding PVs from some of the wind force.

Active Response: Design systems that respond dynamically to wind	Use controlled failure mechanisms to actively mitigate wind forces.		The first gust above a pre-determined speed can cause the array to transition to a latched-flat safety mode. In concept, this is similar to the ability of wind turbines to furl their blades to prevent damage at high wind speeds.
	Develop biomimetic design strategies		Panels hang on curved posts like leaves and can shift in the wind to absorb forces. However, additional technology development, design, and testing are required to develop cost-effective, reliable systems using such flexible, compliant structures.

percent. As such, codes require wind-tunnel tests to verify the integrity of innovative structural designs. A set of industry-standard wind-tunnel tests is needed to ensure the efficient use of testing efforts, while the increased sharing of test results across the industry may expedite changes to code that reduce conservatisms and allow for more efficient designs. In addition, the continued development of better CFD tools will improve designers' ability to use the levers described above.

- **Quantitative integrated design tools**—integrated modeling tools have an important role to play in the evaluation of the trade-offs between tracking systems, tilt angles, labor times, permitting requirements, and other factors affecting the LCOE. Though some companies have developed these tools in-house, design-decision trade-offs stretch up and down the value chain. Open-source tools would let policymakers, industry organizations, code agencies, and standards bodies take a systems view of the impacts of design decisions.

Opportunity 2: Rapid Installation

Variable site conditions, complex racking systems, and specialized tasks contribute to high labor costs for both rooftop and ground-mounted PV systems. As structural component costs fall, labor costs, which currently account for 4–5 percent of BoS costs, could grow in significance. Furthermore, lengthy installation times limit the number of experienced and available workers and managers, further challenging the industry's ability to scale rapidly.

Charrette participants discussed several approaches to increase installation efficiency. On a baseline 10 MW ground-mounted system that take nine weeks to install, pulling the levers described below could reduce total installation time by nearly 40 percent—to 5.5 weeks. Figure 18 shows the contributors to this reduction based on charrette estimates, recognizing that some of the activities actually occur in parallel and thus may last longer than indicated.

Figure 18. Ground-Mounted System Installation Time

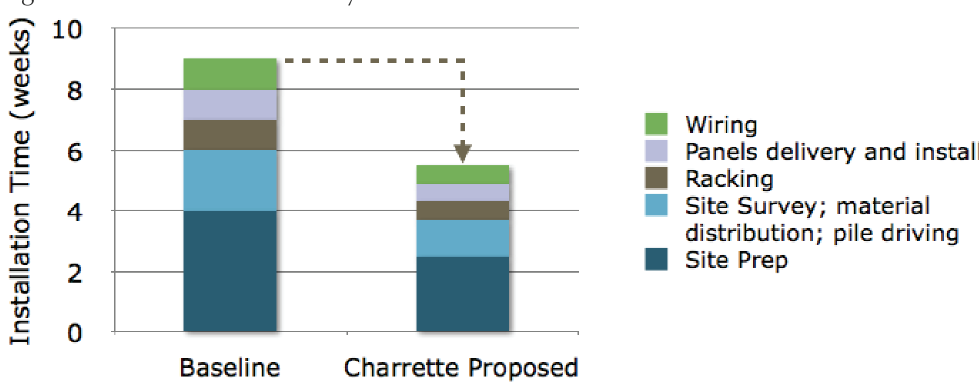
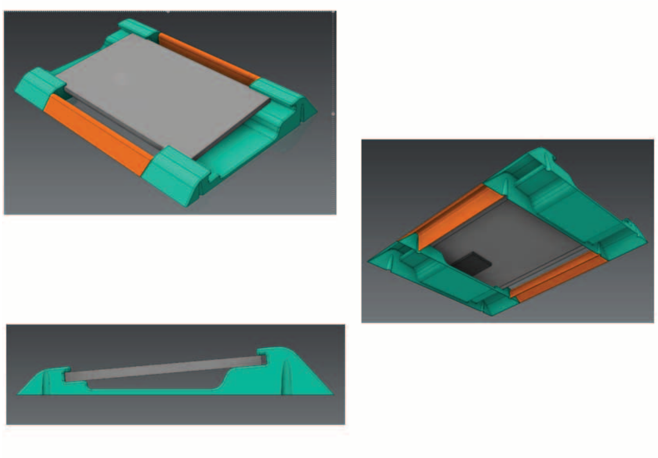


Figure 19. Rendering of Lightweight Plastic Rooftop Conceptual Design



The following strategies could streamline installation and reduce costs:

- **On-site assembly line**—in a temporary on-site assembly line, panels, including wiring hookups, are preassembled on crossbeams. From a specially designed truck, an automated crane installs "super panels" on the racks.
- **Automated pre-assembly**—the panels are connected to each other like the bellows of an accordion and dropped from a truck onto the ground. Although the fully automated installation of mounting systems, modules, and electrical components would save on labor, there would be associated costs (R&D, prototyping, manufacturing) and tradeoffs (loss of agility and versatility).
- **Tool-less assembly**—simple system connections are utilized to eliminate the need for specialized installation tools.
- **Module-integrated wiring (in concert with specifically designed racking systems)**—module-integrated wiring could reduce electrical installation time, and potentially eliminate the need for home-run wiring.

Several of these rapid installation strategies and tactics are currently being pursued by best-in-class component manufacturers and installers. However, there are opportunities to further spread and integrate these approaches.

Sizing the Prize: Conceptual Designs

Charrette participants developed several low-cost, highly scalable conceptual system designs drawing from the opportunities outlined above.

Plastic Lightweighting for Rooftops (Figure 19)

To minimize weight on a rooftop, this design concept uses a lightweight plastic structural system. The shape of the structure reduces wind forces, therefore minimizing ballasting requirements. Electrical connections are integrated into the frame of the panel. The system is designed to be highly flexible—varying amounts of ballast can be added in response to local wind conditions; alternatively, the system can be directly attached to the roof. The mount is designed to spread the weight evenly across the roof while allowing airflow to cool the modules. The parts connect the ends of the modules, but the module itself supports its own weight, reducing racking cost.

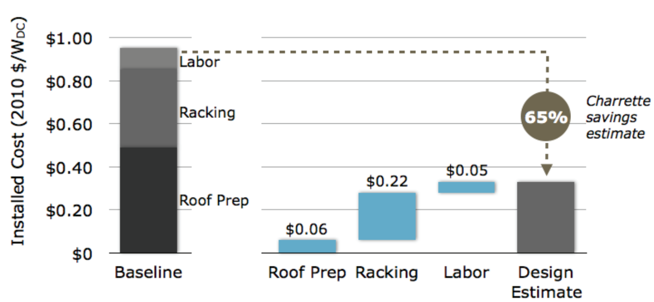
This design approach offers a number of important benefits. By opting for a non-penetrating plastic structure, a very simple system that reduces labor costs and the materials required can be designed with few components. The plastic material reduces the need to install a grounding system. In addition, the small weight of the structure offers opportunities to install PV systems on roofs that could not support heavier systems, potentially expanding the scalability of the design.

This design is similar to SunPower's T5 and T10 roof tiles as well as other racking technologies being developed for large rooftop installations.

At the charrette, a more optimized approach was considered in which the panels in the center of the array—which are exposed to less wind—could be tilted at a steeper angle to increase solar exposure.

Overall, rough cost estimates performed at the charrette suggest that major reductions may be possible from current structural costs, as shown in Figure 20.

Figure 20. Cost Estimate for Plastic Rooftop Systems



Note: Figure 20 *indicates the size of the opportunity and should not be taken as a detailed cost estimate for a specific design. To fully evaluate the feasibility of this design, additional research is needed, including in the areas of roof drainage, theft prevention, and fire code compliance. The baseline design estimate is for a conventional aluminum rack system.*

Figure 21. Rendering of Steel Rooftop Conceptual Design

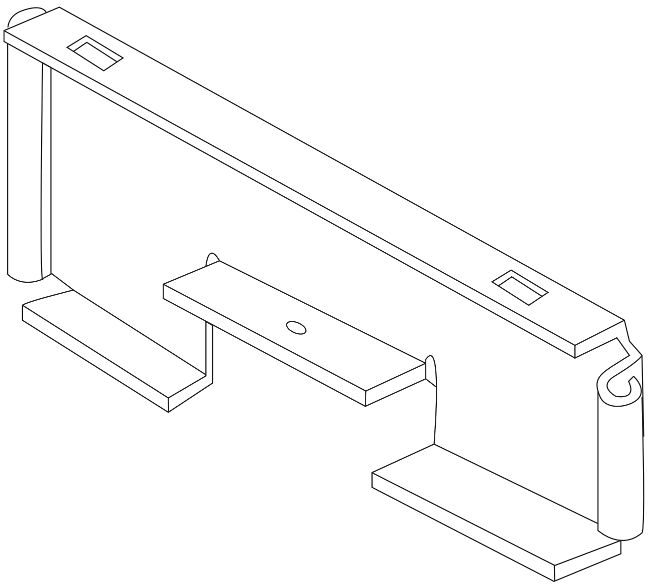
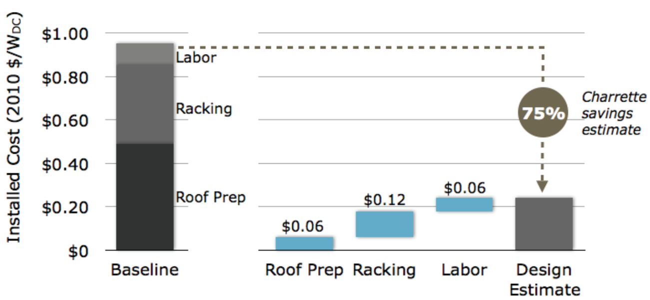
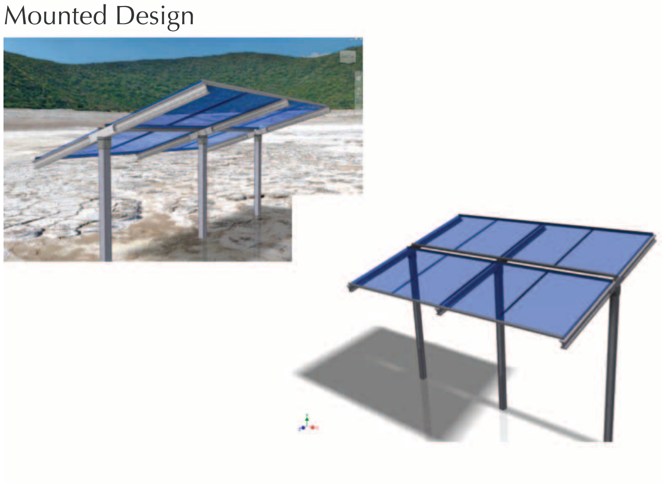


Figure 22. Cost Estimate for Steel Rooftop Design



Note: Figure 22 *indicates the size of the opportunity and should not be taken as a detailed cost estimate for a specific design. The baseline design estimate is for a conventional aluminum rack system.*

Figure 23. Rendering of Proposed Ground-Mounted Design



Steel Structures for Rooftops (Figure 21)

Steel components may offer an opportunity to implement an architecture similar to the one described above, while leveraging higher-volume manufacturing capability and more-durable materials.

This conceptual design uses a stamped steel module mount with built-in interlocking joints between strings. Panels are secured with Tinnerman clips and interlocked together with banana clips. Steel is a widely available and well-understood material, reducing uncertainties associated with the design. Boron steel and carbon fiber may offer additional opportunities. In addition, the steel design offers enough flexibility to be applicable to varying module sizes, ballasting or bolting approaches, and slightly non-uniform surfaces—an important benefit in certain situations.

Challenges that need to be addressed include the conductive nature of steel and the necessity of significant rooftop assembly of individual components. Figure 22 shows a cost estimate for this approach.

Ground-Mounted Galvanized Steel Post Design

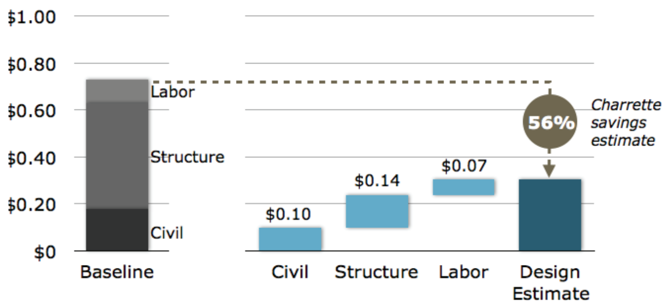
In a scenario where 10 GW of solar PV panels are installed each year using a standardized approach (equating to about 10 million posts per year), the ground-mount group at the charrette developed a design concept that improves on traditional post and top arm structures by using pre-assembled panels with crossbeams and an automated installation process (Figure 23).

This approach resembles current state-of-the-art systems developed and installed by Schletter, among other companies. To save cost, reduced-diameter galvanized steel posts are outfitted with friction-increasing and compliant features to reduce deflection during transportation to the site. The support strut is eliminated and replaced with a freestanding stress-efficient forged aluminum top arm, which is installed and aligned with an automated rig. The aluminum top arm is cost effective in large quantities. The top arm assembly uses mounts with two degrees of freedom and no bolts.

In a temporary on-site assembly line, panels, including wiring hookups, are preassembled on crossbeams. An automated crane installs “super panels” on racks from a specially designed truck. Total installation time is reduced 30 percent, as indicated in Figure 18.

Alternative foundation solutions could be used in soft or unstable soils. These solutions may be used to reset posts that do not pile-drive accurately. These possibilities include traditionally poured concrete piers, shallow-depth or ballasted posts with guy wires and screw-type ground anchors, or preset casings with internal post-alignment features.

Figure 24. Cost Estimate for Ground-Mounted Design



Note: Figure 24 *indicates the size of the opportunity and should not be taken as a detailed cost estimate for a specific design. The baseline design estimate is for a conventional ground-mounted fixed tilt aluminum racking system.*

Figure 25. Design Criteria for PV Electrical System

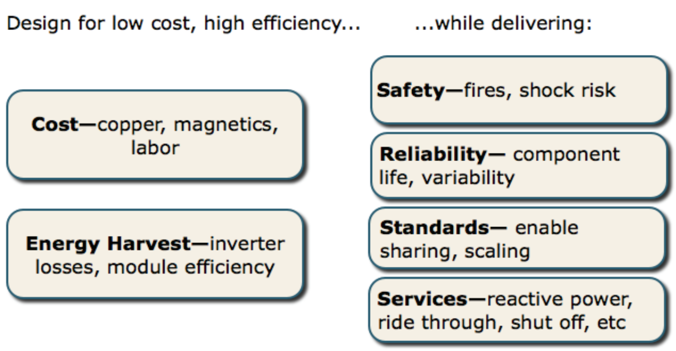
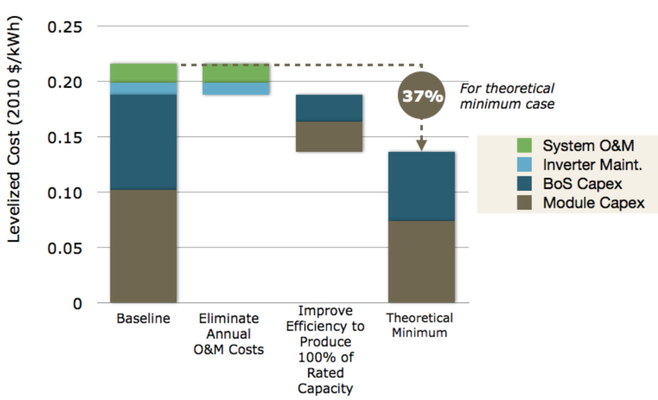


Figure 26. Comparison of Two Hypothetical $3.50/Watt Systems in the Same Location[30]



With high volume installations, significant cost reductions may be achieved over conventional designs, as shown in Figure 24. In particular, large cost reductions can be achieved with structural components, driven by reduced complexity and mass manufacturing (described in more detail in the mass-production section of this report).

Electrical system redesign can significantly reduce costs

Key Takeaway: *PV electrical systems offer some of the greatest potential for cost reduction. Cost reductions are driven by system architecture approaches, performance improvements, and reliability improvements. In particular, charrette participants identified significant opportunities in rethinking aggregation frequencies and voltages and developing new technology approaches such as module-integrated power electronics. With appropriate technology development, these approaches could reduce electrical system costs by 75–90 percent.*

The electrical system is at the core of a PV system's operation. **Its design must be optimized to reduce cost while maximizing energy production.** As highlighted in Figure 25, reducing cost and maximizing energy production have to be optimized in the context of other important factors, primarily: safety, reliability, services to the local utility system, and the alignment of standards with other projects.

To illustrate the importance of efficiency and maintenance on the levelized cost of electricity (LCOE), Figure 26 compares the LCOE of a conventional system to a theoretical minimum design that requires no maintenance cost and no de-rating from its nameplate capacity. These two levers (efficiency and maintenance) offer a nearly 40 percent LCOE reduction *before saving any capital costs.* In the baseline design, operations and maintenance costs alone account for more than 10 percent of the total cost structure, and they could become a much larger percentage as module and non-electronic BoS costs are reduced.

The electrical system design plays a key role in achieving maintenance cost reductions and efficiency gains like those shown in Figure 26. For example, the module's temperature performance is a key contributor to achieving production efficiency improvements. Additionally, the inverter is a source of inefficiency and a major contributor to maintenance costs.
While the inverter plays a key role, **advances in power electronics could result in significant and beneficial changes in the overall system architecture.** This

[30] Assumptions for Figure 26 : fixed tilt system with California insolation; $1.90/watt modules and $1.60/watt balance of system. $0.20/watt up front inverter replacement contract. $25/kW-yr operations and maintenance. Theoretical minimum estimate raises de-rating factor and module performance to 100 percent.

includes the contacts on the module, the aggregation and combiner units, the wiring, and the transformer and other equipment required. On the upside, designing the electrical system is not strictly a cost-reduction effort, as the communications systems and intelligence installed on the PV system can offer significant value to the utility or system owner.

Several concepts emerged from charrette discussions that offer opportunities for electrical system cost reduction and scaling, while balancing optimizations for first cost with the evaluation of energy production and lifecycle cost impacts. These concepts set the context for alternative system architectures.

- **Focus on improving electrical system component reliability to match the modules' expected life time—**power electronics with shorter expected life times (including most inverters) add to project contractual risks and maintenance costs. System and technology designs that ensure performance over time (and reliable testing procedures) are important contributors to industry growth, faster project development times, and lower levelized cost.
- **Leverage scale of mass-produced AC electrical components (and ultimately transition to supply chains dedicated to the solar industry)—**AC combiner boxes and wires are currently produced at large scale, unlike their DC equivalents. Efficient PV-system designs that can utilize these components rather than low-production-volume DC components can capture a cost advantage.
- **Optimize BoS power electronics with module design—**for certain electrical system architectures, there are opportunities to increasingly integrate BoS power electronics functions with module electronics. Specifically, designing power electronics intelligence to match module characteristics may reduce module costs by downsizing or eliminating blocking diodes, module home runs, and backskin material. By some estimates, these opportunities could be worth up to $0.20/watt for systems that incorporate power electronics at the module level. In principle, some of these savings would also be available for intelligent string inverter technologies that can be optimized for their specific sets of modules.

With these high-level objectives guiding improvement efforts, opportunities are available to both adopt new technological approaches and reconfigure conventional system designs.

Opportunity 1: Reconfigure Conventional System Design

At scale, basic changes to typical system design can enable significant savings. High-voltage aggregation and high-frequency switching seem particularly promising.

High-Voltage Aggregation

High voltages reduce resistive losses, and permit the use of thinner wires. Based on estimates from the charrette electrical group, a 30 percent savings in electrical component costs would occur when switching from 600 V aggregation to 1,000 V, stemming from downsizing string wiring, combiner boxes, home-run wiring, and conduit. Based on charrette estimates, home-run wiring and conduit alone account for over $0.03/watt of capital cost savings. In addition, central inverters operating at 1,000 V can run more efficiently than lower-voltage models, offering system efficiency benefits.

High-Frequency Switching

High-frequency power electronics enable new voltage converter, AC inverter, and transformer designs that reduce cost and weight by minimizing the size of iron and steel magnetics. Historically, developing reliable high-frequency power electronics devices has been challenging; with existing materials, miniaturization and component integration are generally only possible in relatively low power applications. However, new materials and circuit topologies offer opportunities to redesign power electronics.[31]

Opportunity 2: New Approaches to DC-AC Conversion

Innovation is occurring quickly in power electronics, offering additional potential for significant near-term changes to conventional electric-system technologies. While a range of new technologies have been proposed, charrette participants focused on integrated module power electronics.

In particular, approaches that convert to AC power at the module or string level offer several advantages. By providing maximum power point tracking services for each module, the overall power output of the facility can be boosted by as much as 25 percent.[32] In addition, a purely AC aggregation system can reduce shock and spark hazards and make systems and mass-produced AC components easier and safer to install.
To be widely adopted, distributed inversion technologies must overcome reliability questions and demonstrate durability equivalent to PV modules'. Otherwise,

[31] The ARPA-E Advanced Power Electronics program is promoting innovation in this area. <www.arpa-e.energy.gov>

[32] This 25 percent estimate is based on promotional materials from Enphase, a leading microinverter manufacturer. This estimate probably applies to residential rooftop systems subjected to shading issues. For larger, unshaded arrays, benefits would be lower, but still quite significant.

replacing inverters at each module would be cost-prohibitive. Many design strategies that address these reliability challenges are under investigation. One, currently developed by Array Converter, would incorporate power electronics components directly into the module, eliminating the conventional inverter entirely (see more details below).

An alternative approach to inversion at the module or string level is the use of DC-DC converters. Like microinverters, DC converters can provide maximum power point tracking at the module level; but they feed into a central inverter architecture. DC converters also face cost and reliability challenges, which are being addressed by many incumbent manufacturers and start-ups.

Sizing the Prize: Conceptual System Designs

The electrical group considered the costs and benefits of various system architecture approaches ranging from conceptual to theoretical. The four concepts considered were:

High-Voltage Aggregation (Figure 27)

Many PV systems in Europe aggregate power at higher voltage; though less common, this approach is also allowed in larger U.S. systems. Precautions must be taken to mitigate shock hazards and arc fires, but with proper safeguards, 1,000 V DC strings can be aggregated to large block inverters in the range of 100 kW. This system design is similar to the baseline case, but it can offer reductions in copper wire use and costs (see cost comparison in Figure 31).

Microinverters Attached to Modules (Figure 28)

An alternative to the centralized inverter approach centers on installing microinverters on each module. This approach, commercialized but not yet widely adopted, offers a way to optimize module performance, however, there are lingering questions regarding the technology's suitability with large-scale plants (as opposed to small, distributed rooftop systems, which have larger shading issues and have been the main market for microinverters). Microinverters convert DC panel voltages to AC at each module, leveraging the benefits of module-level inversion described above. However, current microinverters cost more than centralized inverters, and the prospect of diagnosing and replacing failing inverters on each module halfway through the system's life makes system owners and financiers wary. Charrette participants agreed that these technologies have the potential to reduce cost and increase reliability as designs and manufacturing processes are improved and scaled up. In addition to energy collection improvements, one key benefit of this architecture is that it simplifies system design and installation, since the modules don't need to be organized into strings.

Module-Integrated Plant-Level Inversion (Figure 29)

Moving the AC power conversion as close to the DC photovoltaic cell as possible is an approach developed by start-up company Array Converter. In this design, the entire PV system functions as an inverter, with each module contributing power that is aggregated into an AC waveform. Capacitors on the modules allow the modules to communicate with each other and the AC electric grid to synchronize their output into a form that can be smoothed into AC power. Though this technology still needs to be commercialized and proven at scale, the approach offers large cost savings because the inverter is eliminated entirely, replaced by the intelligence and power electronics components on the module. In addition, this approach may eliminate a major cause of inverter failure—electrolytic capacitors—by replacing them with smaller units based on new technologies. Reliability is particularly important for this system design: the power electronics built into the module must absolutely match the reliability of the module itself. Close cooperation with module manufacturers is required to modify module designs and incorporate power electronics components.

High-Frequency Tesla Solar (Figure 30)

High-frequency system architecture offers several advantages, since high frequency allows magnetic components to be downsized—and downsizing yields large cost savings for the inverter and transformer. This design replaces the inverter entirely with circuitry that converts the 1,000 V DC input to a 10 kHz output (labeled "Tesla Converter" in Figure 30). This concept reduces cost by leveraging several of the design principles discussed above: high frequency to reduce magnetics, high voltage to reduce copper use, string-level inversion to optimize module performance and reduce module cost, and minimization of conversion steps. With most of the system operating in the range of 15 kV and 10 kHz, much thinner transmission wires can be used in place of conventional home-run wires. After aggregating power from the entire site, the final step to grid integration is via a cycloconverter that offers a cost advantage over a conventional transformer. This idea was developed at the charrette; significant design work, testing, and commercialization efforts would be required for it to contribute to PV-system designs.[33]

The four design options show that there are many promising strategies that can achieve significant cost reductions over a conventional system (baseline). Figure 31 summarizes the estimated capital cost of each approach.

[33] This design owes particular recognition to Rob Wills, who developed the concept. In addition, it builds on work associated with DOE's ARPA-E program to develop innovative power electronics designs, including high frequency devices.

Figure 27. 1000V Aggregation System Diagram

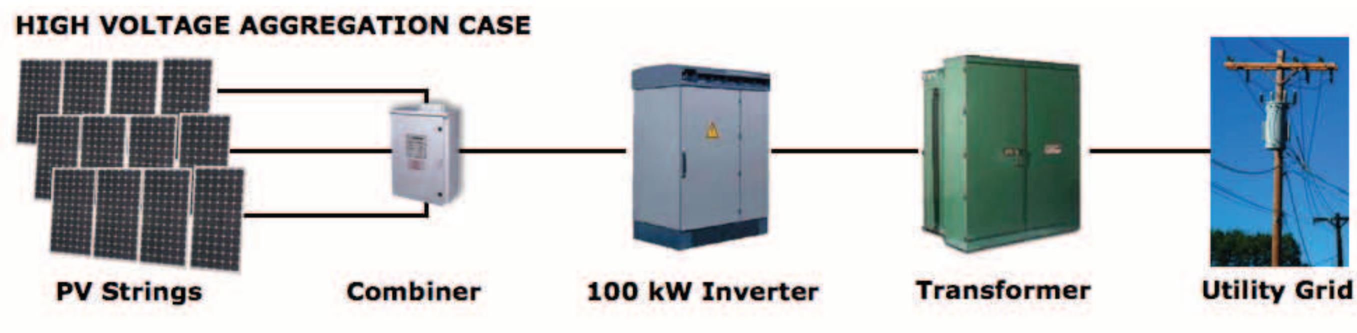


Figure 28. Microinverter System Diagram

Figure 29. System -Level Inverter Diagram

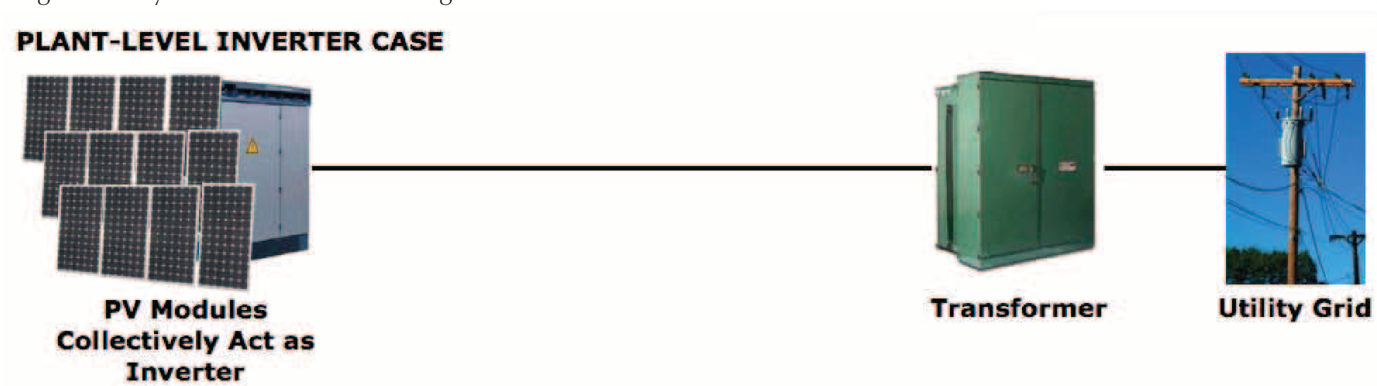
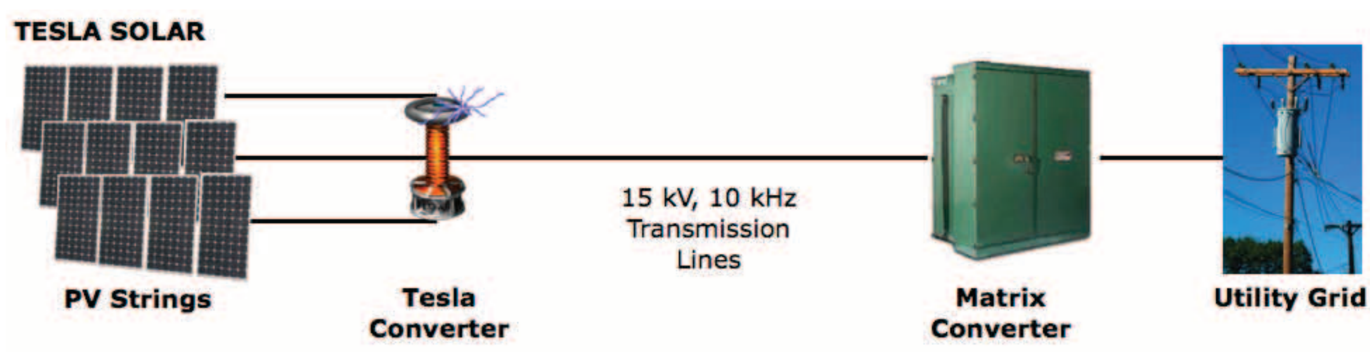


Figure 30. High-Frequency System Diagram



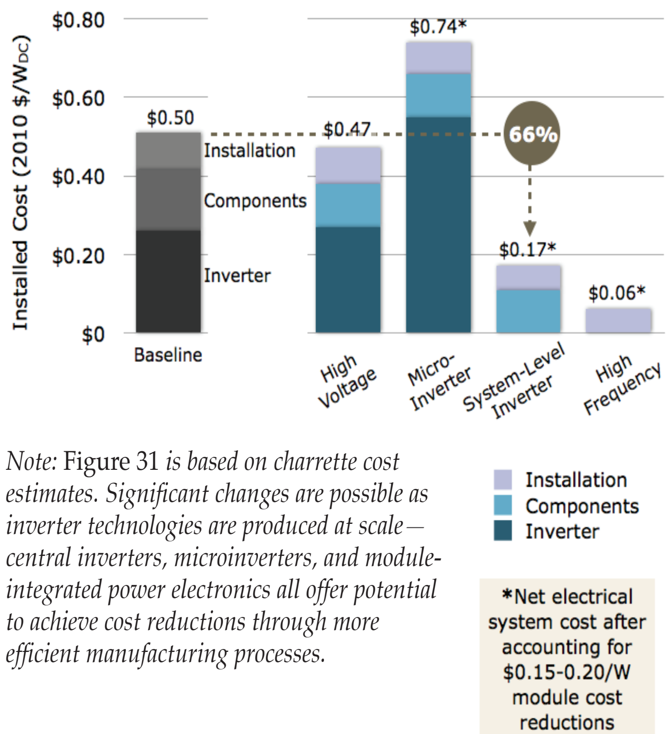
Each architecture has implications for system performance and maintenance costs. As these technologies mature, less maintenance may be required, and inverter replacement costs for centralized as well as distributed inverters could potentially be eliminated. Figure 32 describes the effects of improved system performance, decreased maintenance costs, and reduced capital costs on total system LCOE (for a ground-mounted system using a plant-level inversion design).

A key takeaway from this analysis is that power electronics offer considerable potential for innovation and cost reduction. As new technologies become cheaper and more reliable, they will become major contributors to LCOE goals.

Progress in several areas can help accelerate the implementation of the principles and electrical system designs described above, including:

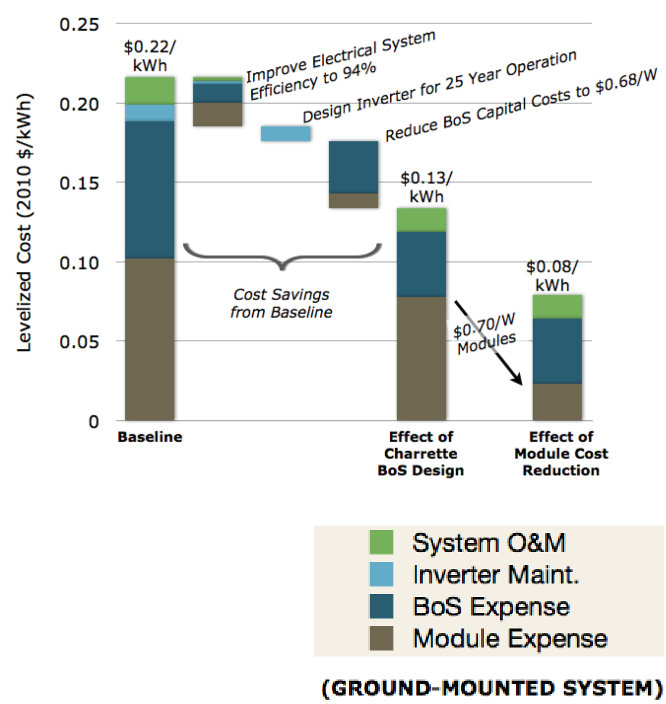
- **Analytical modeling**—so far, there is no clear "winner" in the competition between centralized inverters and microinverters. The value proposition varies based on site-specific requirements and project economics. Part of the challenge for developers deciding between various system architectures is the lack of unbiased modeling tools. Open-source calculators capable of estimating system performance, capital costs, and failure risk could help project designers make informed decisions.
- **Reliability testing**—to inform the technology choices described above, designers need to accurately assess the risk of inverter failure. Risk-averse investors are reluctant to embrace new technologies such as microinverters and DC-DC converters. However, rather than wait until installed systems begin to fail in the field, many industries (such as aircraft manufacturing) use extensive standardized tests to quantify reliability and the failure rates of new designs. Similar testing standards are needed for PV power electronics.
- **Widely use LCOE for system design**—for the electrical system, efficiency and reliability considerations can be as important as capital cost considerations. For LCOE to become a more commonly used metric, customers and financiers must be educated. In addition, established standards should be spelled out in RFPs to reduce confusion among competing project developers using different information for LCOE calculations.
- **Promote design innovation**—as mentioned above, innovative power electronics have the potential to spur substantial cost reduction. To accelerate innovation and encourage new design approaches, a sort of X-Prize could be effective. An X-Prize[34] could be used to reward a system designer who met a pre-established set of performance goals at lowest cost.

Figure 31. Comparison of Capital Cost Estimates for Electrical-System Architectures



Note: Figure 31 *is based on charrette cost estimates. Significant changes are possible as inverter technologies are produced at scale—central inverters, microinverters, and module-integrated power electronics all offer potential to achieve cost reductions through more efficient manufacturing processes.*

Figure 32. Effect of Physical System Design Optimization on Levelized Cost



III. Business Processes: Reduce Cost and Uncertainty

Current State

Key Takeaway: *Business processes[35] are both a cost component of PV BoS and a barrier to substantially higher rates of adoption. Business process costs are incurred at various steps, and they vary significantly between projects because of system size, stakeholder experience, and ownership model. Though additional quantitative analysis is needed, charrette participants observed that current processes are time-intensive, often duplicate effort, and include low-value-added activities.*

Business processes support and enable the construction and operation of PV projects. As a PV project moves from the initial technical and economic assessment to construction and operation, business processes steer PV projects to help them achieve the goals highlighted in Figure 33.

Based on initial estimates gathered before and refined during the charrette, in current best practices, business processes represent slightly more than 10 percent of total project cost, or about $0.39/watt. As shown in Figure 34, these costs are incurred across the six different stages of project development and operation.

Figure 34 represents a best-practice case. Significantly higher costs can accompany more complex projects. Furthermore, the relative sizes of costs, and which stakeholders support or incur them, can vary widely based on project size, stakeholder experience, and ownership model.

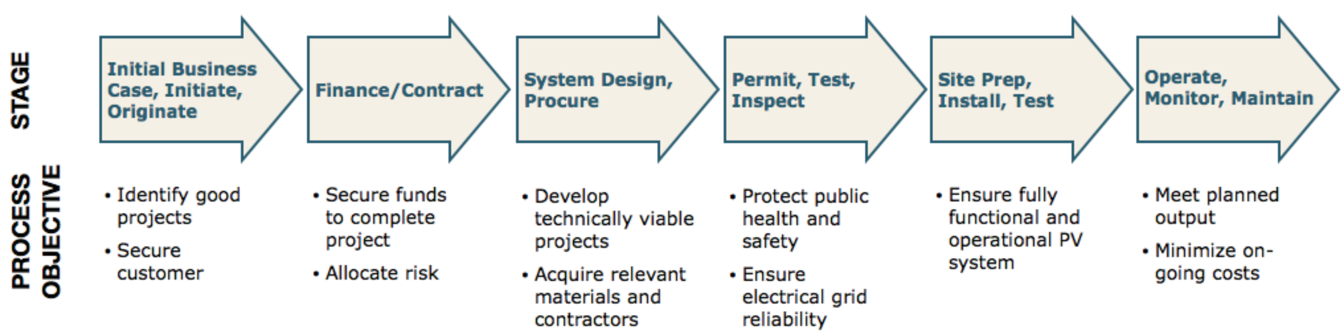
Challenges to Cost Reduction

Key Takeaway: *Business process costs are driven by a lack of information, the customization of each project, often-inexperienced project stakeholders and contributors, and, in most cases, the absence of a single stakeholder with end-to-end accountability. These dynamics make it hard to reduce cost and implement effective processes.*

Solar PV business processes are often cumbersome, time consuming, redundant, costly, and ineffective. This stems from issues related to information, customization, inexperience, and lack of accountability and oversight.

- **The information needed to assess solar site suitability (performance and development) is**

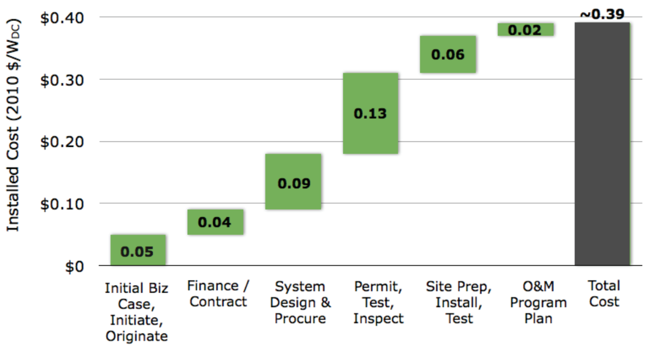
Figure 33. Stages of Commercial PV Business Processes



[34] The X PRIZE Foundation is a non-profit organization that designs and manages public competitions intended to encourage technological development that could benefit mankind.

[35] In this report, "Business Processes" refer to all the enabling processes associated with a PV project, including customer negotiation, contracting and financing, permitting and regulatory approvals, and utility interconnection.

Figure 34: Costs of Best-Practice Commercial PV Business Processes by Stage[36, 37]



Note: Values in Figure 34 *represent charrette participants' estimates of the cost breakdown for a typical large installation. Values may vary significantly between projects based on market dynamics, technology, owner, and system type.*

often unavailable, not easily accessible, or difficult to aggregate—in particular, costs and time requirements associated with permitting (which is jurisdiction-specific) and interconnection (which is utility-specific) may be hard to estimate without local experience. For example, data on grid capacity are not publicly available, making it difficult for project developers to site large projects (tens of megawatts) optimally or estimate interconnection costs for a particular location on the grid. Similar information gaps complicate the task of customers who want to assess developers' qualifications and of system designers, for whom site insolation information is vital. This lack of available information forces developers to invest in expensive and non-replicable due-diligence to evaluate prospective projects. In addition, these challenges breed confusion—notably on the part of the owner (since different bidders may use different input assumptions and models)—and can lead to mistrust between developers, customers, and financiers.

- **Most systems are significantly customized for the specific site where they will be placed**—customization includes the panel technology, the structural and electrical components, and overall system architecture. In addition, customer agreements and financing structures often don't match the size and placement of the PV system. The permitting and interconnection processes and requirements also vary substantially by jurisdiction, utility control area, and state. This customization makes it difficult to broadly apply efficient business processes.
- **Many stakeholders that play a role in solar business processes may be unfamiliar or inexperienced with PV project requirements, technologies, or financing mechanisms—**with PV still relatively rare in many areas, even experienced developers may incur costs stemming from working with inexperienced customers, regulators, financiers, and utility officials.
- **There is a lack of accountability and oversight for the end-to-end business process—**no single stakeholder is responsible for ensuring effectiveness across all stages of solar site development. The existence of multiple actors with distinct (sometimes conflicting) incentives fosters a lack of coordination and results in system-wide inefficiency. For example, customers typically look to minimize LCOE, while developers' primary goal is to maximize revenue, contributing to project dropouts or overpayment. Or municipalities may resist replicating neighboring jurisdictions' permitting requirements in order to shield local businesses from cheaper regional installers.
- **Conventional utility policies and incentive programs may not efficiently promote cost reduction—**in many markets, utility and regulatory policies discourage LCOE reduction or prevent optimal system sizing. For example, net metering programs effectively limit the PV system size to the site demand, potentially thwarting larger PV adoption and cost reduction. In addition, national investment tax credit (ITC) incentive programs are awarded based on total system cost, shifting design focus away from LCOE minimization. Finally, since incentive programs require numerous submittals and approvals, they contribute to business process cost, development time, and project financial risk.

Areas of Opportunity

As the PV industry grows, the challenges described above need to be addressed, and efficient and replicable business processes that support high-volume, low-cost installation need to be promoted. The principles below offer ways to make processes more efficient:

- **Focus streamlining efforts on expensive time—**site evaluation and system engineering have higher hourly costs than many other aspects of the business process. Strategies that minimize repeated site visits or engineering iterations may be cost-effective even if they add to the length of the project.
- **Reduce uncertainty—**uncertain structural, electrical, and utility approvals drive process costs and aggravate project development challenges. On many projects, there is considerable uncertainty surrounding process time as well as the outcome (which often requires additional submittals or another iteration of the review process). These

[36] Process cost breakdown based on estimates from the business process group at the charrette. Additional research is required to verify this estimate and quantify how it varies based on project size, location, and ownership structure.

[37] The finance cost component includes up-front efforts to secure financing. The cost of capital over the lifetime of the project is a separate expense that is embedded in the capital charge rate used to calculate levelized cost of electricity.

uncertainties complicate scheduling and financing. Processes that include clear requirements and timelines will help developers reduce costs.

- **Identify breakpoints**—the speed of the development process is critical when expensive resources are involved, particularly when subcontractors are being scheduled or construction equipment is already on site. Other parts of the process, such as permitting, have lower costs associated with time delays. In order to minimize project process costs, optimization efforts need to decouple the uncertain parts of the process from the known time-sensitive parts.

To achieve these goals, charrette participants focused on reducing project dropout and streamlining low-value-added business processes.

Opportunity 1: Reduce "Dropout"

"Dropouts" are projects that go through initial technical and financial assessments, but are ultimately discarded. Charrette participants agreed that dropout rate is high, with some estimating the rate at 90 percent for some types of projects. These failed deals create an overhead burden that successful projects must bear, inflating total process costs. An important way to reduce dropout is to enhance a developer's ability to gauge the likely success of a potential project.

There are three phases in the development process where a project may fail. First, after an initial site visit, the developer or customer may deem the site inadequate for development. Second, if the site seems adequate, more detailed project cost estimations may lead to a mismatch between potential costs and desired returns. Third, deals that survive initial costing can still fail because of issues involving complex interactions between developer, financier, owner, utility, and suppliers, such as permitting, financing, and procurement. Since projects that fail after the first test (the site visit) do not represent a substantial burden on developers, only the second and third phases are addressed below.

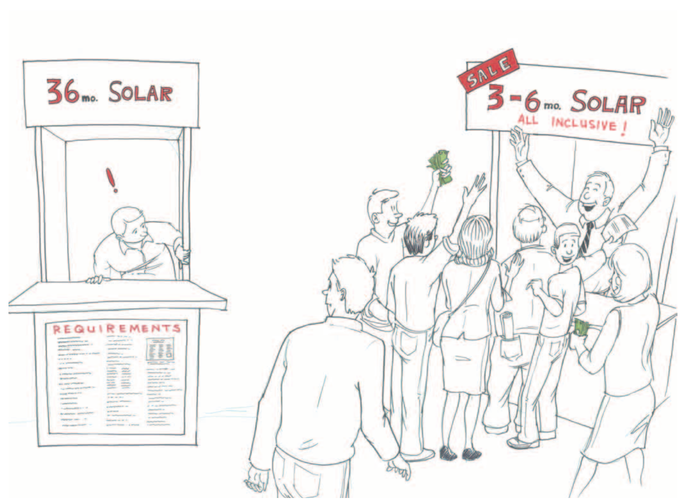
The rates at which projects fail after significant development work has been done vary significantly. For small residential systems, the rate may be quite high. Across the span of project sizes considered at the charrette (250 kW rooftop to 20 MW ground-mounted), dropout rates tended to increase with system size. Rates appear to be comparably low for small commercial rooftop PV systems and high for utility-scale centralized projects that face additional financing, siting, and interconnection hurdles.

Causes of Project Dropout

Projects may fail for a number of reasons, which differ in importance according to project size. In the second period, where dropout occurs because costs and expected returns don't match, dropout is typically caused by a customers' inability to select a developer whose bid meets their expectations. While this may stem from developer inexperience or overpromising early in the process, it is also a consequence of customers failing to appropriately articulate their needs in the initial RFP (request for proposal). When the initial RFP doesn't deliver the proposal a customer expects, multiple rounds of RFPs may follow before a developer is selected and the project moves beyond the initial costing phase.

For projects that progress beyond initial costing, several factors can lead to dropout; almost any stakeholder in the process can be the source these problems.

- **The customer**—problems occur when customers have not secured sufficient internal buy-in to complete the project. Since large PV investments represent new territory for most customers and are expensive, the burden to prove the case for a PV system can be high.
- **The installer**—though there are many installers in the more mature markets (e.g., California), there is still a dearth of well-qualified installers even in those markets. In immature markets, large-project developers often have limited qualifications, and installers often bid on larger or more complex projects than they have delivered in the past. Their inexperience can lead to dropout if they can't deliver the project on budget, they encounter technical problems, they are unable to finance the project, or any number of other reasons. Installer inexperience is a challenge across all system sizes, but it is a bigger problem for small and mid-sized systems. Meanwhile, for large systems, there are far fewer experienced installers.
- **Oversight agencies**—problems with local, state, and federal permitting and utility interconnection



approvals can also cause dropout. Small-community officials responsible for structural and electrical permitting are often unfamiliar with PV systems, making it difficult and time-intensive to secure a basic permit to continue or finish construction. Permitting costs associated with time delays and repeated submittals may make a project uneconomic. Similarly, the interconnection process with the local utility may be expensive if additional equipment or studies are needed to ensure the utility that interconnection of the system will not compromise system reliability. As with local regulators, utility stakeholders may lack experience in large PV-system approval. For ground-mounted systems, state and federal environmental regulations may also cause dropout.

- **Financiers**—for larger systems (10–20 MW and bigger), capital constraints—exacerbated by the world financial crisis—may kill even sound projects. Capital may not be available for large projects, or the demands that capital providers place on developers—in the form of cost of capital and collateral—may prove unacceptable. Capital availability is less of a constraint for smaller projects and rooftop systems. While certain projects cannot be financed due to limited capital availability (as described above), many other projects' (especially smaller systems') inability to obtain financing may reflect one of the other drivers above: customer expectations, stakeholder and/or installer inexperience, or permitting challenges.

Project dropout rates should decline as more installers, customers, and regulators gain experience with solar PV development. To accelerate this decline, an increased availability of information on potential development sites can help developers focus on sites with good potential that are suitable to their experience levels. In addition, the increased education of installers, land/building owners, regulators, and utilities can help reduce dropout. For more information on these needs, see the "Enablers" section below.

Opportunity 2: Eliminate Unnecessary Steps and Streamline Processes

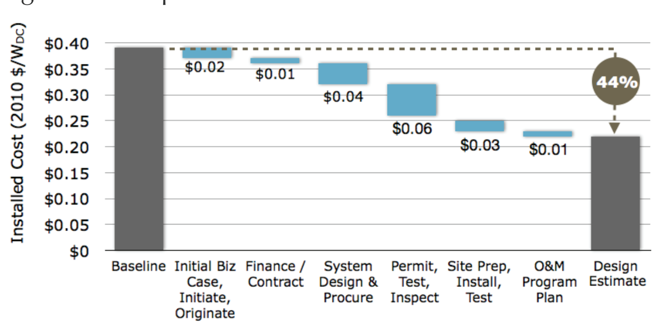
Charrette participants highlighted the significant cost-reduction opportunities available by streamlining the underlying business processes involved in the commercial PV BoS. The charrette business process breakout group considered the processes and associated time commitments for a 1 MW ground-mounted system.[38] Participants also estimated the potential cost reductions from eliminating all delays and non-essential steps (i.e., steps that did not directly contribute to process objectives). With an optimized process, charrette attendees felt the project timeline could be condensed from 24 months to three months—a huge risk and cost-reduction opportunity.

Figure 35 shows a rough estimate of potential savings based on charrette participants' experience. Significant additional work is required to better understand the process cost baseline and reduction opportunities.

Many of the ideas that participants suggested for condensing 24 months to three aligned with broader themes of standardization and education, indicating that these strategies are doubly valuable for their ability to improve process efficiency and reduce dropout.

Standardization is the central component of any plan to dramatically reduce the time and expense of business processes. To streamline business processes, standardization of the entire PV product is needed, from the physical (module, racking, and attachment) to the per-

Figure 35. Proposed Reductions to Business Process Costs



Note: Values in Figure 35 *represent charrette participants' estimates of the cost breakdown for a typical large installation. Values may vary significantly between projects based on market dynamics, technology, owner, and system type.*

[38] Private land, self-owned, self-financed, net metered.

mitting and interconnection requirements, to the agreements between developers, financiers, and customers. Standardized businesses processes help create a level policy and regulatory playing field across geographies, reducing barriers to entry and increasing industry growth. However, the implementation challenges are significant. With 50 states, over 3,500 hundred utilities, and thousands of city and regional planning agencies lacking incentives to respond directly to a market need, a massive effort is required to increase uniformity across jurisdictions.

Enablers of Business Process Optimization

Tackling three general areas—information, standardization, and education/experience—will help address the causes of dropout and challenges of business processes more broadly.

Information

If customers and developers had perfect information, many causes of dropout would disappear. For example, a large commercial PV project may be derailed if the developer finds that the costs to interconnect the system are significantly higher than expected due to required studies or required structural improvements. Better information on potential sites for commercial PV that offer grid connectivity could significantly reduce that kind of failure. Southern California Edison has picked up on this issue, and is identifying preferred areas for solar development within its service territory. Building on the idea of providing better information on potential sites, charrette participants conceptualized a "National Solar Site Registry" (NSSR). The NSSR would compile and disseminate relevant information for site assessment, including:

- Insolation (NREL);
- Current and historical electricity rates and trends (DSIRE);
- Geography/topography;
- Soil content;
- Wind history and trends;
- Seismic activity;
- Electrical grid capacity;
- Retail electricity prices;
- Site ownership (Tiger GIS database); and
- Ease of developing solar sites (based on jurisdictional regulations, and permitting requirements).

In addition to compiling and disseminating this information, the NSSR could use accepted models to evaluate sites and provide a site rating based on developability (how likely is it that a deal will be completed given all relevant factors) and production potential (likely kWh/kW-y output). These ratings could become key information for both the underwriting process and the customer acquisition process. By standardizing information and evaluation, the NSSR could eliminate much of the subjectivity of site assessment and reduce the dropout rate by highlighting differences between developer, customer and financier. It would also reduce the likelihood that developers would unknowingly pursue PV projects with low output and/or poor development prospects.

The NSSR or another independent organization could also rate installers. Based on an evaluation of completed projects—and perhaps modeled on the work of JD Powers in the automobile industry—this installer rating system could offer customers additional insight into the industry and help them make more robust purchasing decisions.

Standardization

The current lack of standardization in the commercial PV market complicates the permitting and approval process, and it increases the complexity of negotiations between customer, developer and financier, contributing to late-stage dropout. Standardizing system components and project valuation and analysis procedures (as suggested in the NSSR) will reduce the chances of permitting delays or failures in customer or financing acquisition.

SolarTech, an industry-supporting non-profit, and DOE have made strides in standardization. SolarTech is piloting a standardized power purchase agreement (PPA) and DOE is advocating that jurisdictions adopt uniform permitting requirements through its Solar ABCs program. For these efforts to take hold, widespread support from industry and regulatory stakeholders is essential.

The success of efforts to standardize PPAs and permitting requirements is linked and possibly contingent on better standardization across panel, structural, and electrical components. Based on this concept, participants discussed the possibility of Underwriters Laboratories (UL) certifying pre-designed systems in the factory. Standardizing and certifying system designs and parts might eliminate the need for some permitting since officials would know that the design conformed to a certified specification and was approved for a certain application (e.g., a roof with a given load-bearing capacity).

Education and Experience

Although PV systems have been around for decades, the technology is evolving rapidly and adoption is still in its infancy. Therefore, the education and experience of developers, customers, financiers, utilities, and local jurisdictions have an important impact on project costs and dropout rates.

Improving the education of customers could reduce the number of RFP iterations required to seal workable deals. Moreover, educated customers would be better able to pick capable developers. For developers, improved experience and education with commercial PV will improve the chances of completing projects and offer them a greater ability to obtain financing. For utilities and governments that must approve PV projects, improved education and greater experience will make it easier and quicker to reject and accept projects or ask for further information. Charrette participants placed extra emphasis on the need to educate local permitting officials on the basics of PV.

As all the stakeholders in the commercial PV market march up the learning curve, capital providers will find it easier to assess project risk and develop enough confidence in project teams to make loans. As stakeholders become more experienced, there will be less need for the site information offered by the NSSR (described above) because developers and customers will be more capable of assessing project feasibility at the outset. Furthermore, as education and experience increase, the value of information will grow as customers and developers become better-able to use it wisely and less likely to run into inexperience-related barriers.

IV. Industry Scale—Ensure Growth and Maturation

The solar PV industry needs to adopt a high-volume mentality and approach as it transitions from a "craft" industry to one of the world's largest. This will change the way suppliers and installers interact with each other and with customers, utilities, and regulators.

Current State

The PV industry has grown substantially in recent years. With more than 10 GW of PV installed globally in 2010, the industry is producing roughly 50 million PV modules per year and growing quickly. In addition to small, residential rooftop systems, modules are being installed on thousands of large and/or commercial rooftops and at ground-based sites, industry analysts predict continued rapid growth.

While significant economies of scale have been achieved as the industry has grown, lean production expertise has been primarily focused on module manufacturing. To a large extent, the BoS industry has resisted efforts to lower costs by commoditizing and consolidating. In a subscale industry, high levels of customization are appropriate for maximizing product innovation and addressing site- and project-specific design constraints. However, the industry's rapid growth suggests that things are about to change.

Areas of Opportunity

More-standardized BoS designs can help the industry scale up while reducing costs through high-volume production. The challenge is to strike the optimal balance between standardization—which leverages economies of scale—and innovation while meeting site- and customer-specific requirements.

Opportunity 1: Increase Standardization of Modules and Components

"Standardization" has a wide range of connotations, as shown in Table 2. As the table indicates, this report chapter is primarily focused on standardized components for BoS designs, though other themes are indirectly applicable. The process chapter contains a more detailed description of the importance of business-process standardization efforts.

Increased component standardization cut across the structural, electrical, and business-process groups at the charrette:

- **Standardize module form factors and connections—** set standards to promote common module dimensions and connection points, which will reduce labor requirements and allow balance of system components to adapt to different constraints.
- **Standardize structural component interchangeability—**set standards that allow different structural components to work together so that industry competition gets promoted and structural and labor costs are reduced.
- **Integrate structural designs with specific module technologies—**while it will be difficult to standardize modules in the near term, there are opportunities to develop structural systems for specific types of modules (or standard groups of modules).
- **Standardize electrical interconnection and communication—**set standards for electrical

components that are aligned with widely used codes, such as ASCE and IBC. In addition, build on existing efforts to promote common data-collection and monitoring approaches.

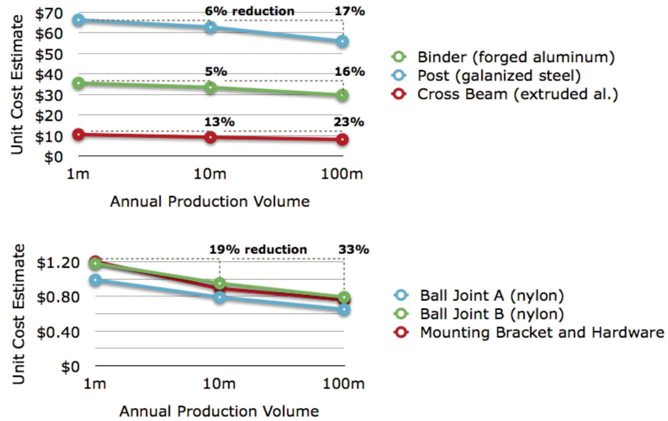
Component standardization can affect nearly every cost in some way—including labor costs, inventory costs, training costs, financing costs, permitting costs, racking costs, and inverter costs. Table 3 shows the connections between standardization efforts and the pieces of the cost structure affected. In order to quantify the full impact of standardization, additional analysis is required.

In general, increased standardization of the physical system enables mass production and reduces labor time. As the solar PV industry moves towards increased standardization, product lifecycles will shorten. "Commonization" and parts re-use in electrical, electronic, and supporting architectures will play a vital role in time to market and cost control. Commonization enables cost reductions, as suppliers do not need to engineer new products or invest in new production tooling and equipment. Re-use and commonization are not necessarily in conflict with innovation or performance optimization; only those elements that do not increase performance would be good candidates for commonization. Suppliers' future engineering efforts can then be focused on value-added core competencies that will drive further innovation, cost reduction, and global competitiveness.

Opportunity 2: Leverage High-Volume, Lean Production

As the industry grows and parts are standardized, manufacturers will go from "craft" to mass production. In addition to reducing materials costs, this transition will expedite project initiation and permitting processes and streamline cycle times, enabling industry growth. Per-unit manufacturing volumes for many components used for solar installations are already in the hundreds of thousands or millions. However, significant cost-saving potential remains because the solar industry is typically characterized by 1) the use of materials designed and produced for a different industry; or 2) numerous manufacturers with small market share producing mutually incompatible products. Consolidation and improved recognition of standard component sizes will increase manufacturing volumes for specific parts. According to analysis by lean-design engineers Munro & Associates, high volume and lean manufacturing best practices could reduce some component costs by up to 30 percent in the short run, as seen in Figure 36.

Figure 36. Benefits of High Volume Manufacturing for Ground-Mounted System



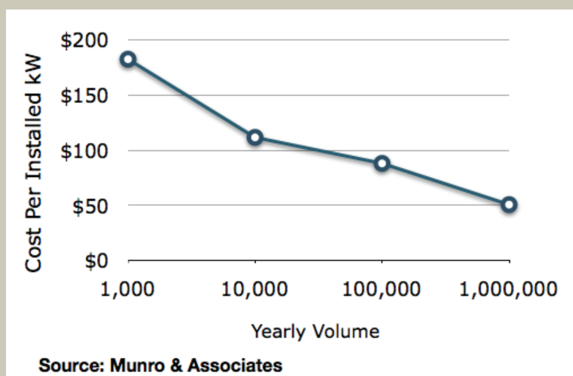
Cost Reduction Through High Volume

Over twenty-year time-frames, many industries have shown that major cost reductions can be achieved with increasing volumes. For example, Figure 37 below describes the results of a study conducted by Munro & Associates of the production costs of automotive PEM fuel-cell stacks.

The cost reductions shown in Figure 37 are derived in part from the economies of scale possible at high volume. However, volume alone was not responsible for achieving the modeled results. Additional engineering, manufacturing, marketing, and legal changes were included in the analysis, as well as increasing the capacity of the fuel cells. The corollary in the PV industry is increasing module efficiencies, which lowers BoS costs indirectly.

Clearly, there are many important differences between the fuel-cell projection shown above and the PV industry. Though specific approaches are not directly transferrable to the PV BoS industry, the fuel-cell example and scores of other examples of manufactured products that have achieved major cost reductions indicate that PV structural and electrical components also have potential.

Figure 37. Projected Learning Curve for PEM Fuel Cell Stacks



Coordinated Efforts Are Needed to Reach Asymptotic Costs

In manufacturing, the cost asymptote is the point at which manufacturing more units does not produce an additional per-unit decrease in costs. In anticipation of higher production volumes than existing machinery can provide, a new manufacturing cell must be invented or created to efficiently handle the increased volume. For most manufacturing processes, a higher-volume production process can be invented, but often the cost of commercializing the required machinery is prohibitively large.

This situation can create a paradox in which a manufacturer is ready to move to the next higher increment of production, but that move cannot be realized without a lower selling price, and the lower selling price is not available without the new machinery. One such example, observed in the mid 1990s, concerned a new increment of production for carbon fiber for structural applications. At that time, ordinary structural fiber could be manufactured and sold for $5.00/lb in the largest volumes. The auto industry was clamoring for carbon fiber at $1.80/lb. The carbon-fiber industry indicated that this would be possible—but only with a multi-hundred-million-dollar investment. The carbon-fiber industry was willing to underwrite this investment, but only with a guarantee (with cancellation charges) of purchase contracts that would pay for the plant. The auto industry did not have the cohesion to finalize the deal, and there was no collective will to support the carbon fiber industry, so today the world suffers short fiber supplies and high prices. Additional capacity has been incremental, and has not reduced manufacturing costs.

PV products pose challenges at very high volumes (10–100 million units/year). Parts are much bigger and most cycles are much longer than the seconds required to cast small, consumer products. Any molded plastic or cast metal part requires minutes to create. Any batch requires huge and expensive machinery. To avoid being at cost asymptote at relatively low volumes, it is important for PV suppliers to recognize several principles:

- For structural components, it will be important to use stamping or forging processes that don't require secondary operations. The tooling and machinery investments will be large, but they are necessary to meet the per-unit price objective.
- The industry should avoid designs that require exotic or short-supply materials.
- There seem to be potential with fully automating fabrication of the transformers, inverters, and other power electronics.
- Designing and building to an established set of standards and specifications will be key. The development of these standards (described above) should include manufacturers.

Table 2. Disambiguation of Standardization Approaches

Standard	Description	Goal
Component Selection	Reduced number of parts and design options for system designs	Focus on mass-producing a smaller catalog of low-cost and widely applicable components
Material Properties	Guidelines for material structural and electrical properties	More efficient supply chain with less variability of product offerings to expedite engineering and procurement timelines
Business Processes	Standard contracts and PPAs, including reducing variability of regulations and requirements between sites	Reduce transaction costs and enable scaling by reducing process variability and risk
Testing Procedures	Testing methods and reporting criteria for new technologies and comparison of design alternatives in the context of pre-set safety and reliability criteria	Reduce product development costs and timelines. Also can enable easier comparison of design alternatives and reduce permitting challenges associated with unfamiliar designs
Performance Expectations	Performance standard to quantify project output and provide a baseline for owner expectations	Reduce complexity of bidding and project development processes

Table 3. Standardization Effects on Cost Structures

Physical Aspect to Standardize	Cost-Reduction Opportunities	Considerations and Challenges
Modules: Dimensions, fram, thickness	• Enable right-sizing of structural components and component standardization (see above) • Minimize installation time and increase automation	• Standard sizes could not be optimized to specific manufacturers' production processes • Would require retooling of existing module production facilities • Module frame thicknesses are highly dependent on safety considerations and the specific PV technology
Modules: Electrical interface and connection point	• Reduce installation costs and training requirements	• Need agreement among manufacturers • Different module power ratings and possible presence of on-module inverters could require multiple standards
Racking components (clips, rails, etc): Size, geometry, materials	• Reduce material and manufacturing costs through mass production • Reduce inventory, training, and on-site labor costs • Reduce design and engineering time • Speed up learning curve and inspection time for building inspectors	• Mass production can reduce material and manufacturing costs • Fewer component sizes and styles reduce inventory, training, and on-site labor costs • Picking a "winning" structural approach to form basis for system is challenging • One-size-fits-all approach would not be specifically designed to any one site, reducing ability to customize design to site-specific conditions
Power Electronics (inverter, combiners, etc): Rated power, inter-connectability	• Reduce installation costs and training requirements • Expedite permitting process by reducing variability • Reduce electrical system engineering time • Leverage increased mass production of inverters and other components	• Decreased ability to customize electrical system architecture and design to site specific constraints (geometry, module efficiency, shading, climate, etc)
Array: Lay-out, preassembly	• Increase installation automation and reduce on-site installation time	• Decreased ability to customize system design to site-specific constraints

Inverters Offer Particular Potential to Reduce Costs at Increased Volumes

Though high-volume manufacturing offers opportunities to reduce costs, large structural and electrical parts may reach asymptotic conditions because of the very high ratio of materials to manufacturing process costs. In particular, this may be true for large inverters and transformers, which have a lot of heavy copper windings. For such technologies, material costs will significantly decrease only if the parts go through a miniaturization cycle. This may be possible for power electronics components, as discussed in the electrical section.

An analysis by Munro & Associates shows that $0.01–0.05/watt appears to be the range for consumer versions of DC-AC inverters. At the low end, the inverter is part of a generator set, and the cost reflects no separate enclosure for the power electronics, and no retail packaging, distribution, sales, or warranty. At the high end of the spectrum, this is a stand-alone product with most or all of the business costs required, and added.

PV inverters will probably always be more expensive than consumer inverters due to different durability requirements and their ability to provide utility grid services. However, based on the laws of scale-up, and the eventual market for very high volumes, one would expect conventional inverter costs for PV to eventually settle far below their current $0.25/installed watt or even their predicted $0.10–0.15/watt range.

Specific Recommendations to Implement Mass Production

- Over the long term, the low costs possible with mass production almost always win out. In this case, PV-system designs will eventually adapt to standardized components, not the other way around. In PV systems, the trend to standardized design, standardized components, and mass production should remain a top priority.
- PV-specific major components should be designed, analyzed, and tested to best match a PV system. At that point, mass production should be encouraged by all means possible, including development of government standards and regulations.
- Establishing and supporting a recognized national or international governing organization should be a high priority. This organization should have arbitration powers (by consent) to resolve inefficiencies, duplication, and similar conflicts. In the auto industry, the USCAR consortium has played a similar role, by providing a venue for members from across the value chain to create basic performance standards. These standards allow suppliers to compete against a common set of specifications, which promotes cost-effective and innovative manufacturing approaches.
- It is important to avoid the situation where two or more suppliers of mainstream components continue this competition beyond the point of being productive. Examples of counterproductive standards competition include VHS versus Betamax videotape systems and Stereo 8 versus cassette audiotape systems. The governing industry organization should make controlling this a priority.
- Once, or as strong design and manufacturing standards are established, having OEMs that can consolidate orders and bid jobs to tier-one suppliers is an important way to accelerate high-volume production. In the BoS industry, installers and integrators could end up playing the OEM role.

V. Conclusion and Recommendations

A Step Change in BoS Cost is Possible

When the many design considerations presented in this report are added into a conceptual system design, BoS costs in the range of $0.60–0.90/watt seem possible in the short term, with a broad variety of designs achieving those costs. For example, Figure 38 shows the cost estimate for the charrette's ground-mounted design using the plant-level inverter approach, yielding a total BoS cost of $0.68/watt (after taking into account a $0.20/watt per module cost reduction).

If this ground-mounted design could be implemented with $0.70/watt modules, the levelized cost of electricity for the system would be $0.078/kWh (see Figure 32 in the electrical design section). A widely scalable PV design capable of achieving costs under $0.10/kWh unsubsidized offers truly game-changing potential because it becomes cheaper than retail electricity in many U.S. markets.

Implementation Requires Dedicated Efforts Across the Value Chain

To realize this opportunity, a variety of activities has been proposed, both during the charrette and as a result of RMI research, synthesis, and industry outreach following the event. These potential activities are summarized in Figure 39, along with their main areas of impact. The table in Appendix B provides more detail on some of these activities.

In addition to the activities proposed for each focus area, a coordinated effort is required to tie together the disparate BoS cost drivers. An idea suggested at the DOE's August 2010 *$1/W Workshop* could serve this purpose: a standard tool that provides an analytic view of costs across the BoS. Building on existing models, such a publicly available integrative modeling module could be used to evaluate the LCOE impacts of specific design strategies, from module to installation, across the value chain. It would also allow designers, customers, regulators, and manufacturers to accurately analyze trade-offs between different designs, codes, incentive programs, contract structures, and finances and economics in terms of system performance and impact on levelized cost.

Development of the LCOE calculator described above, coupled with progress against the other activities proposed in Figure 39, will help promote:

- **Lifecycle cost decision making;**
- **Industry coopetition to promote standardization;**
- **An increased focus of development efforts on high-potential sites and designs;**
- **The ability of regulatory officials and financiers to evaluate projects efficiently;**
- **The ability of regulators to set subsidies at optimal levels and to sunset them judiciously;**
- **An increased consistency of regulations across utility and government jurisdictions; and**
- **The acceleration of updates to structural and electrical codes.**

Future Designs Offer Additional Potential

The Solar PV BoS Design Charrette effort focused on conventional technologies and a less than five-year implementation timeframe. Significant work is required to achieve the $0.60–0.90/watt cost targets described in this report. Beyond these targets ($0.50/watt and below), innovative BoS approaches will be important.

Such approaches may include building-integrated systems, DC-electric microgrids, concentrating PV technologies, bio-based structural systems, or fundamentally different photovoltaic technologies, such as paint-on products or cells that enable the use of radically different mounting structures. BoS cost reductions will also be achieved as module efficiencies continue to improve, adding more wattage per unit area of racking and per dollar of project cost, independently of the savings described in this report.

Regardless, current BoS approaches have considerable potential to drive down system costs and may remain dominant for a while.

Figure 38. Cost Estimate for Charrette Ground-Mounted System Design

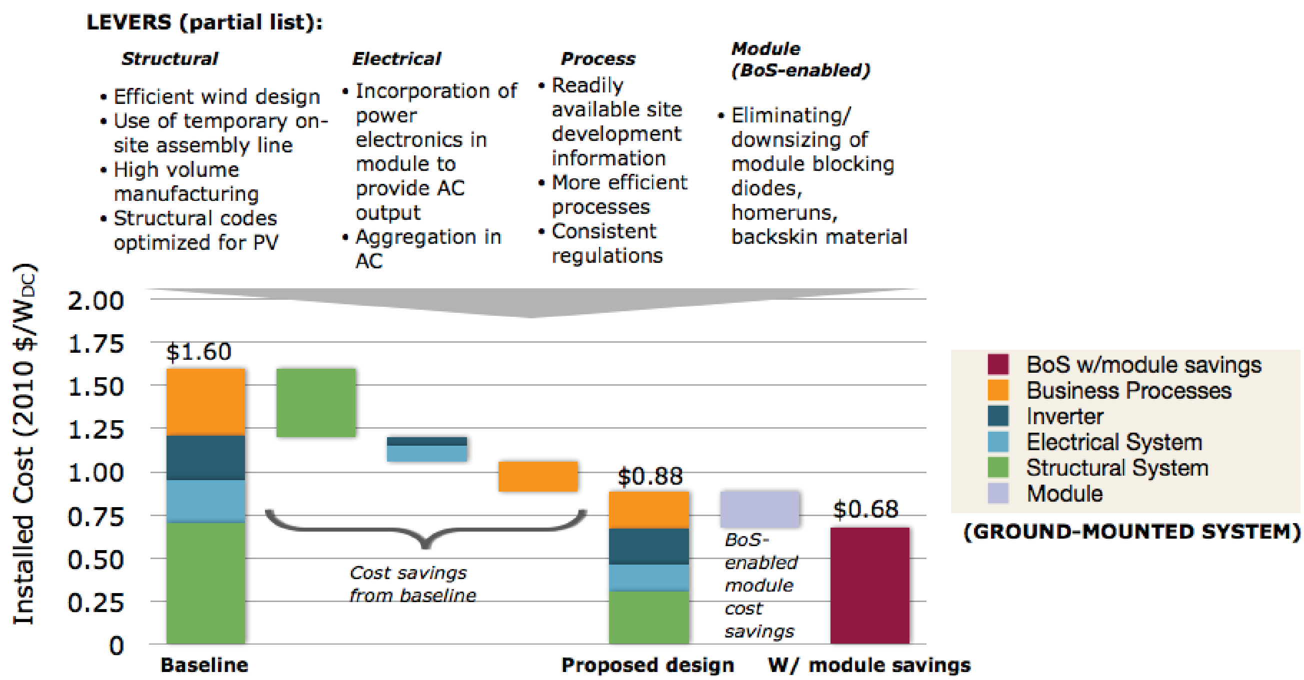
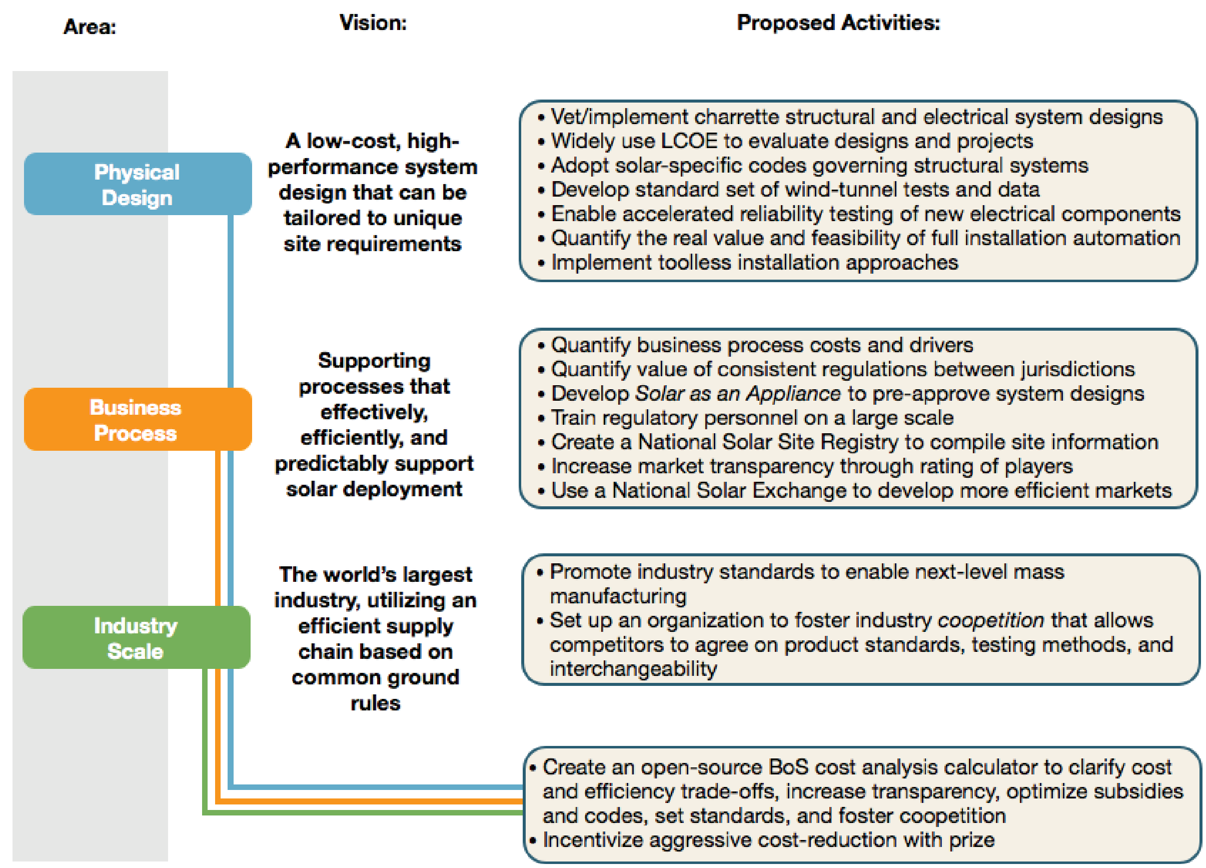


Figure 39. Proposed Industry Actions to Support Cost-Reduction Goal



VI. Appendix

APPENDIX A:

Report Contributors and Charrette Attendees

Charrette Attendees:[39]

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John F. Elter	CSNE, University of Albany
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Seth A. Hindman	Autodesk
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Robert Luor	Delta Electronics
Kevin Lynn	U.S. Department of Energy
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Ravindra Nyamati	Delta Electronics
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[39, 40] Attendance of the charrette/contribution to the report does not imply endorsement of the content in this report.

APPENDIX B:
Proposed Implementation Strategies

The table on the following page offers additional details on some of the main charrette recommendations.

Barrier	Proposed Activity
Rationalize design constraints	**Vet/implement charrette designs:** Work with industry players to select/benchmark/prototype/manufacture specific structural and electrical designs identified at the charrette.
	Develop missing PV codes: Many codes and standards that form the basis for structural and electrical PV-system designs in the U.S. do not contain provisions written specifically for PV systems (e.g. ASCE) or require updates (e.g. NEC). In order for PV-system engineers to design optimally for a specific site, these important codes should be updated with **solar-specific provisions** for PV design that allow efficient design while maintaining safety. The creation of new codes often takes years and draws from a broad accumulation of industry knowledge. However, test results of individual companies are often kept confidential for IP reasons. In order to accelerate development and approval of new codes, an industry-wide **database of PV test data** could be created.
	Develop standards for wind-tunnel testing: There are currently no industry standards for wind-tunnel tests that are performed to verify PV support structures. Creating a **standardized battery of wind-tunnel tests** designed to correspond with solar-specific codes could ensure efficient use of testing time. Given that many of the relevant codes are local, it would be important to get many jurisdictions to buy into this approach beforehand, possibly through Solar ABCs. Education of permitting personnel would be a key component of this action item.
Optimize energy output	**Make LCOE mainstream:** Promoting the **use of levelized cost of electricity ($/kWh) in decision-making** would bring greater transparency and enable a level playing-field comparison between technologies. The challenge in using LCOE is the diversity of assumptions (insolation, temperatures, tax policy, etc.) that frustrate side-by-side comparison of proposals. Customer demand or a government mandate/incentive could accelerate adoption.
	Enable accelerated testing of new components: In order for innovative new technologies to achieve wider adoption, methods of quantifying reliability of electronic components over time are important. Optimized testing standards and accelerated testing programs need to be developed so that innovation failure modes can be quickly identified and addressed. When accurate, such approaches offer the potential to reduce risk and inform decision-making. Standards and testing organizations such as UL could lay out and certify testing procedures.
Minimize installation cost	**Quantify the real value and feasibility of full automation of installation:** Although fully automated installation of mounting systems, modules, and electrical components would save labor, there would be costs (R&D, prototyping, manufacturing) and tradeoffs (loss of agility and versatility) associated with such a move. Studying the net value of full automation of installation would help focus the application of these strategies.
Standardize and mass produce	**Promote industry standards to enable next-level mass manufacturing:** Industry standards are an essential step towards high volume manufacturing. The solar PV industry should create a consortium (à la USCAR) that convenes members from across the value chain to create/select basic performance standards (quality, safety, module sizes, etc.). With industry standards in place, system integrators can more easily set their specs and send out quotes. An industry dynamic with suppliers competing for the chance to participate in an RFQ can promote cost-effective and innovative manufacturing approaches. Without standards, cost reductions will be limited by variations in the customer requests.

	Incentivize cost cutting with prize: The charrette showed that ~50% cost reductions in solar PV BoS are possible short term. One way to give industry players an incentive to collaborate across the value chain to implement or push beyond these recommendations would be to create a "BoS X-Prize." The contest could be backed by an aggregated demand consortium to guarantee a market for winning entries that achieve a target of $0.50 or 0.60/W BoS.
	Speed up market consolidation through rating of players: Among certified PV installers, there is currently a wide range of capabilities and capacities. Certification processes do not look at size, capability or quality. Creating a premium level of certification or a rating that would enable customers to easily identify the most reliable and experienced installers on the market would be a way to decrease cost through higher reliability and quality, and therefore enable a consolidation of the industry around these players. After market, independent evaluation of actual performance history, à la JD Power could be one way to achieve this.
Create an efficient supporting process	**Organize a follow up "Business Process" charrette:** Building on the work of the BoS charrette, a more specific "Business Process" charrette (could be virtual) would refine the analysis of value-add times, and cost associated with each step in business process in order to identify gaps and how to overcome them. The Business Process charrette's goal would be to quantitatively refine/offer new solutions for streamlined processes, and identify specific initiatives and partnerships to make recommendations happen.
	Train regulatory personnel on a large scale: Given the relative young age of the solar PV industry, few project approvers (city or county inspectors) or regulators are well-versed in PV projects. They therefore tend to act more conservatively and less effectively when dealing with such projects. Creating a sustainable model to train regulatory personnel on solar installation requirements and innovations on a large scale and with regular updates would go a long way towards speeding up the approval process and making it more certain. Training should be synchronized with efforts to standardize jurisdiction-level codes on solar. Online training might be a cost-effective way to reach and keep up to date thousands of regulators and approvers.
	Enable "solar as an appliance": One way to save significant time in the permitting and approval processes would be to enable "solar as an appliance." This would allow a kit of parts or systems to be standardized, bundled, and pre-certified by UL. These pre-certified system designs would also be accelerated-tested for performance, reliability, and safety in order to be bankable.
	Create a National Solar Registry: It is often challenging to identify solar sites that have good solar exposure, sit in a beneficial place on the grid, and will benefit from an efficient regulatory process. **The National Solar Site Registry** (NSSR) would compile (as a dashboard and a map) relevant information for site assessment, including: • Insolation (NREL); • Current and historical electricity rates and trends (DSIRE); • Geography / topography; • Soil content; • Wind history and trends; • Electrical grid capacity • Retail electricity prices; • Site ownership (Tiger GIS database); • Ease of developing solar sites (based on jurisdictional regulations, permitting requirements); and • Seismic activity. In addition to compiling this information, the NSSR could use accepted models to evaluate sites and provide a site rating based on its **"developability"** (likelihood of a deal being completed given all relevant factors) and **production potential** (e.g., kWh output). This rating could be a key input to both the underwriting process and the customer acquisition process.

	By standardizing information inputs and evaluation, the NSSR would remove much of the subjectivity to site assessment and reduce the dropout rate by removing the information disconnects between developer, customer, and financier. It would also reduce the likelihood that developers would unknowingly pursue PV projects with low output and/or poor development prospects.
	Increase market efficiency with a National Solar Exchange: Once the NSSR information is available, a standard forum to provide connections between approved site developers, site owners, and/or power purchasers would further increase the efficiency of project initiation business processes. Such transactions could occur on the **National Solar Exchange**, which would be a platform to expedite project development. This market place would promote price transparency and transaction efficiency.
Coordinate efforts across the value chain	**Tie together the disparate BoS cost drivers:** One idea suggested at the DOE's August 2010 $1/W Workshop could tie together the disparate cost drivers: **a standard tool that provides an analytic view of costs across the BoS.** Building on existing models, such a publicly available integrative modeling module could be used to evaluate the impacts on LCOE of specific design strategies—from module to installation—across the value chain. It would also allow designers, customers, regulators, and manufacturers to accurately analyze trade-offs between different designs, codes, incentive programs, contract structures, financing schemes, and economics in terms of system performance and impact on LCOE.

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