

ACCELERATING SOLAR POWER ADOPTION: COMPOUNDING COST SAVINGS ACROSS THE VALUE CHAIN

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ABSTRACT

For solar power to become a significant contributor to energy supply, and hence greenhouse gas emissions reductions, the industry has to achieve high annual growth rates for decades. The challenge cannot be overstated, especially once subsidies can no longer be relied upon to drive industry growth. Several barriers, including high costs, lack of reliable demand, supply chain dynamics, and utility integration issues, threaten to prevent adoption rates from rising as fast as is required. In particular, high costs are a major barrier, since solar power must soon be cost competitive unsubsidized. Fortunately, large cost reduction potential is available, which has not been captured during the hectic expansion of the industry. Based on experience in other industries, the basic tools of end use efficiency, whole systems design, lean manufacturing, and economies of scale will let technology manufacturers and PV installers drive down costs by a factor of two or more. These savings, enabled with support from government policies, industrial collaboration, and process efficiency gains, can bring today's PV technologies to grid parity in many markets, allowing the exponential growth curve to continue.

1. LARGE SCALE SOLAR ADOPTION IS CRITICAL

Electricity generation and consumption is directly linked to major environmental, climate, and security risks due to increasing consumption of fossil fuels. The Intergovernmental Panel on Climate Change has shown that we are running out of time to stabilize the climate. To reach an

atmospheric carbon dioxide stabilization target of 400 ppm, carbon emissions need to decline at about 5% per year starting today. (SI 2009) By 2050, this goal equates to the full decarbonization of the transport and electrical systems.

To provide cost-effective and reliable electricity, the next generation electric system must incorporate energy efficiency as well as renewable energy supplies. Energy efficiency – using less energy to produce the same function or service – is the first, best, cheapest resource to pursue. According to recent estimates, efficiency measures could save more than 25-30% of electricity nationwide. (ACEEE 2008, RMI 2009) However, after aggressive efficiency measures, energy demands should be met with renewables.

Due to the abundance and wide distribution of solar energy, solar electricity must be a fundamental supply technology. However, installed PV systems contribute only about 0.1% of U.S. electricity; the PV industry must grow substantially to make a significant contribution.

Figure 1 depicts the challenge. To supply 30% of current U.S. electricity with solar energy by 2030, the PV industry needs to maintain an average annual growth rate of about 35% from now until 2030. This trajectory would result in nearly 700 GW of PV installed in the U.S. over the next 20 years.

Growth rates must remain steady in order to reach this aggressive future state target. As the blue line in Figure 1 shows, even two years of zero growth will have major ramifications on future installed capacity, reducing the 2030

quantity by 40%. Similarly, slower growth rates over time threaten the long-term contribution of solar energy. The green line depicts a steady state growth rate of 20% per year, which would result in PV supplying just 4% of current U.S. electricity. Clearly, maintained growth is critical if carbon reduction targets are to be met. However, significant barriers threaten to block ongoing exponential growth.

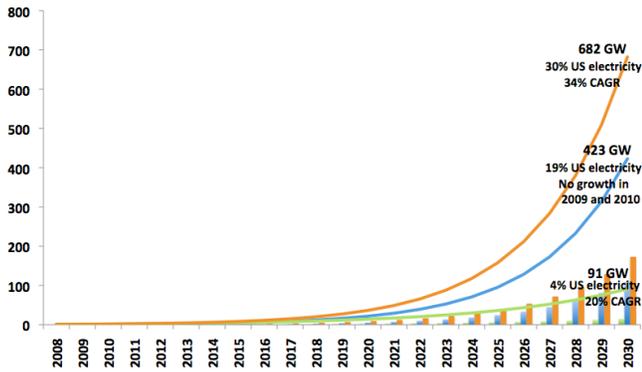


Fig. 1: Potential PV adoption rates, 2009-2030

2. BARRIERS TO ADOPTION MUST BE ADDRESSED

Several barriers have the potential to derail rapid year-on-year growth of the solar industry:

- **High costs.** With levelized energy costs mostly above \$0.20 per kilowatt-hour, solar power still relies on subsidies to compete with other technologies. To accelerate near-term solar adoption at the level required, solar electricity must at least be competitive with residential and commercial retail rates. As Figure 2 depicts, solar electricity prices are more expensive than the vast majority of current retail prices. To be competitive in even 19% of U.S. electricity markets, PV installed costs will need to drop to \$2/watt, an enormous challenge.

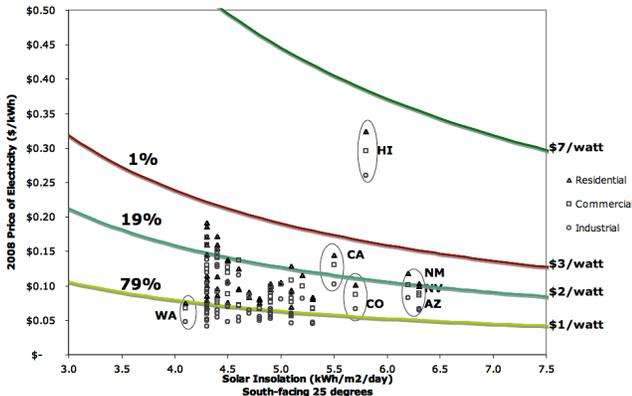


Fig. 2: Electricity state market rates and levelized PV costs

- **Stable demand.** In the past, feed-in tariffs and tax incentives have been a major contributor to predictable demand, reducing risk for solar manufacturers and helping the industry scale. Going forward, bulk buyers are needed to help the industry continue to grow.
- **Technology neutrality.** A balance must be struck that will allow today’s commercialized technologies to scale up rapidly while leaving the door open for breakthrough technologies with long-term cost advantages. Policies that are technologically biased will potentially cost the economy billions of dollars more than necessary.
- **Supply chain bottlenecks.** In the wake of the recent polysilicon shortage, a systematic look at the value chain is required. Supplies of silver, glass, racking components, and installation labor must be ramped up to support a growing solar industry. Without planning, cost reductions could be thrown off track.
- **System integration and storage.** High adoption of solar will require increased attention from utilities to balance supply and demand and account for variable generation profiles. New operating techniques and cost effective storage technologies will be important to overcome these potential hurdles.

Market forces can address these barriers to some extent, but as Figure 1 showed, delays have large impacts on ability to meet future targets. To maintain rapid growth, these barriers must be addressed in a systematic way.

3. NEED SYSTEMATIC INDUSTRY-WIDE APPROACH TO COST REDUCTIONS

Though costs have come down steadily, significant reductions are still required to make solar power widely cost-effective. Many in the industry have predicted major cost reductions over the next five years, but these reductions are not automatic – costs must be forced out through research, product development, and process optimization. Currently, there is no clearly visible roadmap for how to achieve the required savings.

Cost reductions could come from two main areas. First, breakthrough technologies could revolutionize PV manufacturing or installation, immediately dropping costs. Alternatively, costs could be squeezed out of technologies that have already been commercialized. In the long run, several breakthrough technologies have tremendous opportunity. However, they will take time to scale, and PV adoption cannot afford to wait.

Meanwhile, with 87% market share in 2007, proven and reliable crystalline silicon technology has been a remarkably resilient competitor. (Greentech 2009) The technology has not plateaued yet; aggressive optimization and build-out efforts still offer significant cost reduction potential.

Although installed costs vary based on technology type and installation location, they remain generally evenly split between manufacturing costs and balance of system costs, as shown in Figure 3. Therefore, cost reductions are necessary across the entire value chain.

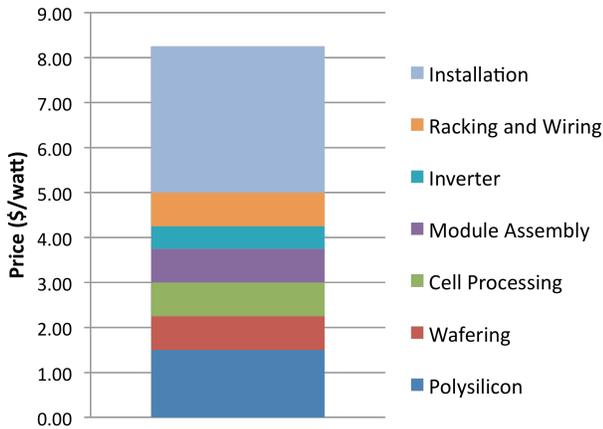


Fig. 3: Cost of a Residential PV System (WSJ 2008)

Companies in the PV industry are working hard to eliminate costs, but many opportunities remain on the table. The industry, including installers, must adopt a Moore’s Law mentality with respect to ongoing cost reductions. The following sections identify opportunities to drive down costs of today’s technologies through manufacturing and installation process improvement.

4. IMPLEMENT MULTI-DIMENSIONAL APPROACH TO MANUFACTURING PROCESS OPTIMIZATION

4.1 Process Efficiency Opportunities Have High Potential

Several approaches are available to reduce unit costs of today’s commercialized PV technologies. Ultimately, improving manufacturing efficiency through end use efficiency, whole systems design, and lean manufacturing best practices has high leverage to reduce capital and operating costs. As Figure 4 shows, savings are realized through a series of compounding benefits.

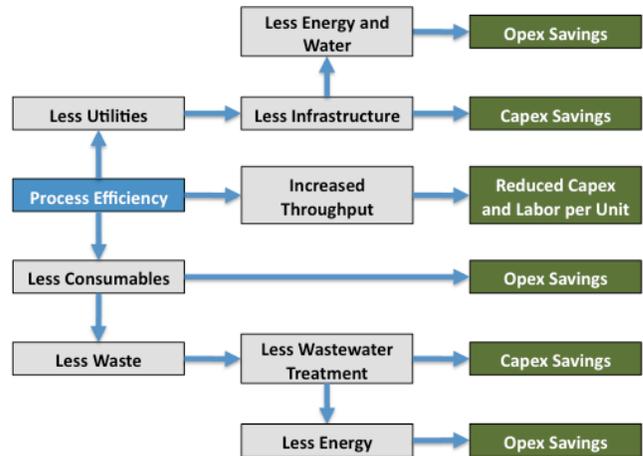


Fig. 4: Leverage of improving process efficiency

- End use efficiency.** When improving facility efficiency, it is important to consider the right steps in the right order. Since end use energy and resource efficiency measures focus on the point of use, they have high leverage. Efficiency measures provide value as savings compound upward through the system. By saving a liter per second of hot water at the point of use, savings are realized upstream through pumping systems, electricity supply systems, and water supply systems. Ultimately, the saved liter impacts several liters of water at the source and many BTUs of carbon-intensive fuel at the power plant. Figure 5 shows an example of a typical pumping system where 100 units of energy are required to provide just 9.5 units of service.

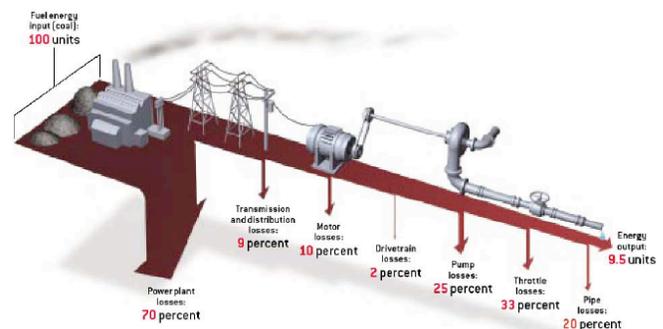


Fig. 5: Energy losses in a pumping system

Energy and resource efficiency measures are directly linked to operating cost savings. In cell manufacturing plants, many opportunities exist to reduce electricity demand directly (such as more efficient vacuum pumps) or indirectly (for example, through heat load reduction). Potential also exists to reduce water demand and chemical inputs. Similar opportunities exist at each step of manufacturing, from polysilicon production to module assembly.

- Whole systems design.** Frequently, system components are not optimized at a whole systems level when new facilities are designed. A classic example is a piping system. If the pipes are optimized in isolation, small pipe diameters will be selected because smaller pipes are cheaper than larger pipes. However, if the system impacts are considered, it turns out that small pipes require large pumps. Not only are the larger pumps more costly, they use more energy, thus having higher lifetime operating costs. In many situations, optimizing the system as a whole (in this case, by specifying bigger pipes and smaller pumps) results in reduced capital costs *and* reduced energy usage.

Whole systems design concepts are applicable to a variety of processes in PV manufacturing. In addition to piping systems, power supply systems (where uninterruptible power and generator systems depend on downstream system design), building shell design, and mechanical system design all offer potential. Through good design of these systems, capex and opex savings may be realized which ultimately reduce PV costs.

- Lean manufacturing.** Lean manufacturing principles offer potential to reduce inventories and increase throughput in factories. In the solar industry, where capital costs account for more than 20% of production costs (Photon 2008), maximizing throughput decreases the effective capital cost per unit. Like many other industries, average utilization of capital in the solar industry is relatively low, indicating substantial opportunity for improvement.

An important lean manufacturing tool is the key performance indicator (KPI) tree. Figure 6 provides an example. KPI trees dissect progress metrics (such as \$/watt) to identify processes with high leverage over total costs. In many cases, increasing utilization of a main critical path item will clear a bottleneck, allowing major improvement in performance.

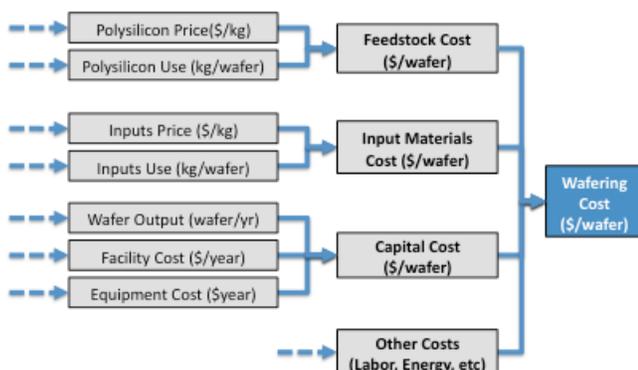


Fig. 6: Example KPI tree for wafering process

Though these opportunities are already being addressed to some extent, much potential remains. Fifty years of lean manufacturing knowledge need to be compressed into rapid adoption by the solar industry. In this way, waste at each step of the process can be reduced through labor and capital productivity gains.

- Economies of scale.** As economies of scale continue to develop, manufacturers can refine best practices and exert pressure on suppliers. Though the PV industry has seen remarkable growth, it is still a comparatively small, immature industry that must become much bigger. Growth will continue to bring advantages and opportunities for cost reduction as solar manufacturers gain increasing demand power. Manufacturers will be able to realize savings by committing to long-term purchases of production equipment and input materials. In addition, vertical integration and joint ventures with materials suppliers will enable significant decreases in input material costs at each step of the value chain.

To pull these levers, companies will need to engage their own R&D labs to analyze the quantities of energy, water, and chemical inputs that are actually needed at each process step. To implement improved processes, close collaboration with toolmakers is critical, since toolmakers ultimately determine the energy and material usage of each step, be it ingot pulling, wafer cutting, or annealing. Whereas many toolmakers focus on minimizing the first cost of their equipment, a better metric is lifecycle cost, which accounts for the efficiency of the equipment.

Savings from these tactics offer potential to reduce PV panel manufacturing costs by at least a factor of two. Rapid growth has come at the expense of high process efficiency. With tight timelines to get new facilities built and operating, decision makers have had little time to look for optimization opportunities across traditional boundaries. As a result, few have had the information necessary to identify economic advantages associated with maximizing end use efficiency and whole systems design.

4.2 Handoffs are Not Optimized

Optimizing hand-offs between each step of the value chain is another area that can benefit from increased attention. In mature industries, clearly defined standards and guidelines govern exchanges through supply chains. However, the young PV industry is still developing such programs.

As standards are developed, equipment manufacturers can design their products to utilize known material grades and standard sizes. Applicability spans the value chain, from the upstream end – where varying grades of metallurgical silicon are refined to produce polysilicon – to the downstream end – where installers struggle to coordinate

racking materials measured in inches with the metric dimensions of many modules.

Efficiency can also be increased through better collaboration between suppliers and consumers. At each step of the value chain, products can be tailored to the needs of the next step, eliminating redundant processes and wasted time and materials. Lean manufacturing efforts and economies of scale offer potential to reduce costs by streamlining hand-offs.

4.3 Efficiency Opportunities are Real

Solar industry site visits have identified concrete examples of low-hanging fruit for cost savings. Even though companies' success is measured in large part by their ability to squeeze cost out of their processes, indicators of opportunity are prevalent across the value chain. A few examples observations are summarized below:

- **Excessive waste of consumables.** Though consumables (including lubricant, abrasive, chemicals, wire, ink) account for a large part of the PV cost structure, they are frequently wasted. Improperly sized input feedstocks, lack of automation and scale, and redundant repetition of processes contribute to waste. For example, at the wafering step, wafers are cleaned after they are cut and then cleaned again before cell processing, requiring substantial water and chemical usage.
- **Lack of coordination and misaligned incentives with tool manufacturers.** As with semiconductor manufacturing, cell production tools are not produced by PV industry plant owners or operators. This can lead to adjacent tools in a plant with different operating requirements and therefore inefficient use of energy in specialized tools whose sole purpose is to enable the connection of one tool with the next. Tool manufacturers also try to make a low capex target in order to win bids, often at the expense of opex over the lifetime of the tool.
- **Lack of right-sizing and overcooling.** Cooling costs are high in production facilities. When hot process steps are not thermally isolated, their large heat load contributes substantially to the cooling system's task. In addition, the energy required to maintain high classes of clean room space is high. However, clean rooms are oversized to simplify design and operation of facilities, resulting in oversized HVAC systems to maintain air flow.
- **Use of materials designed for other purposes.** Many rooftop installation systems utilize racking components originally designed for other

applications. While off-the-shelf components were originally cost-efficient, as the industry grows, this is no longer the case. Instead, these materials lead to unnecessary installation labor time and materials consumption.

These examples show a few areas of opportunity. These types of issues must be addressed in order to drive out costs.

4.4 Look to Other Industries for Lessons Learned

There are many examples of industries that have increased profitability by improving energy and resource efficiency. Basic principles of end use efficiency and whole systems design are quite applicable to companies ranging from mining to trucking to oil refining.

In 2005, Texas Instruments kicked off the design of a state of the art chip fab. Like solar plants, the TI fab consumed large volumes of energy and water. Though many strategies were pursued to improve efficiency, the highest leverage came from tool redesign. Through direct collaboration with tool manufacturers, TI developed a design that used 20% less energy and 35% less water, saving an estimated \$4 million per year in operating costs while reducing upfront costs by 30%. (Westbrook 2006)

EDS, a major provider of information services to corporations, offers a second case study. As a major data center owner, EDS felt increasing pressure from rising data center energy usage and costs. By 2007, since most data centers had been designed before efficiency was a primary concern, server lifetime operating costs had surpassed their initial capital costs. As in PV plants, accelerated project schedules and reliability considerations trumped other design concerns, making energy efficiency a low priority.

Despite widespread agreement that significant savings potential was available and that efficiency was critical, implementation lagged. Funding could rarely be approved for simple measures, such as an initiative to improve cooling system effectiveness by blocking holes in the raised floor. A lack of communication between key stakeholders kept a holistic efficiency program from moving forward. Capacity planners, business executives, accounts managers, IT operators, and data center facility managers were all focused on meeting budgets and fulfilling their specific responsibilities. Since a business case for efficiency measures required contribution from a wide range of stakeholders, a program could not gain momentum until it was identified as a top priority. Now the efficiency program proposes to eliminate millions of dollars in new construction costs while accommodating substantial business growth at only slightly higher operating costs.

Both of these projects offer lessons for the PV industry. Though companies are working hard to reduce costs, a lack of focus on the highest leverage opportunities and an inability to bridge internal silos can leave significant potential on the table. Like TI, solar companies need to work with their suppliers and toolmakers to streamline processes and reduce waste. Like EDS, they need to eliminate internal barriers to improved efficiency and provide holistic information to decision makers. In both cases, efficiency required new thinking but ultimately enabled opex and capex savings.

5. TIME TO RETHINK HOW CELLS ARE INSTALLED

Rooftop installations of less than 100 kW are responsible for about half of the PV capacity installed annually in the U.S. Distributed generation offers numerous benefits, so cost-effective rooftop installations offer major value. (RMI 2002) However, centralized systems have historically been able to benefit from economies of scale to reduce capital costs by \$1-2 per watt. (LBNL 2009)

Despite growing volumes, rooftop installation is still largely a cottage industry. As in manufacturing, there are many opportunities to reduce installation costs that have not been fully captured due to rapid growth in the sector, a lack of competition, and persistent split incentives between stakeholders. To improve the process, labor costs, inverter costs, and racking system costs must all be reduced.

For rooftop systems, installation labor cost can contribute up to \$2 per watt, accounting for 25% of the total system cost. (WSJ 2008) Approaches that reduce labor time per module installed are critical if installation cost reductions are to keep pace with declining module costs.

Fortunately, rooftop assembly offers significant potential for labor productivity gains. Even experienced workers spend much of their time setting up materials, waiting for critical path items such as grounding wire connections, and adjusting modules with simple tools like plumb bobs and T-squares. Applying lean manufacturing principles will increase productivity of workers, reduce installation times, and cut installation costs. By working with top tier structural designers, solar installers can eliminate unnecessary racking components and move away from traditional “rule of thumb” engineering that results in oversizing.

Additional improvements are possible through increased system prefabrication. Standardized arrays can be produced in the shop, then lifted into place and attached with substantially less labor. Standardized system designs will also enable reductions in design time and material inventories.

In many cases, streamlining installation practices are technology neutral. Best practices learned by installers working with crystalline modules can easily be transferred to module-based thin film technologies. In fact, for less efficient modules, installation and balance of systems costs account for a larger relative share of the cost structure. With new technologies, installation best practices will be even more important to efforts to bring down levelized costs of energy.

6. A COORDINATED APPROACH IS NECESSARY TO ACHIEVE REQUIRED GROWTH

The PV industry can help itself by reducing costs, but governments and industry groups are critical for their roles as enablers and ability to look at the industry from a high level. In particular, these groups can help by (1) providing predictable demand while promoting cost reductions and innovation; (2) reducing costs and delays associated with permitting and interconnection; and (3) taking a big-picture view of the supply chain and acting early to reduce risks of bottlenecks such as the recent polysilicon shortage.

- **Stable demand.** Until solar power is widely competitive in bulk electricity markets, uncertainty about demand is a major risk to continued industry investment. The best policies can provide predictable demand while promoting cost reductions, possibly via an auctioning system. By taking bids for a set amount of capacity each year, the government can provide a market for a large enough quantity of solar power to incentivize investments throughout the value chain. At the same time, manufacturers will need to continue to drive out costs in order to win future contracts. At any point, a breakthrough low-cost technology could enter the field and be quite successful. There is also a role for other large buyers, such as universities, electric utilities, and companies who can create stable demand by committing to large-scale PV system purchases.
- **Standardized regulations.** Varying regulations between states, municipalities, and utilities add costs and delays to PV installations. To allow installers to function more effectively and to open up markets, uniform standards on net-metering, permitting, and interconnection are important enablers. As solar adoption increases, smart grid controls and time of use pricing mechanisms will be necessary to maintain grid reliability and reward solar power for contributing energy to the grid during peak hours. Many efforts are underway to raise awareness about the importance of standardized policies and push governments and utilities to make these changes.

- **Supply chain.** Exponential growth will place great stress on the supply chains supporting the PV value chain. Materials ranging from polysilicon and silver to glass, steel, and aluminum will be required in great quantities. For example producing 100 GW per year of modules would require up to one billion square meters of glass, a figure representing 20% of 2008 global manufacturing capacity. (Freedonia 2008) The industry will need to scale substantially to meet PV industry demand. The polysilicon shortage has demonstrated how a bottleneck can seriously interrupt progress on cost reduction and capacity growth. Since each material shortage cannot be allowed to hold up the entire industry, systematic analysis must proactively identify potential bottlenecks before they become critical.

Like material inputs, labor is a critical input, especially for installation. Green jobs programs which have gained momentum from the stimulus package will be helpful in training workers to install and connect solar panels. The growing PV installation industry will require increasing amounts of workers, so training programs must be ramped up to meet this need.

In general, these barriers are secondary to direct costs. But since each impacts cost in important ways, they must be addressed as part of a holistic effort to help the industry keep growing.

7. NEXT STEPS

For solar power to become a meaningful contributor in the effort to mitigate climate change, more than an order of magnitude of scaling is required. To achieve more than a decade of exponential growth will be difficult, but it has been done before. In the first decades of the twentieth century, demand for cars and planes skyrocketed as costs came down. Similar trends have allowed personal computers and consumer electronics to capture major market share over a short time.

The opportunities described in this paper should be prioritized to help the solar industry meet growth targets. Manufacturing companies must take a hard look at their processes and apply best practice end use efficiency, whole systems design, lean manufacturing, and economies of scale to drive out costs. Installers must match and exceed the improvements made by manufacturers by standardizing installation designs and processes. And industry groups and governments must enable the process by keeping demand strong and streamlining regulations, permitting, and interconnection.

8. ACKNOWLEDGEMENTS

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