$1/W Photovoltaic Systems

White Paper to Explore

A Grand Challenge for Electricity from Solar

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I. Introduction

A key plank of the Obama Administration's Energy Policy is to put the country on a path to reduce Green House Gas (GHG) Emissions by 80% by 2050. Solar energy technology has the potential to play a major role in achieving this goal but to date has been limited by high costs.

The U.S. Department of Energy (DOE) estimates that a $1/watt installed photovoltaic solar energy system – equivalent to 5-6 cents/kWh – would make solar without additional subsidies competitive with the wholesale rate of electricity, nearly everywhere in the US. A solar energy system priced at $1/Watt would unlock the potential of the sun to provide low-cost, clean limitless electricity to the U.S. and the rest of the world, at the same cost of coal-based generation. At this price, solar generated electricity combined with affordable storage technologies could then meet all conventional electricity energy needs, providing solar energy potentially 24 hours a day. Meeting this challenge would result in a revolution in the world's generation and use of energy.

With the current rate of progress, the cost of a utility-sized photovoltaic (PV) system is likely to reach $2.20/watt by 2016, and $2.50/watt and $3.50/watt, for commercial scale and residential scale systems respectively. Reductions significantly beyond that in the next four to eight years are unlikely absent dramatically new ideas and significant investment.

Preliminary DOE analysis on required component costs to reach a $1/watt installed PV system implies the following breakdown: 50 cents/watt for the module, 40 cents/watt for the balance-of-system and installation, and 10 cents/watt for the power electronics. Private investment is unlikely to bring about the types of ambitious advances required to meet these goals as the capital market has focused funding on shorter-term commercialization goals and international markets with attractive government support and high electricity rates.

This white paper was developed by DOE staff to stimulate a dialogue about technology pathways to achieve $1/watt. The paper contains initial ideas on how to achieve significant reduction in the cost of modules, power electronics and balance-of-system/installation. For example, analysis suggests that modules with 25% efficiency, power electronics with double the rated lifetime, and simpler and quicker PV installation methods are all required.

II. The Technical Challenge

Installed PV array prices for utility-scale systems were $8/watt in 2004 and bids below $3.50/watt are expected by the end of 2010 if not sooner. Residential and commercial prices are over $6/watt since they are much smaller in scale and incur much larger installation prices and retail markups. With current market trends and cost reduction opportunities, utility scale system costs are expected to reach $2.20/watt by 2016 if no new program is launched. The $1/watt goal will require a major change in the rate of innovation. (See Table 1.)

Reaching the goal will require dramatic improvements in at least three areas (each is discussed in greater detail in Appendices E and F):

- **Arrays:** High array efficiency is essential both for reducing array costs and cutting the area (and thus cost) of installed arrays. Fortunately, there are technology pathways that might achieve this goal. It is expected, however, that the most promising is likely to be one that does not require glass and can be deposited inexpensively on a thin metal or polymer substrate. Reaching the goal will require finding ways to (a) design manufacturable cells capable of achieving efficiencies demonstrated in laboratories and (b) making use of the kinds of roll-to-roll production devices or other approaches that greatly simplify manufacturing processes.

Installed System Price ($/W)

	2010	2016	$1/Watt
Module	$ 1.70	$ 1.05	$ 0.50
BOS/Installation	$ 1.48	$ 0.97	$ 0.40
Power Electronics	$ 0.22	$ 0.18	$ 0.10
	$ 3.40	$ 2.20	$ 1.00

Cost of Energy ($/kwh)

	2010	2016	$1/Watt
Module	$ 0.063	$ 0.037	$ 0.018
BOS/Installation	$ 0.055	$ 0.034	$ 0.014
Power Electronics	$ 0.008	$ 0.006	$ 0.004
O&M	$ 0.013	$ 0.009	$ 0.003
	$ 0.139	$ 0.086	$ 0.038

Table 1: Potential utility scale system cost breakdown to reach $1/watt (note capacity factors assumed are 26% in 2010 and 28% in 2016)

- **Power Electronics:** Converting the DC output of arrays into high quality AC at useful voltages requires equipment that adds both to initial installed cost and to maintenance costs since current designs often fail after 10 years. Building on ongoing power electronics work at DOE, at least two promising approaches could be pursued: (a) radical redesign of current large inverter units and use of innovative components, and (b) designing modular inverters that could be cheaply mass produced and attached to each module.
- **Installation:** The cost of mounting and wiring arrays and the associated equipment is about half the cost of today's systems. Two approaches will be pursued to achieve the dramatic cost reductions required: (a) installing arrays in fields on lightweight frames with equipment that has the sophistication of agricultural combines capable of covering hundreds of acres a day, and (b) finding ways of building PV arrays into building components such as roofing so that the incremental installation cost could be very low. Arrays that follow the sun are somewhat more expensive than installations that don't move but can produce more electricity per year per watt of installed PV and can produce more energy late in the day when many utilities need most power. Tracking is usually also needed for units that concentrate sunlight on high efficiency cells. Concentrating systems add to costs but can reduce the area and cost of the photovoltaic devices.

While each of these areas could be pursued as a separate task, the success of the project depends on ensuring that each of the programs understands the challenges faced by other areas. Arrays should, for example, be mass produced for easy installation.

III. Other Requirements

A number of other objectives will need to be met in order to make a $1/watt system commercially viable and scalable to meet long-term energy needs. In order to represent a significant advancement from existing industry trends and make a significant impact on Administration Greenhouse emission goals, the $1/watt goal should be demonstrated by 2017. The target could be demonstrated by full systems or incremental to existing system costs, such as for PV systems integrated within new roofing systems. To ensure large volume scalability, the $1/watt system should be based on earth-abundant materials and capable of full recycling. Finally, the $1/watt system should meet all applicable safety and environmental standards.

$1/watt installed by 2017: Defining the Objective

- **By 2017**: Demonstration of all key components and installation methods in systems at least 5MW in size and initial production orders for equipment capable of delivering $1/watt installed systems in 2017
- Includes all components, equipment and installation processes to produce grid compatible electricity
- Target could be met with systems installed on the ground or on buildings
- Earth-abundant materials
- Recyclable components
- Meets all applicable safety and environmental standards

Appendices

Appendix A: Potential Impacts of $1/watt to U.S. Electricity System

Appendix B: Business as usual and the challenge of the US electricity market

Appendix C: Cost Goals of the Current DOE program and $1/W Goal for utility scale systems

Appendix D: Management Alternatives

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Appendix G: Preliminary analysis of Efficiency, Cost, and Reliability Barriers

Appendix H: The need for Government funding

Appendix A: Potential Impacts of $1/watt to U.S. Electricity System

Preliminary NREL analysis conducted with ReEDS[1] and SolarDS[2] suggests that if the $1/watt goal is reached by 2020[3], more than 100 GW of PV could be installed cumulatively, representing about 5% of the nation's electric generation capacity.[4] By 2030, installed capacity could grow to 389 GW representing 14% of U.S. generation capacity.

2030 Results	Reference Case	$1/Watt no ITC post-2016
% Generation of PV	1%	14%
Cumulative Installed Capacity (GW)	40 GW	389 GW, *232 GW Utility-scale, 157 GW Distributed*
National Average Electricity Price	10.45 cents/kWh	10.23 cents/kWh
Annual CO_2 emissions from the Power Sector	2,408 MMT CO_2	2,194 MMT CO_2

Table 2: Potential impact on the U.S. electricity system in 2030 from the deployment of a $1/W PV system by 2020

If these capacity additions are realized, utility systems will need to adjust their generation mix and operations to adapt to larger amounts of solar energy generation. The analysis indicates that if 14% of a utility's energy comes from solar, these adjustments could be relatively small, only minimal amounts of new transmission and storage would be required. The total amount of natural gas-powered intermittent and peaking capacity would fall, but a higher fraction of this equipment would need to be maintained as "spinning reserve." Inexpensive storage would cut overall costs.

At these levels of PV adoption, consumer prices of electricity could be 2% lower in 2030 if the $1/watt goal is met. Further, by 2030 CO_2 emissions from the power sector could be reduced by approximately 213 MMT CO_2 annually and the growth of CO_2 emissions from the sector could be cut in half by 2030.

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[1] NREL's Renewable Energy Deployment System (ReEDS) is a linear capacity expansion model that optimizes the regional expansion of electric generation and transmission capacity within 356 regions of renewable resource data while specifically addressing the variable nature of some renewable resources. http://www.nrel.gov/analysis/reeds/

[2] NREL's Solar Deployment System (SolarDS) is a market penetration model for commercial and residential rooftop PV, which takes as input regional electricity prices, financial incentives, regional solar resource quality, and rooftop availability. Denholm, P., Drury, E., and Margolis, R., 2009, "The Solar Deployment System (SolarDS) Model: Documentation and Sample Results," NREL/TP-612-45832.

[3] The Reference Case uses preliminary technology cost and performance assumptions being developed for another EERE study and assumes a 30% ITC for solar through 2016 due to ARRA and then the ITC expires after 2016 that has not yet been peer reviewed. The $1/Watt 2020 Case uses the same technology and policy assumptions as the Reference Case, but the cost of PV ramps down to $1/Watt by 2020 for utility-scale and commercial applications. For residential applications, PV is available in 2020 at $1/Watt for new construction with roof re-surfacing modeled by a 5% house rebuild rate and retrofits at a 40% cost penalty (or $1.40/Watt). For both cases, ReEDS and SolarDS were run together in an iterative fashion. The fossil and nuclear numbers reflect preliminary estimates by an engineering consulting firm and have not been reviewed by DOE. They are being used here as placeholders only, to allow the exploration of the potential impact of $1/W installed PV scenarios for this study.

[4] These results are preliminary, not peer-reviewed or vetted for citation or quotation. Proper study of this issue would require additional ReEDS/SolarDS analysis to provide a more robust understanding of the potential impact of reaching this cost goal on the U.S. electricity system.

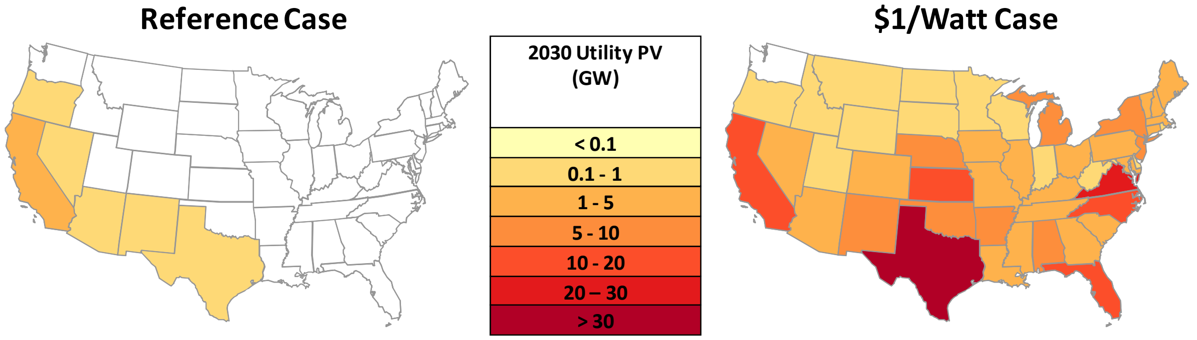

Figure 1: Geographic Diversity of PV Deployment

Figure 1 shows that with the $1/Watt systems solar electricity could be cost-competitive with other forms of generation in almost every state in the country by 2030.

Summary Results from ReEDS and SolarDS Cases

Installed Capacity (GW)	2010		2030		2050	
	Reference	$1/W Case	Reference	$1/W Case	Reference	$1/W Case
Solar PV	.3	.3	40	389	83	592
Wind	35	35	49	38	118	70
Storage	21	21	23	24	24	30
NG	389	389	516	412	635	567
Coal	308	308	302	303	355	301
Nuclear	100	100	96	96	57	57

Table 3: Installed Capacity in Reference and $1/Watt Cases

The results from the Reference case and the $1/Watt case are presented in Tables 3 and 4 and are not an official DOE perspective on the future, but possible outcomes based on one set of technology cost and performance projections and other aspects of the ReEDS and SolarDS models, with parameters as supplied by an external engineering consulting firm, which have not been peer reviewed nor reviewed by DOE. These values for nuclear, fossil, and renewable technologies are being used here as placeholders only, to allow the exploration of the potential impact of $1/W installed PV scenarios for this study. Market penetration levels of different technologies can be attributed to a number of factors including projections on cost and performance.

Generation (TWh)	2010		2030		2050	
	Reference	$1/W Case	Reference	$1/W Case	Reference	$1/W Case
Solar PV	0.4	0.4	60.5	654	128	986
Wind	115	115	170	129	427	250
NG	767	767	1025	675	1313	1188
Coal	1886	1886	2235	2138	2629	2129
Nuclear	790	790	757	757	448	448

Table 4: Electricity Generation in Reference and $1/Watt Cases

Appendix B: Business as usual and the challenge of the US electricity market

Figure 2 below highlights the current state of the art for the two leading photovoltaic technologies, wafer based silicon and thin film CdTe. The costs are based on systems installed in Phoenix, AZ and does not include federal, state, or utility incentives.

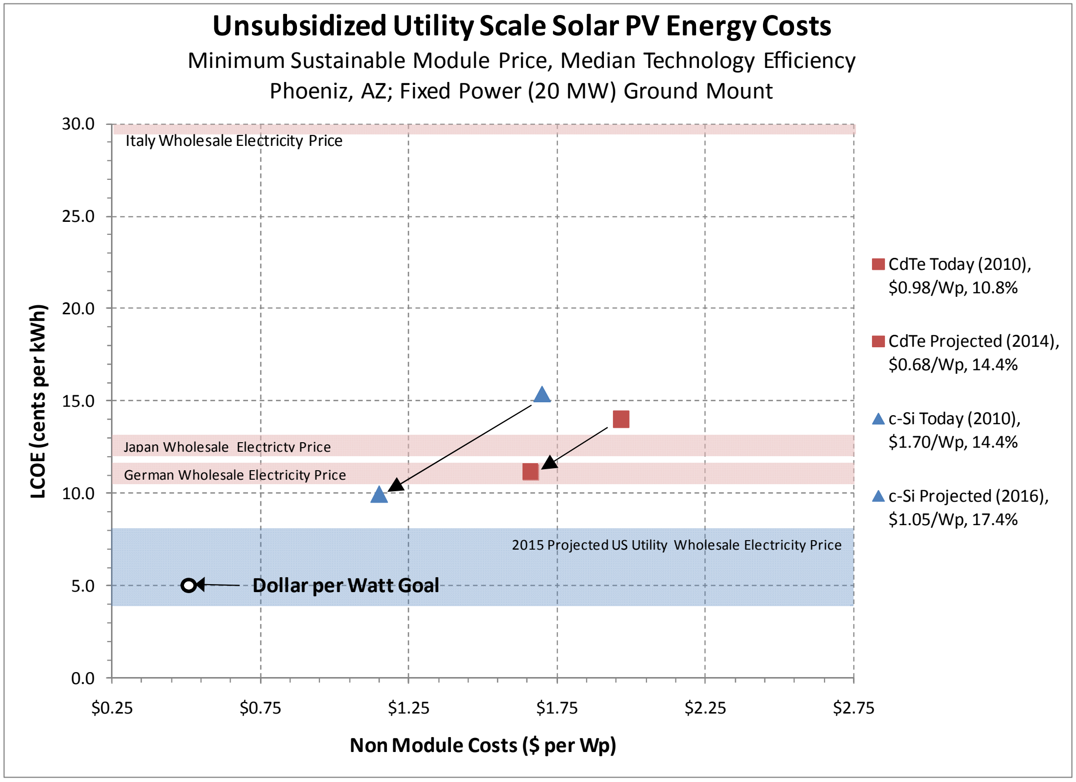

Figure 2: Comparison of current and projected Solar PV costs (Phoenix, AZ) to US wholesale electricity rates (wholesale rates of leading solar energy adopted countries included for reference to US rates only)

The US and other countries' national average wholesale electricity rates are represented by bands on Figure 2 (Source: EIA). *The industry is currently focused on those markets with high electricity prices and high subsidies.* Since PV is already attractive in those regions, manufacturers are focused on servicing those opportunities through incremental improvements that increase their profitability and market share. Reaching $1/W is a challenging goal that is more important for the US than some of those other countries. Projections for cost reductions for the leading silicon and cadmium telluride technologies suggests that utility scale systems, while already attractive in other regions of the world, will not be broadly competitive with the US average wholesale rate of electricity without subsidies by 2016.[6,7,8,9] The cost reductions needed are unlikely to be achieved with technologies now in widespread production. Analysis shown in greater detail in Appendix F suggests that current crystalline silicon and cadmium telluride technologies are reaching the limits of what can be achieved through incremental improvement of current production methods. Dramatically new ideas are required.

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[6] Appendix C
[7] Appendix E
[8] Appendix F
[9] First Solar Analyst Investor Meeting, Las Vegas, June 24, 2009

Appendix C: **Cost Goals of the Current DOE program and $1/W Goal for utility scale systems (Figure 3 & 5)**

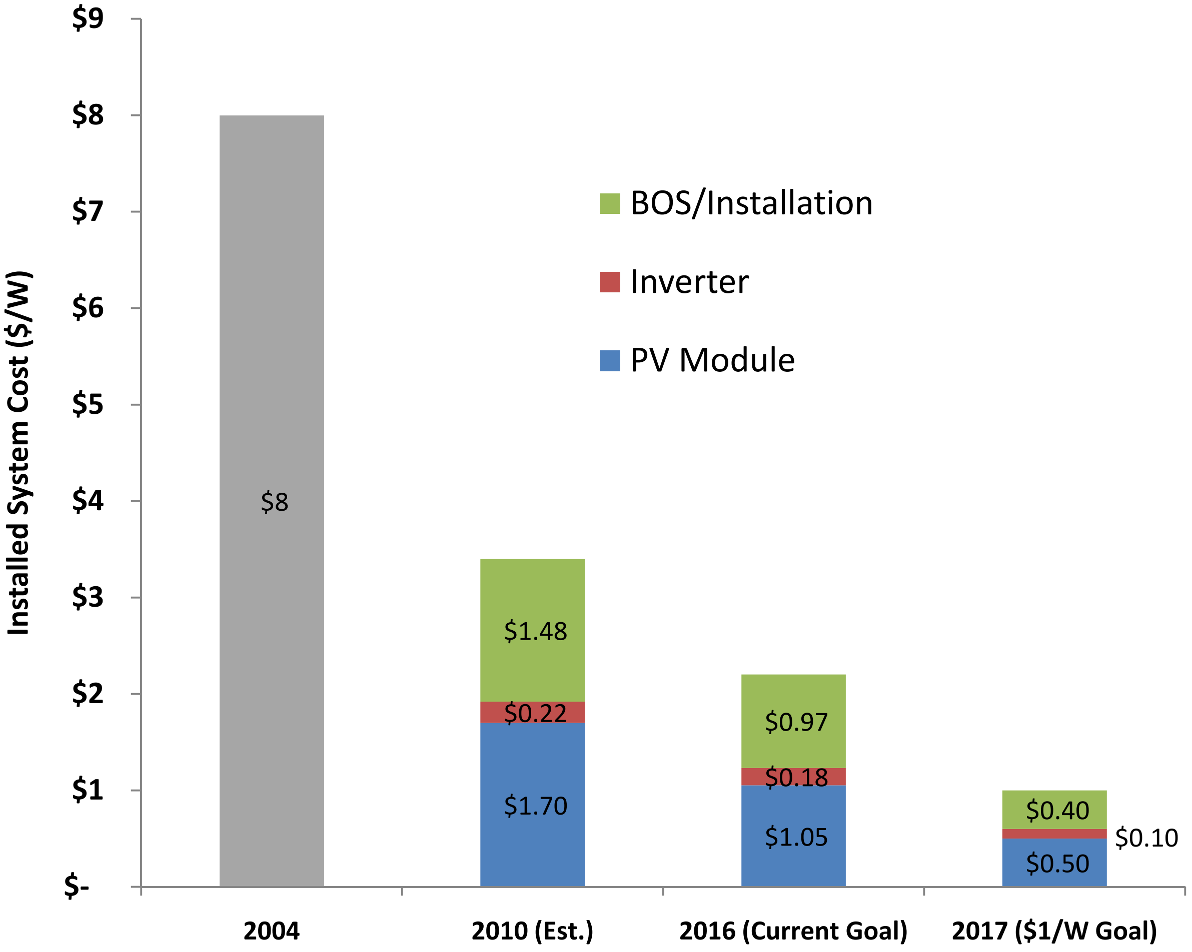

Figure 3: Cost Goals of the Current DOE Program (2016) vs. $1/W Goal (2017) for c-Si utility scale systems

Component Cost ($/W)	2010 (Est.)	2016 (Current Goal)	2017 ($1/W Goal)
PV Module	**$ 1.70**	**$ 1.05**	**$ 0.50**
Semiconductor	$ 0.54		
Raw Materials (Si feedstock, saw slurry, saw wire)	$ 0.36		
Utilities, Maintainence, Labor	$ 0.04		
Equipment,Tooling, Building, Cost of Capital	$ 0.06		
Manufacturer's Margin	$ 0.08		
Cell	$ 0.45		
Raw Materials (eg. metallization, SiNx, dopants, chemicals)	$ 0.18		
Utilities, Maintainence, Labor	$ 0.04		
Equipment,Tooling, Building, Cost of Capital	$ 0.04		
Manufacturer's Margin	$ 0.20		
Module	$ 0.70		
Raw Materials (eg. Glass, EVA, metal frame, j-box)	$ 0.26		
Utilities, Maintainence, Labor	$ 0.01		
Equipment,Tooling, Building, Cost of Capital	$ 0.01		
Shipping	$ 0.08		
Manufacturer's Margin	$ 0.34		
Retail Margin	$ -		
Inverter	**$ 0.22**	**$ 0.18**	**$ 0.10**
Magnetics	$ 0.03		
Manufacture	$ 0.05		
Board and Electronics (Capacitors)	$ 0.07		
Enclosure	$ 0.04		
Power Electronics	$ 0.03		
BOS/Installation	**$ 1.48**	**$ 0.97**	**$ 0.40**
Mounting and Racking Hardware	$ 0.25		
Wiring	$ 0.14		
Other	$ 0.17		
Permits	$ 0.01		
System Design, Management, Marketing	$ 0.15		
Installer Overhead and Other	$ 0.19		
Installation Labor	$ 0.38		
Total	**$ 3.40**	**$ 2.20**	**$ 1.00**

Table 5: $1/W Goal of Utility Scale Systems based on c-Si

Appendix D: Management Alternatives

Several different research models should be considered. These include:

1. **SEMATECH:** The SEMATECH research consortium was conceived in 1986 out of a concern that the United States was about to lose the entire semiconductor manufacturing industry to the Japanese. Jointly funded by the Defense Advanced Research Projects Agency (DARPA) and industry, it reported to a board with one government member. The consortium won a competitive solicitation. It had a Class 1 clean room operating in 32 weeks and attracted the best people in the industry. It developed detailed roadmaps showing what needed to be done to produce next-generation CMOS semiconductors and focused research on challenges the corporate members shared. Government funding, and government board membership, ended in 1995, and the organization continues as an independent organization.
    a. **Advantages:** The organization ensures that the topics chosen are closely aligned to the real needs of industry. It could operate flexibly and quickly without federal red tape.
    b. **Disadvantages:** The organization was able to identify a number of critical areas (such as manufacturing equipment) which were needed by all members but were not part of the businesses lines of the members – which revolved around the details of chip design not materials or manufacturing technology. This meant that they could share the intellectual property. Conversations with PV manufacturers have raised concerns that this model may be difficult to apply to the array industry since materials and manufacturing details are at the core of their intellectual property.
2. **Skunk Works:** The Lockheed Advanced Development Projects (aka Skunk Works) put together a team that crafted some of the most amazing aircraft ever built – including the U-2 and the SR-71--and did it in record time. The SkunkWorks team designed and built a prototype of the XP-80, one of the first turbojets, in only 143 days and played a major role in the Korean War.
    a. **Advantages:** Allows a highly creative team to address complex applied design and fabrication problems with few constraints.
    b. **Disadvantages:** This model may not work without an exclusive relationship with an individual corporation. It also relies on extraordinary leadership. The creativity for which the organization was famous began to dissipate when leadership changed. The infamous F22 aircraft was developed by the same organization.
3. **HUBs:** HUBs have the ability to pull together a diverse research team and form tight alliances with industry partners ensuring active movement of ideas out and problems in.
    a. **Advantages:** Model is well established and could be set up quickly
    b. **Disadvantages:** The HUBs are well designed to address a range of individual research problems but are not managed around tight roadmaps aimed at meeting hard price/performance targets by a date certain. It might be possible to change this.

4. **General Groves:** The Manhattan project succeeded because of creative, but very hierarchical, management, led by Lt. Gen. Leslie Groves. Some of the nation's most creative scientists were allowed room for creativity, but tightly focused on the practical problems at hand.
    a. **Advantages:** With the right management it can build creative alliances between scientific research and the design of practical devices.
    b. **Disadvantages:** The project did not need to develop commercial products or concern itself with intellectual property or similar issues. It was able to avoid most of the limitations that create delays in federal procurement and hiring. And it was extraordinarily expensive since the federal government picked up the entire bill.

Appendix E: Potential Pathways to Cost Reduction

Characteristic	Value or Qualifier
Module	
Efficiency	> 25%
Substrate	Lower cost and weight than glass
Reliability	30 years or can be replaced with minimum labor
Materials	Earth-abundant, non-toxic or established recycling plan.
BOS/Installation	
Labor	Can be done with non-specialized labor
Process	Lightweight (ease of handling, no special equipment)
Assembly	Snap together mechanical and electrical
Power Electronics	
Efficiency	>95%, improved module-peak power management
Reliability	30 years
Assembly	Integration of wiring, components to minimize electrical connections

Table 6: Success Characteristics

A top-level analysis of first estimate potential system and component performance requirements and characteristics of a $1/W system is summarized in Table 6. One of the greatest opportunities for cost reduction lies in module and system efficiency enhancements. Efficiency advances reduce not only the PV module cost but also much of the Balance of Systems (BOS) and fixed system costs. For example, if modules were twice as efficient, with the same labor and mounting hardware, twice the power can be obtained, thereby reducing the BOS cost.

Analysis of the manufacturing and installation costs of PV systems reveals several pathways to achieve the 50 cents/watt module cost target that is consistent with a $1/watt total installed system cost. The primary requirements are that module efficiency needs to be 25% or greater and product lifetime needs to exceed 30 years.[10] Meaningful BOS cost reduction is not possible without raising module efficiency. Product lifetime needs to be long enough to amortize the installation and disposal costs.[11]

A. Low Cost Arrays

The goal is to build an array at a cost which makes a price of 50 cents per watt feasible, while achieving efficiency greater than 25% and a lifetime of at least 30 years with minimal maintenance. The modules must be built at tremendous volume which requires that they be based on earth-abundant material. And they must be recyclable. The low cost suggests that they almost certainly will not use traditional thick glass or significant amounts of purified silicon that contribute significantly to today’s array costs.

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[10] Appendix F

[11] Non-Module Cost Sensitivity to Efficiency, “DOE $1/W Workshop Photovoltaic (PV) Industry Primer,” July 2010.

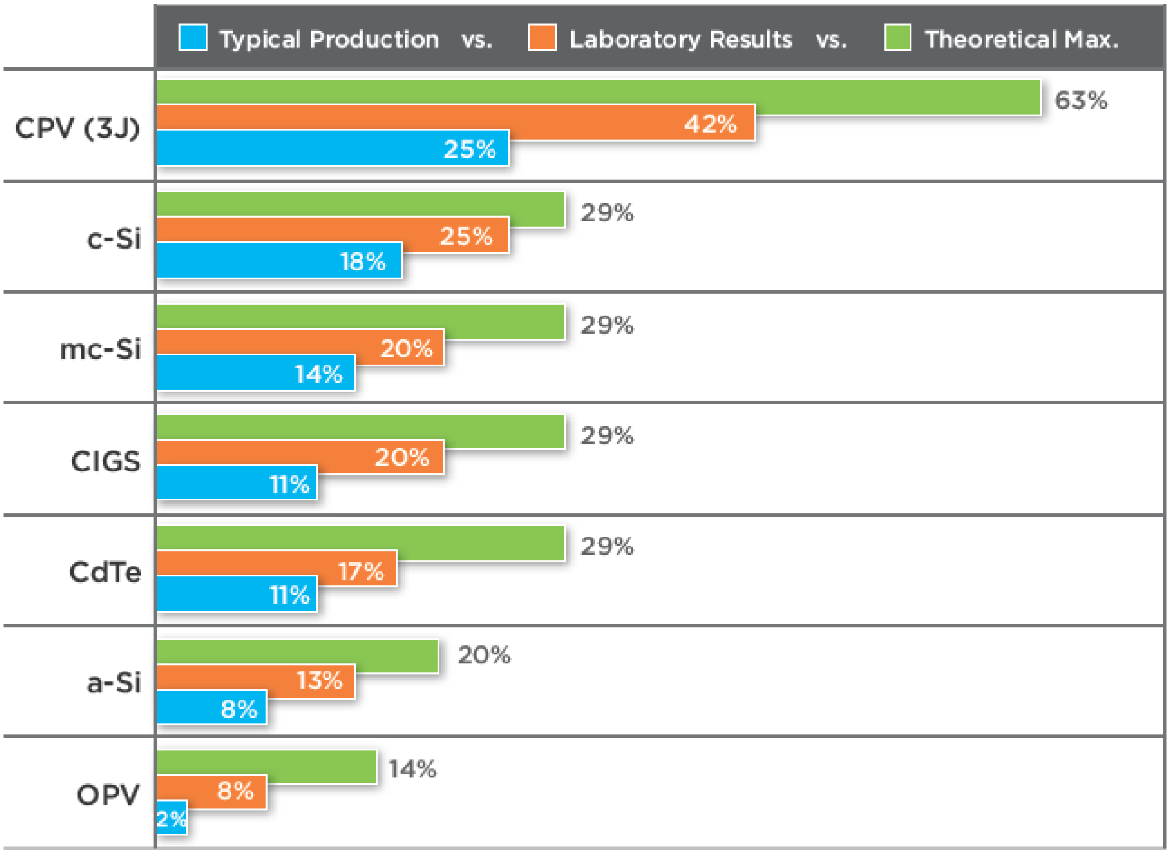

Figure 4: Gaps in efficiency between best laboratory results and theoretical limits and between production and best laboratory results provide opportunities for improvement. (Theoretical based on Shockley-Queisser limit and bandgap of semiconductor. NREL verified best cell efficiency)

Devices capable of meeting the goal:

As shown in Figure 4, commercial cells operate far below theoretical potential efficiencies and well below efficiencies demonstrated in the laboratory.[12,13] Due to the compounded system cost benefits associated with efficiency gains, closing these gaps is critical.

Wafer silicon is a mature technology and efficiencies of commercial cells are approaching theoretical limits. Thin film approaches can reach 25% or higher module efficiency on inexpensive substrates with potentially scalable and cost-effective deposition methodologies, but since they are comparatively new, the gap separating theoretical from production arrays is quite large. Cadmium telluride arrays are in large scale production but have only achieved 11% module efficiencies in production; and 17% in laboratory devices. There is also concern that the cost of reclaiming, and recycling cadmium-containing PV modules will escalate in the future.[14] Thin film CIGS, which also currently contains very small

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[12] http://www.tfp.ethz.ch/Lectures/pv/thin-film.pdf

[13] http://scitation.aip.org/getpdf/servlet/GetPDFServlet?filetype=pdf&id=APPLAB000095000016163302000001&idtype=cvips&prog=normal&doi=10.1063/1.3243986&bypassSSO=1

[14] http://seekingalpha.com/tag/transcripts?source=headtabs

amounts of cadmium sulfide, has even greater opportunity for efficiency improvement with 10% to 11% in production and more than 20% in the lab. The future cost of CIGS modules and this technology's ability to contribute to very large scale PV power markets depends upon the availability of indium and gallium. CZTS, a material system very similar to thin film CIGS but with indium and gallium replaced by more earth-abundant zinc and tin, provides a relatively new opportunity for a transformational change of the PV market in support of reaching 50 cents/watt module costs.

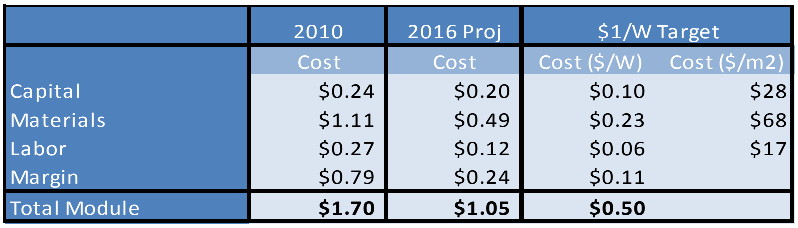
Organic photovoltaic (OPV) and dye-sensitized cell (DSC) devices have received significant interest as promising paths to very inexpensive solar modules. To be commercially viable, these technologies must solve significant issues with efficiency as well as lifetime. Significant breakthroughs in these areas are still needed.

Concentrated PV (CPV) takes a different approach to conventional flat modules by leveraging advanced optical systems to shift the cost balance of cell manufacturing to module manufacturing. Higher efficiency CPV devices as well as innovative systems approaches to CPV module assembly could increase the typical 25% or lower efficient modules currently produced to greater than 35% module efficiency if the semiconductor device can exceed 50% efficiency. Advances in optical design, manufacturing and assembly would also be required. An alternative approach is to apply lift-off process to the high efficiency III/V cells used in CPV modules. These processes have the potential to significantly reduce the costs of III/V cells and make them available for un-concentrated flat-plate or flexible modules.

While the uncertainties are much higher, it is possible that inexpensive arrays with efficiencies much higher than those shown in Figure 4 can be built using advanced multi-junction thin films for many III/V and II/VI systems through bandgap engineering such as tandem junction structures on thin-film materials (Ex: InSb on thin-film CdTe, or GaP on thin-film Si). Such innovations would require breakthroughs in tunnel junction formation over large areas across potentially highly lattice mismatched polycrystalline interfaces. Perhaps recent advances in thermo-electric devices could make it viable for photovoltaic devices in a concentrating system.

Module Production Technology:

Low production costs are clearly essential to meet the price goals. This will require dramatic innovations that can cut both capital and labor costs in array manufacture.



	2010	2016 Proj	$1/W Target	
	Cost	Cost	Cost ($/W)	Cost ($/m2)
Capital	$0.24	$0.20	$0.10	$28
Materials	$1.11	$0.49	$0.23	$68
Labor	$0.27	$0.12	$0.06	$17
Margin	$0.79	$0.24	$0.11	
Total Module	**$1.70**	**$1.05**	**$0.50**	

Table 7: Detailed cost breakdown for c-Si PV module ($\$/m^2$ values assume 29% efficiency

Based on DOE analysis, cells produced below 50 cents per watt would likely mean 10 cents per watt for capital depreciation, 23 cents per watt for materials, and 6 cents per watt for labor.

Capital costs: Assuming a seven-year depreciation period, initial capital costs will need to be on the order of 70 cents/watt. This is approximately 50% lower than the costs of today's state of the art thin film PV facilities.

Material costs: if we assume an extremely ambitious module efficiency of 29%- the limit of wafered silicon – reaching a materials cost of 23 cents/watt would be equivalent to an area cost of \$68/m^2. Even at this high efficiency, current commodity materials such cover glass, substrates and backsheets, silicon, silver, aluminum framing could consume the entire budget with little current potential for cost reduction (Figure 6 shows a graphical depiction of these and other materials). At current costs, glass with Transparent Conducting Oxides (TCO) and anti-reflection coating might take up as much as 16% to25% of this total, indicating the need for cheaper substrates and better coating technology. Frames and other structural parts might take up as much as 25% of the total indicating the need for frameless, possibly flexible module technology.[15]

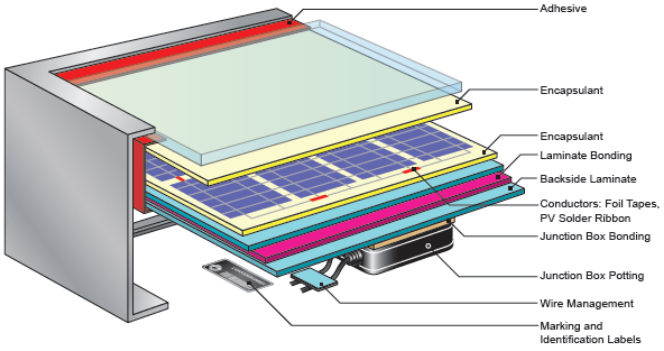


Figure 5: Silicon PV module contains many commoditized raw materials including silicon, glass, and aluminum. The challenge will be to reduce the costs or utilization of these materials while improving module efficiency. (Graphic source: Hisco)

Production costs can be reduced sharply with process innovations including low-cost highly scalable approaches such as deposition on low-cost non-woven textiles or roll-to-roll film processing (Figure 6).

Innovations in a number of areas could sharply cut production costs for advanced module designs including:

- Low cost or virtual single crystal enabling substrates reducing waste associated with sawing wafers, thereby reducing materials usage (grams per watt) by a factor of 2 or more
- Ultrathin wafers that not only enable greater material utilization, but also inherently improve certain loss mechanisms (ie. bulk recombination losses); optimize wafer thickness
- Low stress tabbing techniques, such as pre-patterned backsheets that not only enable the stringing of ultrathin cells into modules but may also enable semi-flexible roofing laminates, greatly reducing deployment costs.
- Defect engineering and a deeper scientific understanding of the role of impurities and structural defects as well as ways to make them electrically inactive can improve the efficiency of solar cells
- Flexible PV solutions that enable innovative BIPV and field deployment approaches that could significantly reduce BOS costs. PV modules that serve a dual purpose as a building facade, or roofing membrane further reduce installation costs.

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[15] NREL Analysis memo, "Solar Manufacturing Cost Models," Alan Goodrich, April 29, 2010.

- Inexpensive and high performance (conductivity, transmissivity; absorption) TCOs or designs that eliminate the need for vacuum processing of TCOs entirely reduces the series resistance of PV modules.
- Atomic barriers that can provide better moisture impermeability to the PV device than glass, thereby increasing reliability and functional module lifetime.
- High growth rate epitaxy of Group IV, III/V, and II/VI semiconductors on low cost substrates. Very high frequency plasma deposition or other processes has the potential to increase PV deposition rate and reduce equipment cost by 10X while maintaining large area uniformity and material quality through new approaches to source and process design.

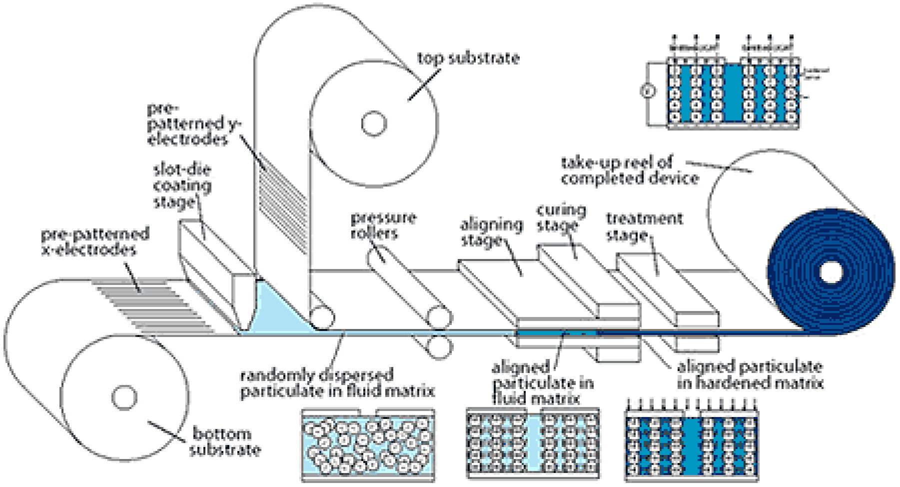

Figure 6: Roll to Roll continuous processing can significantly reduce manufacturing costs has it has done in a number of other industries

- Breakthrough approaches to deposition from atmospheric pressure liquid processing could significantly increase throughput and lower deposition costs
- Plasmonics and nanowire thin films can enhance light trapping
- Combinatorial approaches to materials discovery and characterization as well as device optimization can greatly speed up the development of new technologies and allow efficiency to approach theoretical limits. A PV Materials Genome Project could enable researchers to rapidly screen candidate PV absorber systems and link theoretical understanding PV materials with experimental confirmation of material properties.

Figure 7: Highly automated agriculture equipment revolutionized harvesting of crops. http://www.businessweek.com/magazine/content/08_22/b4086072681496.htm?chan=search

B. Balance of System and System Installation

The BOS and installation costs include for example: mounting and racking hardware, installer overhead, permits fees, land preparation, and installation labor. This currently adds about $1.48/watt to the cost of an installed system. The $1/watt goal requires a reduction to about $0.44/watt (Table 1). It will probably be necessary to cut installation labor costs to approximately 5 cents/watt and mounting and racking hardware must reduce to about 20 cents/watt. This will require fundamentally new approaches.

Figure 8: Low levels of automation for solar field installations are just beginning to be developed. http://www.philadelphia-solar.eu/philadelphia_solar_gallery.html

As a benchmark, a modern 20-MW utility solar plant covers approximately 150 acres. The installation takes a crew of 100 people six months to install completely.[16] Labor alone adds 10 cents to 15 cents/watt. Two principal strategies for reducing installation costs will be in competition: (1) reducing the cost of installing huge arrays in open fields, and (2) incorporating the arrays into building components that could substitute for standard roofing materials.

Figure 9: Plastic covering a strawberry field demonstrating the potential of rolling-out PV.

http://photosbygarth.com/samples-lg/050115_202p_9584lg.jpg

Field Installations:

Modern agriculture uses highly productive machines called combines that can process (reaping, binding, and threshing) 200 acres a day, as shown in Figure 7. These machines offer a model of what could be possible employing innovative robotic approaches to PV field installation.

Figure 10: Solar roof tiles demonstrating the potential for large automated snap-together PV.

http://www.reuk.co.uk/OtherImages/solartiles.jpg

Limited automation for PV installation is already in existence where currently some PV installations machines drive posts into the ground, as shown in Figure 8, but this device is designed only to put tens of thousands of posts in the ground. Much greater

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[16] Quote: Data provided by an installer for c-Si array deployed with 1-axis tracking.

cost reductions could be achieved using a device that combined 1) post digging; 2) rack hardware installation; 3) module mounting and 4) electrical connection.

In addition to automated installation, innovative array designs can lead to major cost reductions. These include:

- Rolling-Out PV (i.e., PV on a flexible substrate, similar to how plastic is rolled across farm fields for fumigation, Figure 9).
- Continuous PV (i.e., modules that can nearly continuously be deployed analogous to paving crews that drive down the road removing pavement and installing fresh pavement in a continual process)

Building Installations:

Installation costs can also be cut sharply if the photovoltaic arrays can be installed as a building material. Arrays integrated into roofing materials could combine weatherproofing with electric generation. The incremental cost of installing the arrays could be quite small and little or no additional structural support would be required. The systems would be easiest to design for new construction, but it is possible that the devices could be integrated in membranes or other equipment used to replace worn commercial roofing. One such concept is shown in Figure 10 using modules that rapidly interconnect and displace the costs of current roofing materials and labor.

Central to each of these proposed installation cost reduction strategies is the need to reduce the amount of specialized labor that is required. The following sections propose methods for integrating into the module the power electronics and other system components, thereby significantly decreasing PV installation labor.[17]

C. Power electronics

The power electronics – specifically the inverter – is the interface between the module and the grid converting the direct current output of the arrays into the high voltage alternating current needed for most power applications. It currently adds about 22 cents/watt to solar installations and this must be cut to about 8 cents/watt to meet the goal.[18] The cost and performance of the inverter may not be a dominant portion of the total installed systems cost but it is a significant portion and needs to be addressed in order to achieve $1/watt. Today, the power electronics (1) are the dominant point of failure for the installed system and are a major component of maintenance, (2) are

Capacitor Type	Failure Rate (%/1000h)
Electrolytic	0.2
Tantalum	0.1
Paper	0.05
Ceramic	0.025

Table 8: Approximate Reliability of capacitor types

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[17] Electrical component installation labor can account for as much 78% of the man-hours required for a utility scale system. The national average (source: RS Means, 2010) burdened electrician rate is $72.85/hour. PV hardware installed by general or roofing contractors would provide a savings of up to 19%.

[18] Data provided by an anonymous systems installer.

responsible for a loss of approximately 4% of all of the electricity generated, and (3) add complexity and cost to wiring and installation. Megawatt-scale inverters weigh in excess of 10,000 pounds, and occupy more than 500 cubic feet of space.

Figure 11: Example of a failed electrolytic

Current generation inverters are only expected to last about 10 to15 years, requiring at least one replacement during an anticipated lifetime of 30 years or longer for a PV array. This limited life means that the inverter's contribution to a levelized cost of electricity is higher than the original installed cost. One reason for limited lifetime is the use of electrolytic capacitors which have failure rates that are 10 times greater than that of lower energy density thin film capacitors (see Table 8, Figure 11). It is projected that current cost reductions in the inverter will be achieved through advanced circuit architecture that avoids the need for electrolytic capacitors; however, this alone is not sufficient to permit large scale deployment. Besides cost, inverter performance and functionality will become an increasingly important factor with higher levels of penetration of renewable electricity on the grid. Better communications and functionality will require radically different architecture for PV power electronics.

Approaches to major improvements in power electronics fall into two categories: (1) major redesigns of existing large-scale inverters, and (2) developing small units that can be mass produced and attached to individual modules.

Major redesigns of existing large-scale inverters:

Existing MW-scale inverters employ high-voltage silicon switches and large magnetic transformers. The high voltages on the transmission side of the inverter are managed through a combination of large 60 Hz transformers and stacked silicon switches. Advanced high-voltage, high-frequency switch components, low loss magnetic materials, and novel circuit architectures have the potential to significantly reduce the size and cost of MW-scale inverters while simultaneously increasing the overall efficiency.

For example, wide-bandgap semiconductors such as SiC have the potential to switch at 13kV with frequencies as high as 50 kHz. The higher voltage reduces the packaging cost and complexity of the system. The higher switching frequencies dramatically reduce the size and cost of the transformer because for fixed impedance, the inductance scales inversely with the switching frequency. Advanced magnetic materials, such as nano-crystalline composites with low electrical conductivity and low hysteresis, can enable switching frequencies that are 100-1000 times higher than employed today. Scaling the switching frequency from 60 Hz to 50 kHz can allow the core-transformer to scale from 8,000 lbs. to less than 100 lbs.

Power electronics attached to modules:

Electronic components and circuit architectures that can be embedded in the module frame would allow maximum power point tracking to occur at the module or sub-module level. The resulting modules would be more tolerant to partial shading (allowing for potentially denser installations) and could 1) route power around sub-optimal modules or cells (improving system availability and mitigating reliability of individual cells), and 2) directly produce AC voltages (simplifying residential installation while increasing the safety and reliability).

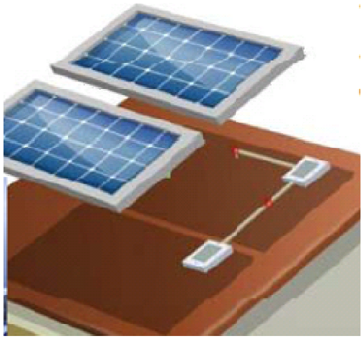


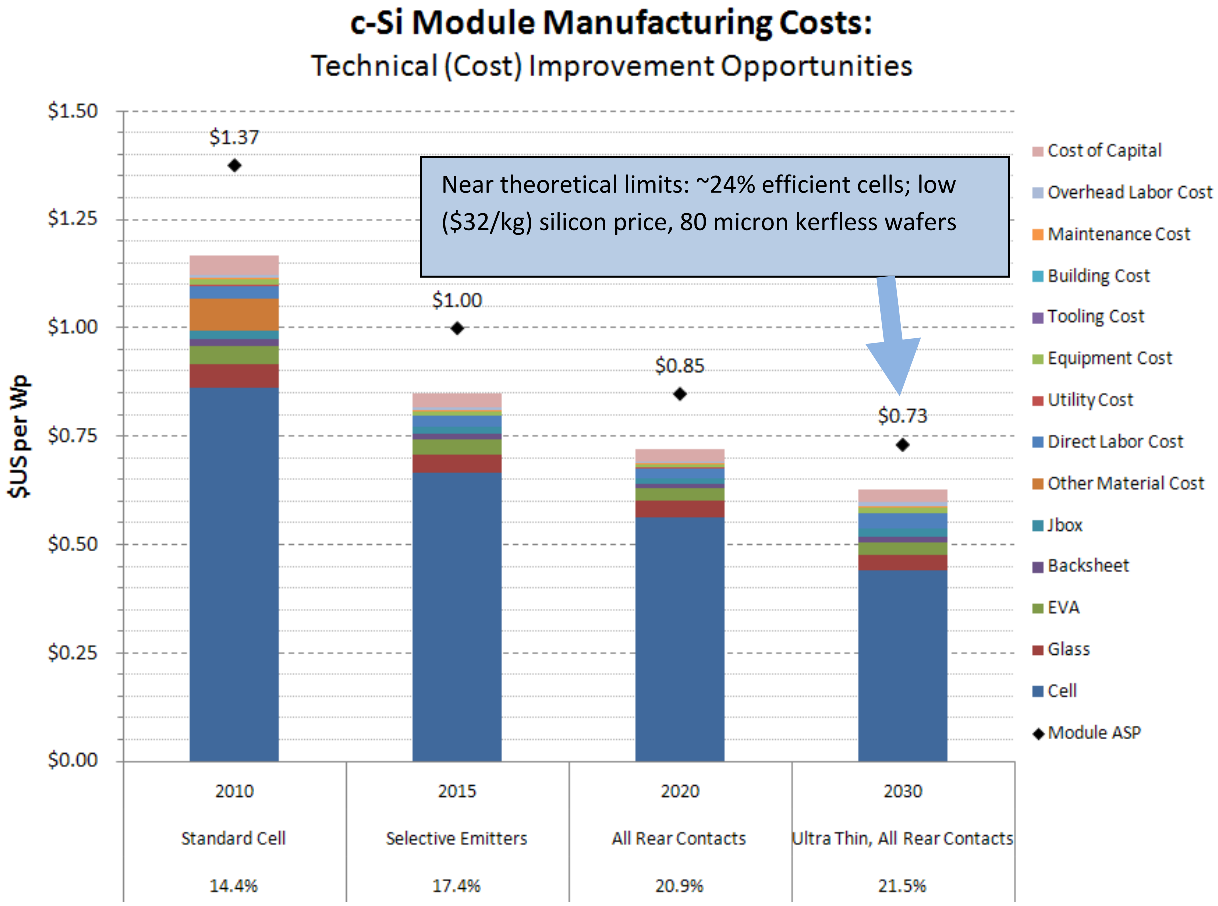
Figure 12: Microconverters on each module promote better communication and functionality amongst modules.

One possible approach would be to create module integrated power electronics where advanced semiconductors would need to be integrated with beyond state-of-the-art magnetic and dielectric materials to realize low-cost, small-form factor, batch manufactured power converters that could potentially be installed on each module (Figure 12). These electronics would require advanced semiconductor materials that could withstand high temperatures (100 C back skin temperatures) and maintain high-frequency switching.

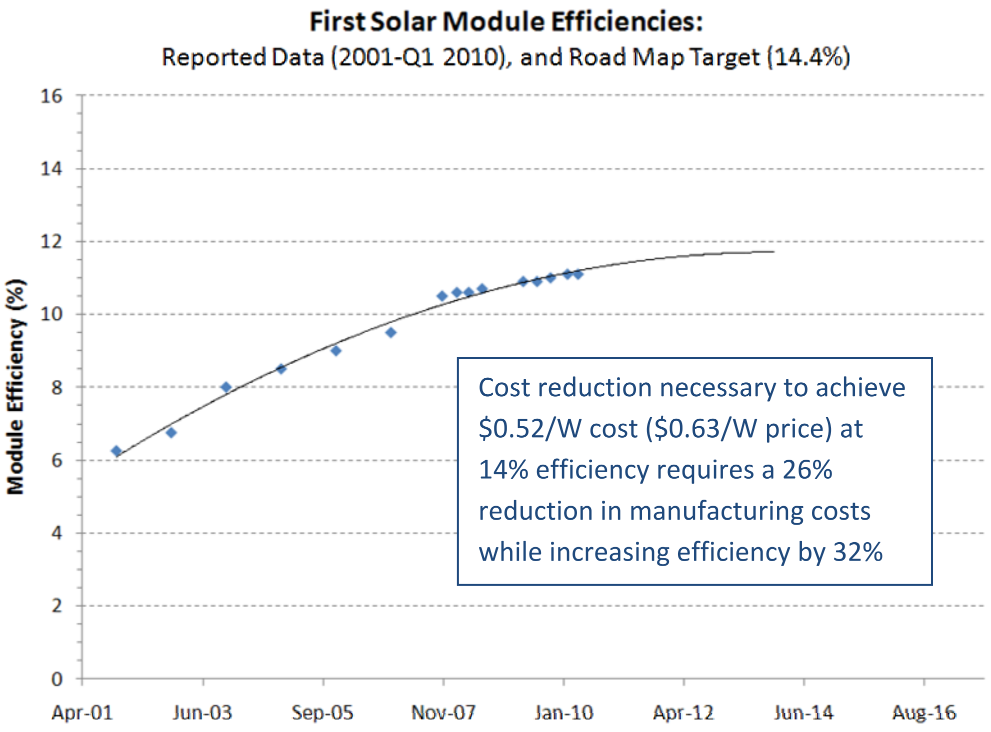
The same approach of higher internal switching frequency that was discussed for utility scale inverters could also be applied to module integrated power electronics. Such an architecture would permit modules to be easily connected and improve the overall energy efficiency of the system by allowing each micro-inverter to frequency match each module.

Appendix F: Challenges for Cost Reduction in Array Production

Solar PV technologies have, to date made significant progress reducing the cost of modules but a detailed analysis of the future of crystalline Silicon and Cadmium Telluride cells suggest that they are unlikely to meet the target prices given technologies driving current learning curves. The figure below shows that crystalline silicon module prices could reach around 73 cents per watt prices if they are able to achieve 80% of the theoretical limit of single cells (29%) and if wafer thickness can be reduced to 80 microns (they are about 180 microns thick today).



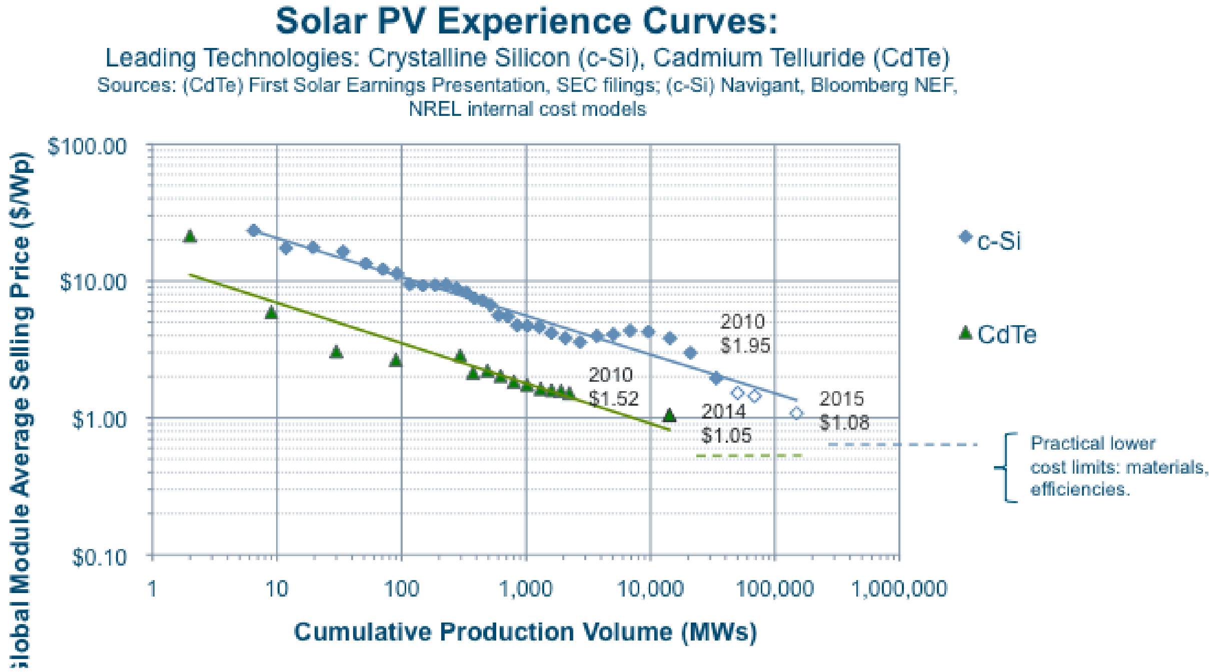
Cadmium Telluride modules have achieved sharp price reductions and are on a path of continuous cost reduction driven in part by continuous improvements in efficiency. Current cells have an efficiency of approximately 11% but efficiencies of 17% have been achieved in the laboratory and theoretical efficiencies are approximately 29%. The experience of the past few years suggests, however, that efficiencies above 11% are extremely difficult to achieve in practice and the rate of efficiency increases has slowed considerably in recent years. Making the optimistic assumption that efficiencies can reach 14% while the cost of producing a unit of array area declines by 26%, array prices would still be around 63 cents per watt.



First Solar Module Efficiencies:
Reported Data (2001-Q1 2010), and Road Map Target (14.4%)

Cost reduction necessary to achieve $0.52/W cost ($0.63/W price) at 14% efficiency requires a 26% reduction in manufacturing costs while increasing efficiency by 32%

Figure 13 Quarterly reported module efficiencies for the leading CdTe manufacturer First Solar suggests that significant innovation is required to continue to advance the technology.



Solar PV Experience Curves:
Leading Technologies: Crystalline Silicon (c-Si), Cadmium Telluride (CdTe)
Sources: (CdTe) First Solar Earnings Presentation, SEC filings; (c-Si) Navigant, Bloomberg NEF, NREL internal cost models

Practical lower cost limits: materials, efficiencies.

Figure 14: Global solar PV module price trend: silicon wafer based and CdTe, historic and short term forecast[19]

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[19] Sources: Mints, Navigant; Bloomberg NEF; First Solar Earnings Reports; NREL internal silicon PV cost model

Nevertheless, past performance is not necessarily an indicator of future progress. The trend of module prices depicts the composite impact of several complicated factors, including for example: manufacturing efficiencies, economies of scale, and innovation.[20] As these technologies mature, the contribution of manufacturing efficiencies and economies of scale to further cost reductions will diminish. The importance of continued and impactful innovations will become critical to maintaining the historic trend.

For c-Si, without new module encapsulation materials, costs will reach a natural asymptote defined by the cost of commodity materials like glass (asymptote, or lower limit of current c-Si module costs depicted in Figure 14 by blue dashed line).

For CdTe, the leading thin film technology, further cost reduction will require higher average module efficiency, expected to reach over 14% by 2014 based on a roadmap provided by First Solar. While the pathway to this goal is known and involves technical innovations, implementing these innovations in a high volume production scenario will be challenging. Greater challenges exist to increase this technology's efficiency beyond 14%, such as improving the lifetime of the absorber layer. It is generally believed that in order to improve the quality of the absorber, the grain size will need to be increased. One way to accomplish this is to slow down the deposition process, but this has the undesirable effect of increasing the cost. Innovation in materials technology is required to eliminate this tradeoff.

If we assume a breakdown between capital, materials, and labor following the proportions projected for a typical c-Si module in 2016, given in Table 7, then this 48 cents will be composed of 9 cents/watt for capital depreciation, 22 cents/watt for materials, and 5 cents/watt for labor. This breakdown provides further illustration of the challenges to reach $1/watt total systems. For example, assuming a seven-year depreciation period, initial capital costs will need to be on the order of 63 cents/watt, approximately 50% better than First Solar's and 25% to 33% of current wafered silicon.

For materials, if we assume an extremely ambitious module efficiency of 29% -- the Shockley-Queisser limit of wafered silicon – the 22 cents/watt would be equivalent to an area cost of $65/m^2. Even at this high efficiency, current commodity materials such cover glass, substrates and backsheets, silicon, silver, aluminum framing could exceed the system's budget for module cost. At current costs, glass with a TCO and anti-reflection coating might specifically take up as much as 16% to 25% of this total, indicating the need for cheaper substrates and coating technology. Frames and other structural parts might take up as much as 25% of the total indicating

	2010 Est.	2016 Proj	$1/W Target	
	Cost	Cost	Cost ($/W)	Cost ($/m2)
Capital	$0.20	$0.20	$0.09	$27
Materials	$0.79	$0.49	$0.22	$65
Labor	$0.09	$0.12	$0.05	$16
Margin	$0.62	$0.24	$0.11	
	$1.70	$1.05	$0.48	

Table 9: Detailed cost breakdown for c-Si PV module ("$1/W Target" assumes 29% efficiency)

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[20] Gregory F. Nemet, "Beyond the learning curve: factors influencing cost reductions in photovoltaics", Energy and Policy 34 (2006) 3218-323, August 2005

the need for frameless, possibly flexible module technology. Going toward flexible or other lightweight structural module approaches could also significantly reduce shipping costs, currently 8 cents to 10 cents/watt.[21]

Table 9 assumes significant potential cost reduction through production models that condense the supply chain. Wafered silicon modules currently have as many as four different steps in the supply chain (polysilicon processing, wafering, cell production, and module assembly), each extracting a separate margin which adds cost to the final product. While there has been some attempts at integration (mostly through combining polysilicon processing and/or combining wafering and cell and module production) there has also been counter trends toward disaggregation. Moving toward thin film technologies that are inherently more integrated would significantly reduce margins. First Solar for instance brings in basic materials such as glass, deposition gases, and other materials in one of their factories and ships out finished modules from the other end. There is currently no analogous production facility for wafered silicon. Moving the industry toward thin film technologies would also counter current competitive advantages of Chinese wafered silicon manufacturers and potentially create more opportunities for U.S. exports.[22]

	2010	2016 Proj	$1/W Target	
	Cost	Cost	Cost ($/W)	Cost ($/m2)
Mounting, Wiring, Other	$0.87	$0.38	$0.17	$50
Installation Labor, OH, othe	$1.10	$0.41	$0.19	$54
Permitting, Design, Mgt	$0.23	$0.18	$0.08	$24
	$2.20	$0.97	$0.44	

Table 10: Detailed cost breakdown for BOS/Installation ("$1/W Target" values assumes 29% efficiency)

Similar analysis could be done to look at the challenges with the Balance of Systems (BoS) and Installation cost components. Referring to Table 10, installation labor and over head to install the $1/watt system would be approximately 19 cents/watt. For large utility systems, only one-fifth of the labor is for mechanical installation with the majority being for electrical connections. This indicates that there exists an opportunity to reduce installed costs through efficient component design. For example, micro-invertors integrated into each module might be developed to exploit new innovative connection schemes that reduce electrical installation labor costs. Other paths for cost reduction might include having larger panels, potentially installed as rolls of flexible material, with many of the electrical connections integrated.

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[21] NREL Analysis internal memo, "Solar Manufacturing Cost Models," Alan Goodrich, April 29, 2010.

[22] Asia: 65% silicon wafer-global market share; Company production capacities Silicon for Solar Cell", RTS Corporation, September 2009

Appendix G: Preliminary analysis of Efficiency, Cost, and Reliability Barriers (Table 11)

	Barriers to 25% Efficiency		Barriers to $125/m2 Module ($0.50/W)		Barriers to 30 year reliability	
CPV	For CPV, target is 35% Module, currently <30% Module. Potential path is to integrate with thermoelectrics.		1) Streamlined module assembly supply chain to support low cost module assembly and low shipping costs		1) Thermal design to keep devices at a low enough temperature.	
	1) Improve control and mitigation of dislocations to less than 1e6/cm2 (i.e. a factor of at least 2 to 4 improvement) for junctions with bandgaps of 1 eV and below.	🔴	2) Cost reduction of optical elements - migration away from glass optics	🟡	2) Long term reliability of plastic optics.	🟠
	2) Improve carrier transport across heterointerfacesat high concentrations to lower effective lumped series resistance through the cell by a factor of 4 or better.	🔴	3) Cost efficient 1 or 2 axis trackers	🟡	3) Low or no maintainence 1 or 2 axis trackers/motors.	🟠
	3) Multi-terminal devices to decouple bandgaps from solar spectrum	🟡				
c-Si	1) Reduce front and back surface recombination velocity to less than 10 cm/s	🟡	1) greatly reduced silicon usage - film silicon or kerfless; yield associated with thin silicon	🟡	1) Light Induced Degradation (B-O-P)	
	2) improve bulk material lifetime over 1 ms	🟠	2) Control of cell bowing	🟠		
	3) improve Jsc over 43 mA/cm^2 by novel light trapping and reduction of front finger shadowing	🟠	3) Glass and other commodity costs	🔴		
			4) corner rounding losses	🟡		
Film Si	1) Light Trapping to increase absorption	🟡	1) Low temperature high throughput epitaxy	🔴	1) interconnect reliability	🟡
	2) Reduce front and back surface recombination velocity to less than 5 cm/s	🔴	2) Cost efficient seed layer (silicon on glass, virtual substrate, layer transfer)	🔴		
	3) Rear contacted cell design	🟠	3) Module level cell processing	🟠		
mc-Si	1) Improve minority carrier lifetime; Defect engineering to understand and passivate defects and impurities which tend to localize near grain boundaries	🟠	1) greatly reduced silicon usage - film silicon or kerfless; yield associated with thin silicon	🟡	1) bias induced degredation for modules	
	2) Reduce back surface recombination velocity	🟡	2) Control of cell bowing; migration away from Al back surface field	🟡		
	3) IncreaseUV absorption with higher emitter sheet resistance	🟡	3) Reduced glass and other commodity costs (Al, Ag, EVA, Tedlar,...)	🔴		
	4) multijunction with a-Si	🔴	4) Novel low or no pressure processing	🔴		
CIGS	1) Large area inhomogeneity	🟠	1) High rate low cost deposition	🟡	1) moisture and oxygen permeability of flexible barrier	🟡
	2) Lower resistance microgrid or transparent conductor	🟠	2) Reduced glass and other commodity costs	🔴	2) puncture and hail resistance of flexible barriers	🔴
	3) Understand and control Na, O2, and Cu diffusion	🔴	3) Flexible Atomic layer Ultra-barriers	🟡	3) Ultra edge sealing (moisture and O2 ingress from edges)	🔴
	4) Increase VOC with wider bandgap around 1.4-1.5eV	🔴	4)Reduced Indium cost and availability (Thinner absorber)	🔴	4) Copper diffusion	🔴
CdTe	1) Understand and control oxygen and chlorine passivation of defects to improve minority carrier lifetime; increase p-type doping while maintaining lifetime	🔴	1) High rate low cost deposition	🟡	1) moisture and oxygen permeability of flexible barrier (stability of CdTe under moisture and oxygen exposure)	🟠
	2) Lower resistance microgrid or transparent conductor	🟠	2) Larger modules	🟡	2) puncture and hail resistance of flexible barriers	🔴
	3) Understand fundamental VOC limitations	🔴	3) High throughput streamlined manufacturing with low Capex	🟡		
	4) Reproducible functionality of Te-rich CdSTe layer/CdTe junction with low recombination without high-temperature	🟠	4) All dry processing	🟠		
	5) Improved back contact, control copper diffusion	🔴	3) Terrawatt scale materials availability	🔴		
a-Si	1) Improve TCO's sheet resistance better than 10 ohm/square and transparency over 90%; improve	🟡	1) High rate low cost deposition	🟡	1) Staebler Wronski Effect of light induced degradation	🔴
	2) improve Jsc over 20 mA/cm^2 - improve quality of low bandgap junction	🟠	2) CAPEX for manufacturing equipment	🔴	2) module level reliability of interconnects and laminants	🟡
	3) improve a-Si hole mobility to 1 cm^2/Vs	🟠	3) Glass and other commodity costs	🔴		
	4) improve multi-junction cell performance	🔴				
OPV	1) Development of acceptor polymers (n-type) with increased red absorption and homo/lumo so as to optimize Voc and Isc simultaneously.	🔴	1) Industrial scale manufacturing (yield and purity) of fullerine derivatives in cost effective manner	🔴	1) Reliability more than 5 years, control of moisture (water/PDOT interaction), O2 (calcium and lithium interaction) and UV (ionization) degradation mechanisms	🔴
	3) Optimize the interfacial properties between the acceptor and donor and the bulk heterojunction and contacts to optimize Isc/Voc/FF and to enhance stability.	🔴	2) Cost effective synthesis of diephene and other potential high efficiency compounds	🔴	2) Develop an understanding of the degradation mechanisms in OPV and develop a rational to minimize their effects.	🔴
	2) Increase mobility and carrier transport	🔴	3) pinhole and homogenaity	🔴	3) Flexible ultrabarriers with low moisture and O2 pemeability	🟡

Following the example of the Sematech roadmap, the above table, divides problems into four categories:

Manufacturable solutions exist and are being optimized	
Manufacturable solutions are known	🟨
Interim solutions are known	🟧
Manufacturable solutions are NOT known	🟥

Appendix H: The need for Government funding

Venture capital and other private capital sources have fueled significant growth in the development and manufacturing of PV and other solar technologies over the last 5 years, as shown in Figure 15. These investments focused largely on technologies that could be commercialized in 2 to 4 years, in order to respond to government incentive programs. This trend has peaked, however, and, as shown for 2009, overall VC and private equity capital investments in solar are decreasing. This is due to the current economic conditions which have limited opportunities for private capital sources to exit their investments through public markets, also shown in Figure 15. The development of solar technologies is capital intensive and many private capital sources are focused on seeing their existing investments through to maturity rather than considering new investments. These and other factors have therefore limited the available pool of private capital to invest in the next generation of solar technologies.

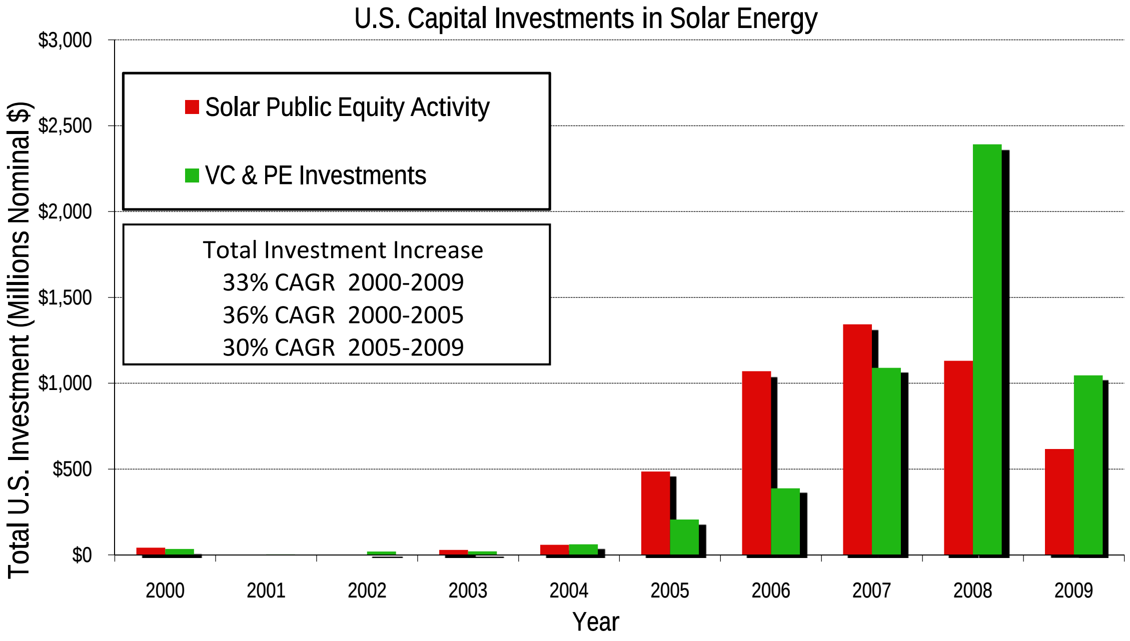

Figure 15: US Capital Investments in Solar Energy

The current environment therefore provides a need and an opportunity for Federal R&D funding to fill a gap in the solar technology investment pipeline. The Federal government has played this role before in launching the current solar technology industry as well as other new industries in electronics and biotechnology.

In addition to addressing the administration's energy and environmental goals, an investment by the Federal government that targets the utilization of the country's extensive research and manufacturing infrastructure will contribute significantly towards export and economic growth initiatives. It is estimated that by 2012, and assuming standard solar PV cost targets and global demand projections export opportunities throughout the solar PV supply chain will exceed $18.0 billion.[23]

Other countries, including China and Malaysia have made a renewed commitment to their nation's solar PV industry, attracting global manufacturers, including companies whose technologies were, in some cases, at least partially developed at US institutions.

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[23] NREL analysis memo in support of the President's National Export Initiative, "SOLAR ENERGY TECHNOLOGIES: US Export Opportunities", May 2010