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

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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.

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

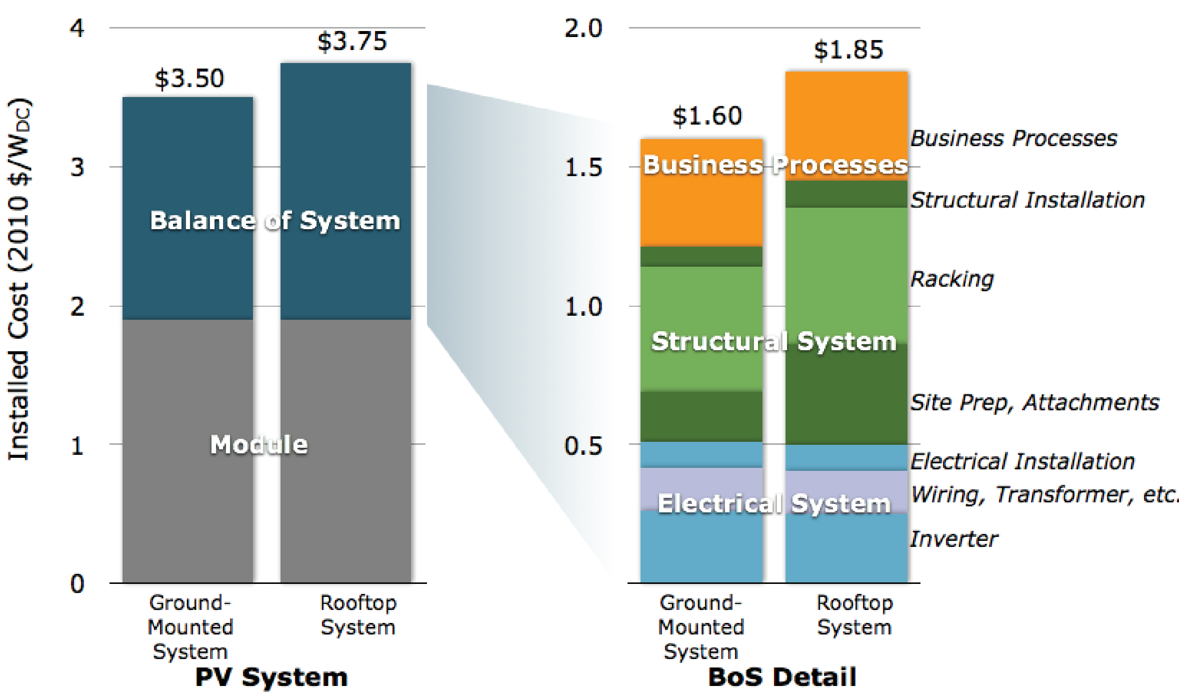
In the context of numerous global challenges—including climate change, volatile fuel prices, energy infrastructure insecurity, and rising energy costs—solar photovoltaic (PV) technologies have made great strides during the past fifty years from their origins in special applications like satellites and 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.

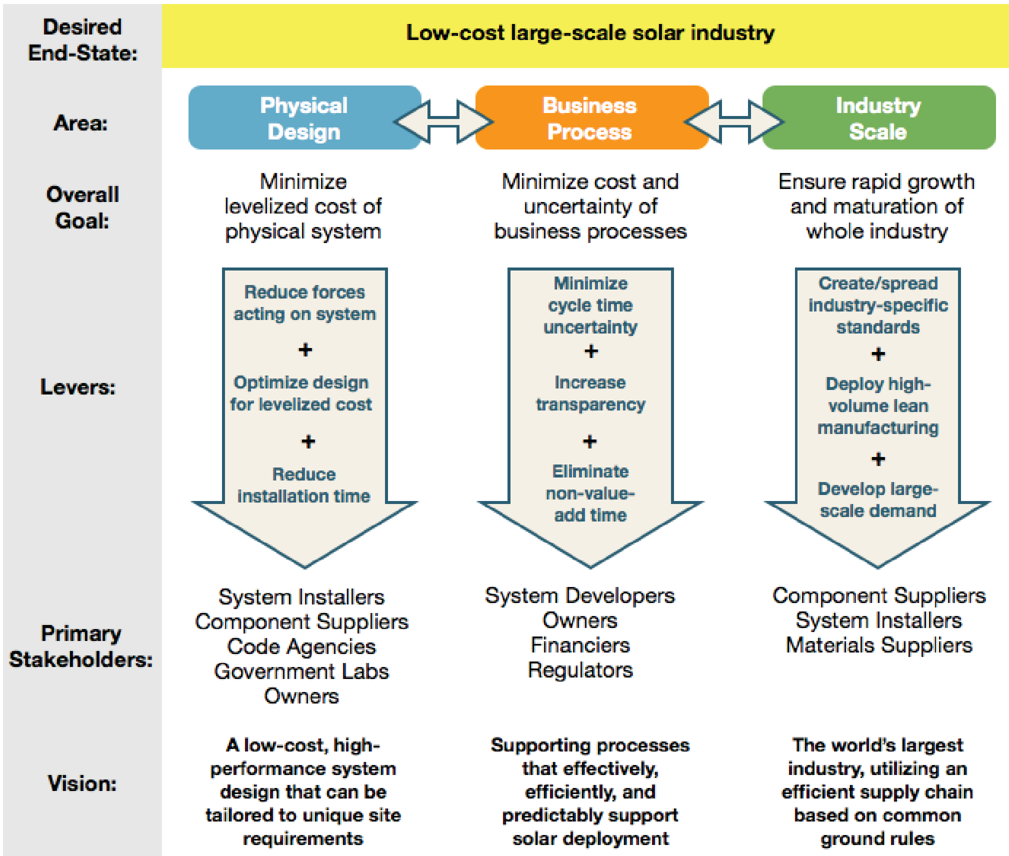
[9] Attendees included PV installers, PV system designers, PV component manufacturers, utilities, system owners, auto industry engineers, design experts, lean manufacturing experts, process experts, PV module manufacturers, and numerous other backgrounds.

[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.

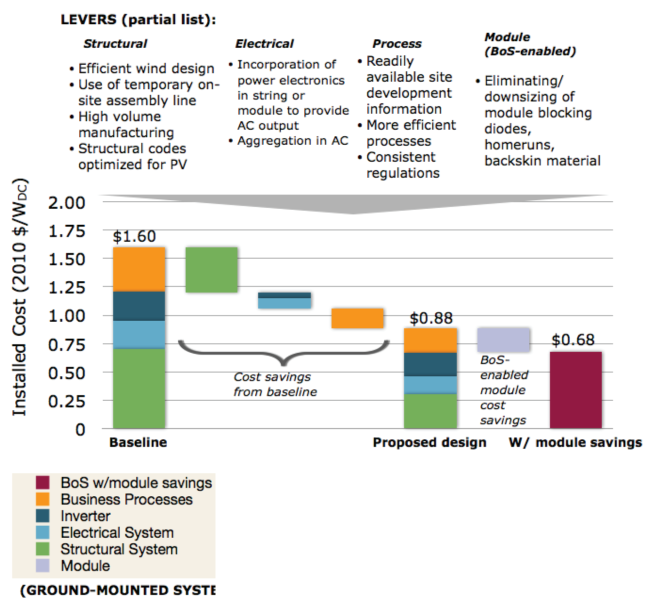
Industry Scale—Ensure Growth and Maturation

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.

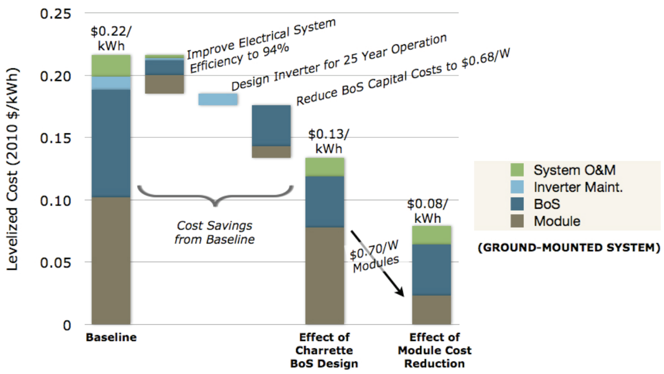
A widely scalable PV design capable of achieving costs under $0.10/kWh unsubsidized offers truly game-changing potential because it becomes cheaper than retail electricity in many U.S. markets.

[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

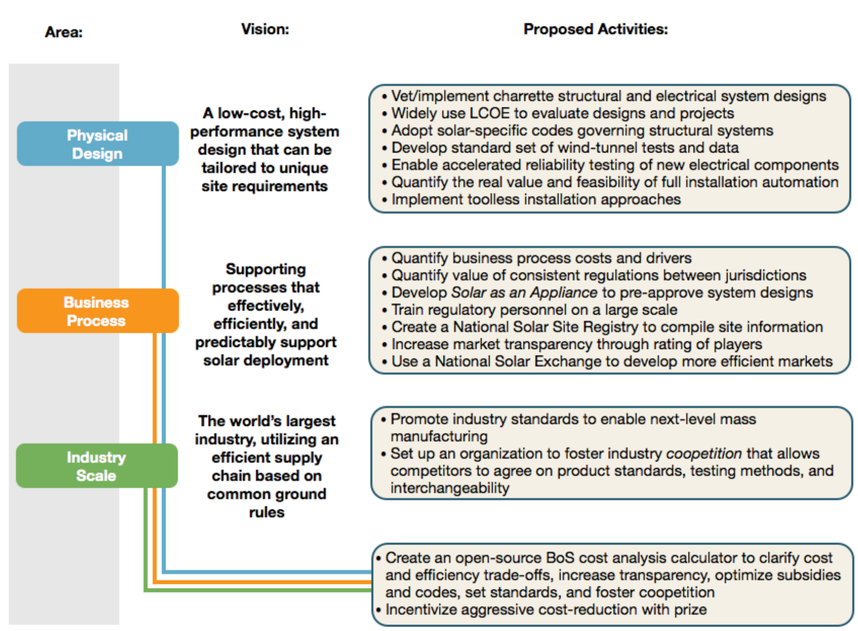


A Comprehensive Industry-Wide Effort is Needed Now

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.

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



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

- **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.**

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.