Line-Focus Solar Power Plant Cost Reduction Plan

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

Milestone Report
NREL/TP-5500-48175
December 2010

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

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Prepared under Task No. CP09.1001

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Introduction

Line-focus solar collectors, in particular parabolic trough collectors, are the most mature and proven technology available for producing central electricity from concentrated solar energy. Because this technology has over 25 years of successful operational experience, resulting in a low perceived risk, it is likely that it will continue to be a favorite of investors for some time. The concentrating solar power (CSP) industry is developing parabolic trough projects that will cost billions of dollars, and it is supporting these projects with hundreds of millions of dollars of research and development funding. While this technology offers many advantages over conventional electricity generation—such as utilizing plentiful domestic renewable fuel and having very low emissions of greenhouse gases and air pollutants— it provides electricity in the intermediate power market at about twice the cost of its conventional competitor, combined cycle natural gas. The purpose of this document is to define a set of activities from fiscal year 2011 to fiscal year 2016 that will make this technology economically competitive with conventional means. Section 1 describes current costs and cost goals and the overall ways that cost reductions can occur. Section 2 identifies and discusses specific cost reduction opportunities. Section 3 describes specific activities aimed at addressing those opportunities. Finally, Section 4 provides a schedule of the activities that will complement and support industry efforts including costs and priorities.

1 Cost Reduction Paths

The U.S. Department of Energy (DOE) has set a levelized cost of electricity (LCOE) goal for parabolic trough collector technology, and this report proposes activities for meeting or surpassing that goal. The goal is to reduce the real levelized cost from today's value of about 19¢/kWh nominal (15¢/kWh real) (nominal includes inflation) with a 30% investment tax credit (ITC) (which is equivalent to 24¢/kWh nominal or 19¢/kWh real if the tax credit were 10%) to a value in 2017 of 12¢/kWh nominal (10¢/kWh real) with a 10% ITC. The cost goals were developed by estimating the projected cost for fossil generation in target markets. The National Renewable Energy Laboratory (NREL) normalized generation costs from several sources [References 1-7] to a common set of financial assumptions and examined the resulting predicted range of LCOE. The intermediate load market was assumed to be represented by a natural gas combined cycle plant operating at a capacity factor of 40%. The estimated costs were 8¢/kWh to 12¢/kWh in nominal dollars, with the upper end representative of the California market. This predicted value of 12¢/kWh nominal (10¢/kWh real) is consistent with the California Market Price Referent (MPR) when the MPR is weighted for a solar generation profile. The baseload market costs assumed that carbon capture and sequestration (CCS) technologies would be deployed for the fossil generators by 2020. The increased cost for CCS was offset by the lower generation costs for baseload operation and coincidentally the baseload target was also 12¢/kWh nominal or 10¢/kWh real.

The values above indicate the goal for line-focus systems is to cut the cost over the next seven years by 50%. The LCOE can be reduced in two ways: by increasing performance (both initial and long-term) and by lowering costs (both capital and operating). This report discusses both of these means.

Performance can be increased by:

- improving the solar field optical efficiency
- reducing the solar field thermal losses
- reducing parasitic power consumption
- developing improved configurations that lead to higher utilization and efficiency
- identifying more efficient overall system designs.

Cost reduction can be achieved by:

- reducing equipment capital cost via lower material content, lower-cost materials, more efficient design, or less expensive manufacturing and shipping costs
- reducing field assembly and installation costs (via simpler designs and minimization and/or ease of field assembly)
- lowering operation and maintenance costs via improved reliability, automation, reducing need (as with self-cleaning mirrors), and better techniques
- building larger systems that provide economies of scale, particularly in the power block
- deploying more systems to benefit from learning-curve effects.

Figure 1 summarizes the impact of the performance and cost improvements described above. By achieving the targets described in the figure, parabolic trough systems can achieve a nominal levelized cost of energy of 12¢/kWh (10¢/kWh real), achieving DOE's objective of cost parity with conventional intermediate load power plants.

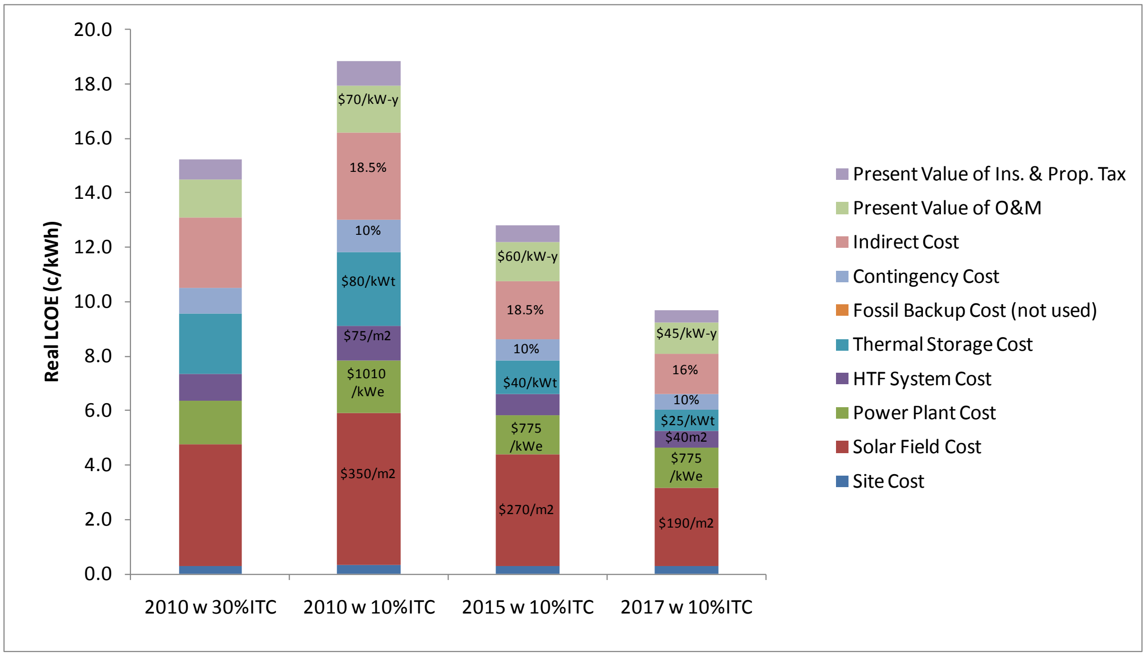

Figure 1. Projected LCOE (Real $2009) and associated cost targets. The figure does not include projected performance improvements described in detail in Table 4 in this report.

While this report focuses mostly on performance improvements and the first four cost reduction means listed above, certain DOE-funded activities will strongly impact the last two cost reduction paths. The ultimate goal of the Program is to achieve large-scale field deployment of parabolic trough collector systems so that they become major carbon-free contributors to our nation's energy supply. Of course, deployment will be encouraged by lower trough system costs, higher costs of the competition (for example, resulting from carbon pricing), or a combination of the above. But large-scale deployment will also require that utilities and investors observe successful operation of trough plants. There are currently contracts for approximately 10,000 MW of new CSP plants in the U.S., and about 5,000 MW of these involve troughs. In addition, BLM leases have been sought for approximately 40,000 MW of trough plants. For even a fraction of these plants to be financed and built, it is critically important that the first new plants be successful. DOE is playing—and should continue to play—an important role in ensuring their success by performing testing of evolving components and installations and providing rapid feedback to industry. This will foster economies of scale and encourage cost reductions due to learning curve effects.

2 Examination of Potential Improvement Opportunities

The costs of electric power generated by a line-focus solar power system are dependent on the capital equipment cost and performance, operations and maintenance costs, and parasitic power penalties. Innovative plant designs can also impact delivered energy costs. This section will discuss where opportunities lie and what is currently being done. Specific recommendations for activities are given in Section 3.

2.1 Capital Equipment

The capital equipment for a CSP plant involves solar components (solar collector field, heat transfer piping, and storage subsystem) and the more-or-less conventional thermodynamic power cycle components. We will focus on the solar components and address opportunities for both cost reduction and performance improvement.

2.1.1 Cost

Under contract to NREL, WorleyParsons analyzed the current costs of a typical parabolic trough power plant. NREL adjusted the numbers based on costs provided by actual plants, assumed an Arizona site (non-union labor), and normalized the data for a 100 MW-net plant with 6 hours of thermal storage [10]. The cost breakdowns in terms of dollars per square meter of collector aperture area for the solar field, the heat transfer fluid (HTF) piping, and the storage are shown, respectively, in Tables 1 through 3. (Note: numbers are rounded to avoid decimals, so totals may differ slightly from the sums of individual numbers.)

Table 1. Current cost breakdown for the solar field.

Solar Field Component	**Material Cost ($/m^2)**	**Labor Cost ($/m^2)**	**Total Cost ($/m^2)**
Mirrors	48	-	48
Receiver Tubes & Fittings	70	-	70
Collector Frames	79	-	79
Misc. Collector Components	2	-	2
Foundations and Support Structures	18	-	18
Instrumentation & Controls	8	0	8
Electrical	2	1	3
Field Installation	-	62	62
Fabrication Tent	1	1	1
Sun Tracker	4	-	4
Totals	**231**	**64**	**295**

Table 2. Cost breakdown for the heat transfer fluid piping system.

HTF Component	**Material Cost ($\$/m^2$)**	**Labor Cost ($\$/m^2$)**	**Total Cost ($\$/m^2$)**
Freeze Protection System	1	0	1
Ullage System	1	0	1
Pumps	6	0	6
Expansion and Blanketing Systems	7	1	8
Solar Field Piping	34	15	49
Power Block Piping	1	0	1
Foundations and Supports	1	1	2
Fluid	22	-	22
Totals	**73**	**17**	**90**

Table 3. Cost breakdown for the thermal storage subsystem.

Storage Component	**Material Cost ($/m²)**	**Labor Cost ($/m²)**	**Total Cost ($/m²)**	**Total Cost ($/kWh-t)**
Pumps & Heat Exchangers	33	2	35	17
Tanks	44	6	50	25
Storage Fluid	72	1	73	36
Piping and Fittings	1	1	2	1
Foundations and Support Structures	0	1	1	0
Instrumentation & Controls	3	4	7	3
Electrical	-	-	0	0
Totals	**153**	**14**	**167**	**81**

The total collector aperture area is 854,000 m^2. The total cost of this plant was $824,900,000, representing $8,250 per kW or $966/$m^2$. The total direct cost is $658,900,000 or $772/$m^2$. Total costs are obtained from direct costs by adding a fixed percentage to each direct cost item to account for project indirect costs. So by looking at the percentages of direct costs we obtain a result very close to the percentages of total costs. At a cost of $295/$m^2$, the solar collector field (materials plus labor) represents 42% of the total plant capital cost. The solar field cost divides out as 78% materials and 22% labor, and virtually all of the labor cost is in the collector installation. There was great debate regarding this cost split among the solar field developers; WorleyParson's analysis suggested the labor fraction was much higher, while some developers claimed it was as low as 15% of the total cost. It is believed the different percentages result from different cost accounting practices and a 22% labor split was adopted as a representative value. In any event, field assembly costs are a significant contributor to total cost. The material cost for the solar field is dominated by three components: collector frames (34%), receiver tubes and fittings (30%), and mirrors (21%). The cost of foundations and support structures (8%) is also significant.

The heat transfer fluid system at a total cost of $90/$m^2$ (81% materials and 19% labor) represents 13% of the total plant capital cost. Fully 54% of the fluid system cost is due to the piping (materials and labor). It is unlikely that CSP Program research can have much impact on a component as conventional as piping; however, improved designs might be able to reduce the total amount of piping needed. The fluid itself represents 24% of the fluid system cost and an improved fluid can have ramifications beyond its material cost impact.

The thermal storage subsystem cost at $167/m^2 or $81/kWh-t (92% materials and only 8% labor) represents 24% of the total plant capital cost. The storage subsystem cost is dominated by three components: the tanks (30% of total storage subsystem cost), pumps and heat exchangers (21%), and the molten salt (44%).

In summary, the collector field, the storage tank, and the storage and heat transfer fluids are major areas for component cost reduction. This plan focuses on improving the performance/cost ratio of these components as well as reducing parasitic power and O&M costs.

2.1.2 Performance

The performance of parabolic trough collectors can be described in terms of two efficiency components: optical and thermal. The optical efficiency is a measure of the percentage of incoming direct normal radiation that is absorbed by the receiver tube. The thermal efficiency is the percent of energy absorbed by the receiver tube that is transferred into the heat transfer fluid (the rest is lost to the environment).

The optical performance of the collector determines how much of the sunlight is converted to heat in the absorber surface. Optical efficiency of the collector is a critical characteristic because it is directly proportional to the energy delivered by the collector field to the power cycle. Hence, a 5% improvement in optical efficiency (with no increase in capital cost) essentially lowers the cost of delivered electricity by the same 5%. The thermal performance determines how much of that heat is transferred to the working fluid as opposed to being lost to the environment. Heat loss is determined by the emittance of the receiver, the integrity of the receiver vacuum, as well as both operational and overnight losses from the piping and storage subsystems. For each major component, we will address opportunities to reduce cost and improve performance (both optically and thermally).

In the following sections we describe potential opportunities for performance improvement and cost reduction in the different component areas. We also address operation and maintenance (O&M) costs, parasitic power, and advanced systems options.

2.2 Collector Field Component Improvement Opportunities

2.2.1 Collector Frames

The support structure for the reflectors must support the weight of the mirrors and have sufficient strength to keep the mirrors optically aligned with the receivers under wind loading conditions. However, survival wind loads, which vary with location, tend to drive the overall frame design. The frame must also have sufficient torsional rigidity to minimize twisting of modules successively further away from the central drive mechanism. Depending on the choice of reflector material, the reflector may or may not play a role in the structure. (Glass mirrors are mounted onto the structure and do not generally carry any structural load themselves, whereas a thin film reflector substrate can provide some structural contribution.)

Several different types of designs have been used. In one design, a steel torque tube (as in the Luz LS-2 and more recent designs by Flagsol and Sener, for example) or torque box (as in the Eurotrough and Flabeg) carries all of the torque load. Cantilever struts attached to the tube or box provide mounting points for the reflectors. Another common alternative is to use an aluminum or steel truss, or space frame, structure as in the Acciona or SkyFuel designs. This structure consists of many frame elements. It both supports the reflector and provides torsional rigidity. While it reduces material content compared to a torque tube, it could, in some cases, increase installation time and the associated labor cost. Combinations of the space frame and torque tube (or box) are also possible. The torque tube concept may assemble more quickly while the space frame can be lighter weight. The torque tube (or box) typically requires fabrication on an accurate, on-site jig in an assembly building; space frame concepts are normally assembled "in place" at the solar field.

In addition, various attempts have been made to use monocoque designs that employ honeycomb or an internal structure to make the reflector similar to an airplane wing. This concept can reduce field assembly time and also lend itself to easier shipping. It is possible to use tensioning cables in front of the collector, as has been done by IST with their industrial process heat troughs. Finally, various stretched membrane concepts have been proposed over the years, including the idea of a low-cost inflated design. Work on these various designs is being undertaken by several of the Funding Opportunity Announcement (FOA) contractors. There is still a need, however, to perform an independent, detailed cost-performance optimization that addresses material content and cost, structural performance, number of parts, attachment mechanisms, ease of manufacture, and ease of assembly.

The choice of materials also plays an important role. Steel is stronger and stiffer than aluminum. Aluminum is lighter weight, corrosion-resistant, and more easily processed. Different design alternatives should be evaluated for each metal, and combinations of the two metals should be considered. For example, a space frame made from steel could potentially be less expensive than one made of aluminum, but we would need to develop easy-to-manufacture joints and address corrosion issues. Just as Alcoa has sought to optimize the design of an all-aluminum collector, the steel industry could potentially be interested in developing an all-steel design. Other materials such as composites and honeycombs can also be further explored. Potential cost savings can be obtained by better understanding the actual wind load experienced by interior collectors in a collector field and by taking measures to minimize wind loads, allowing for a lower-cost structure and reflector design. Material price trends also influence the choice of material, and price fluctuations can be significant.

2.2.2 Receivers

Receivers have both optical and thermal performance characteristics. Receiver tube manufacturers use anti-reflection (AR) coatings on the glass envelopes to increase the transmittance of sunlight. This is especially important when the sun strikes the receiver tube at an angle. NREL utilizes its outdoor test facility to directly measure the overall optical efficiency of parabolic troughs at normal solar incidence as well as a range of off-normal sun angles (which an array of parabolic trough collectors will actually experience in the field). These tests can help identify when better optical performance is needed. Current receiver coatings have very high absorptance of short-wave radiation (sunlight). A challenge is to reduce their emittance for long-wave (infrared) radiation while maintaining the high absorptance. Industry has made considerable progress in improving solar selective coatings.

NREL conducts indoor heat loss tests on receiver tubes. Sandia National Laboratory conducts outdoor trough module test measurements on their rotating platform to simultaneously yield both optical and thermal performance. (Collector efficiency curves can be generated either by using NREL's separate optical and thermal test results or by using Sandia's overall collector performance measurements.) Today's high-vacuum receiver tubes are capable of virtually eliminating conduction and convection heat losses to the environment, leaving radiation as the only important heat loss mechanism. Radiation heat loss from the absorber tube is minimized by using a selective coating with a very low long-wave emittance (0.10 or less). Low-cost, high-performance, durable advanced optical materials are necessary to meet the demands of advanced system designs and to achieve the cost and performance goals that are needed to commercialize CSP technologies. Increasing the operating temperature from 390ºC to >450ºC or higher can increase overall solar-to-electricity efficiency, reduce thermal storage volume, and reduce the LCOE. Further decreases in emittance are possible, although this may be nearing the point of diminishing returns. Reducing or maintaining low emittance and high absorptance at higher operating temperatures is an important goal.

NREL has developed an improved receiver coating that has a low emittance (as low as 0.07) while maintaining a high absorptance (0.96) and having good oxidation resistance at high operating temperatures even if air leaks into the vacuum space. NREL is working with an industry partner to bring this improved absorber coating to market. In addition, infrared-reflecting coatings are used on commercial glass envelopes.

While the vacuum in a new receiver tube effectively eliminates conduction and convection heat losses, receiver tubes can degrade in the field. NREL has developed and transferred to industry a Receiver Infrared Imaging System that allows plant owners to identify degraded receiver tubes in the field. On the basis of these tests, FPL Energy has replaced millions of dollars of receiver tubes at their SEGS plants.

Many receiver tubes in the field have exhibited a problem of hydrogen (H_2) permeation from the heat transfer fluid into the vacuum space, resulting in greatly increased heat loss. Manufacturers are addressing this by using more getter material, changing the location of getter material, and using hydrogen permeation barriers. NREL is investigating alternative ways to solve this problem. NREL has shown experimentally that by introducing a small amount of inert gas such as xenon (Xe) or argon (Ar) into the vacuum space, these larger molecules will effectively inhibit motion of the H_2 molecules, thereby reducing heat loss to near-vacuum levels. It is possible that injecting argon by blanketing or flushing could obviate vacuum pumping and reduce receiver manufacturing cost, albeit with a small performance penalty up front. By avoiding a hard vacuum, it might be possible to use a thinner glass envelope. The argon could also avoid the cost of getters, which can represent as much as 20% of the receiver cost.

NREL has also developed a model of hydrogen diffusion throughout the plant and identified a means to remove the hydrogen centrally. An agreement with FPL Energy is in place to test this concept at an operating SEGS plant.

Finding ways to reduce the receiver cost and decreasing the number of receivers in the field by increasing the trough aperture width might bring further cost reductions, as is being investigated by FOA contractors and proposed by Sandia. Because the number of suppliers of receiver tubes is limited, additional manufacturers could help increase product availability and help lower cost. The entry of low-cost suppliers into this market could provide significant downward pressure on cost. Greater use of Design for Manufacturing and Assembly (DFMA) techniques by manufacturers could be extremely helpful and is especially beneficial at the beginning of the design process.

2.2.3 Reflectors

After collector frames and receivers, the reflectors represent the largest solar field cost item. For concentrating collectors it is important not only that the surface have a high reflectance but that it also be highly specular, i.e., that it reflects sunlight into a narrow cone angle so that that the focused sunlight will intercept the receiver tube. These properties must be demonstrably maintained for long-term service lifetimes. Currently, parabolic trough power plants use thick second-surface silvered glass mirrors. The glass is 4-mm-thick, low-iron (or white) glass with high transmittance. These are second-surface mirrors in which the light passes through the glass and reflects off of the reflective layer on the back side of the glass. Silver reflective layers are used primarily because they have the highest spectral reflectance across the solar spectrum (300 nm–2500 nm). The mirrors are coated by traditional wet-chemistry processes and protected with a copper layer and low-lead mirror paint systems. Several companies are working to improve glass solar mirrors by improving glass transmittance; bending, finishing, and strengthening; using thin (1-mm) and laminated glass mirrors; improving the silver back coating; and using no-lead paint systems and adhesives. Long-term durability needs to be proven, however.

There are a number of efforts underway, including several FOA contracts, to develop improved low-cost polymer thin film reflectors. Specific examples include the ReflecTech silvered polymer film developed by NREL and SkyFuel, the silvered polymer reflector developed by 3M and NREL, the Alanod anodized aluminum reflector, and the Abengoa front-surface mirror. Compared to glass mirrors, thin film reflectors are lighter in weight, potentially lower in cost and higher in reflectance, and they can serve as part of the structure with an appropriate substrate. Elimination of glass facets also removes all of the individual struts and attachments needed for the mirrors and can reduce installation costs, although it also eliminates the ability to make field adjustments of mirror alignment. Mirror breakage is also avoided. However, some thin reflectors may not have sufficient abrasion resistance to allow the vigorous cleaning needed to maintain high long-term specular reflectance. The development and successful application of hard coat finishes could resolve this issue.

Even for a highly specular mirror surface, the fraction of the reflected direct normal radiation that intercepts the receiver tube, or the intercept factor, is also a function of the shape of the mirror and the size of the receiver tube. How close the intercept factor is to 1 (100% intercept) depends on how closely the reflector surface approaches that of a perfect parabola and how well the reflector is aligned to the receiver tube. Irregularities in the mirror facets, the influence of structural support elements, deflections due to weight, wind, drive forces, and thermal expansion/contraction will all impact the shape. Obtaining a highly accurate reflector shape is a critical step in the development of a new parabolic trough collector. NREL's Video Scanning

Hartmann Optical Test (VSHOT) laser ray trace technique can characterize the point-by-point slope error of a reflector, and manufacturers have made use of this tool to tune their designs.

Even with a perfect mirror in terms of shape and reflectivity, if it is not aligned correctly, it will not perform well. The next step is to take into account the whole solar collector assembly. There are multiple modules on a single drive and one tracking sensor. Sandia's Theoretical Overlay Photographic Collector Alignment Technique (TOPCAT) system has been used successfully in the field to correct alignment of the mirrors with the receiver tubes, which takes into account module-to-module misalignment as well as any receiver misalignment. Optical alignment is superior to mechanical means and provides the best option for aligning mirrors. TOPCAT had a demonstrated improvement for one loop at SEGS VIII of 3.5%. Better mirror alignment also allows the use of higher concentration ratios and higher temperatures, reducing storage cost.

The design of new reflectors must consider that the optical performance of the reflector has a one-to-one correspondence with the levelized cost of electricity (e.g., a 5% drop in reflectance will cause a 5% increase in LCOE). However, the cost of the reflector represents only about 4% of the total plant cost. (A reflector design will also impact the collector frames. The collector and frame costs together represent about 10% of the total plant capital cost.) So reductions in reflector cost may not lower the levelized cost of electricity unless they have very little negative impact on reflector performance. (Conversely, even a small increase in optical performance could justify an increase in reflector cost.)

2.2.4 Optical Materials Testing

Optical materials testing provides DOE and industry with characterization of the optical properties (specular reflectance, absorptance, and emittance), durability performance and cost improvements of potential advanced solar mirrors and solar selective receiver coatings. Candidate materials are identified based on their potential for low cost and high optical performance and durability. Candidate solar reflectors under test include thin, thick, and laminated glass, aluminum reflectors, and silvered polymer. Materials are optically characterized prior to being subjected to exposure in real and simulated weathering environments. Optical durability is quantified by periodically re-measuring hemispherical and specular reflectance of solar mirrors and absorptance and emittance of solar selective coatings as a function of exposure time to assess optical durability. These materials are subjected to outdoor weathering at a variety of geographically diverse exposure sites. In addition, accelerated exposure testing (AET) of these materials in parallel under laboratory-controlled conditions is correlated with the outdoor results to predict service lifetimes. A historical database of optical durability results is available and contains more than 1,000 experiments containing more than 20,000 samples encompassing more than 300,000 measurements, which date back over more than 21 years. This data provides the confidence needed for financing projects using these materials.

2.2.5 Foundations

Foundations represent about 7% of the collector field cost. Various types of piers, footings, slabs, and anchor systems are possible. Costs and performance of these various alternatives will depend on collector size and design, as well as local soil conditions. The FOA contractors are exploring various foundation options.

2.3 Storage Subsystem Improvement Opportunities

As pointed out earlier, the thermal storage subsystem cost at \$167/m^2 represents 24% of the total plant capital cost. The storage subsystem cost is dominated by three components: the tanks (30% of total storage subsystem cost), pumps and heat exchangers (21%), and the molten salt (44%). Typically, two-tank indirect systems are used with a hydrocarbon working fluid in the collector field and molten salt in the hot and cold tanks.

Changes in the collector field can impact the size of storage that is needed. Specifically, operating at higher temperature will mean a larger temperature difference for the storage with a consequent decrease in the required storage volume. A higher operating temperature also results in higher power cycle efficiency. Because the higher temperature also means a greater driving potential for heat losses, additional attention must be paid to this by using a higher concentration ratio (which puts more stringent requirements on the optical components) or by developing an absorber surface with lower emittance. But the main challenge in going to a higher collector field operating temperature is finding a suitable heat transfer fluid (HTF). Previous research at NREL and elsewhere has essentially eliminated consideration of organic HTFs at temperatures greater than 393°C due to thermal degradation of the HTF and the resulting generation of hydrogen gas. Molten salts currently offer the best option for near-term development of a high-temperature HTF. It is ideal if the molten salt storage fluid can be used directly in the collector field. In that case, the cost of heat exchangers and the performance penalty associated with the temperature drop across the heat exchangers can be eliminated.

However, while molten salts have the capability to operate over 500°C, their freezing points are in the neighborhood of 100°C–200°C. Although the hot salt would be circulated through the field at night to prevent freezing, there is still a potential for a freezing of the HTF. It is thus generally assumed that a reliable and demonstrated means must be provided for thawing out the field in the event of freezing, either by use of electric resistance, steam heating, or some other means. If it is not thawed out evenly, piping or receiver damage can result. Sandia, Solar Millennium, and Halotechnics are developing salt formulations with lower freezing points (but lowering the freezing point tends to also lower the maximum operating temperature of the fluid). Additionally, experiments are underway at Sandia to determine how frozen pipe can be thawed safely. The Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA) has also done work on this.

High-temperature fluids other than salt are being investigated. These fluids distinguish themselves from the molten salts in that they are not single-phase homogeneous formulations. NREL and Texas A&M University are developing nanofluids. These fluids consist of traditional homogeneous fluids such as molten salts with added nano-scale particles. These particles have unique properties and are also able to modify the thermophysical properties of fluids. As such, these fluids are considered heterogeneous but may behave and function as homogeneous HTFs with enhanced thermophysical properties. Ongoing work to date has focused on using nanoparticles to increase the heat capacity of storage fluids. NREL is considering expanding this work to include lowering the melting point and increasing the liquid temperature range of fluids that already exhibit high-temperature stability.

The current storage material of choice, molten salt, is very expensive, so there has been interest in moving to a single-tank thermocline design in which a filler material (rock or sand) is used, thus reducing the salt volume by 70% or more. In such a design, the hot fluid resides in the top of the tank and the cold fluid is in the bottom. Maintaining a good thermocline (i.e., a sharp demarcation between the high and low temperatures) is important to ensure that the lowest-temperature fluid always goes to the collectors and the highest-temperature fluid always goes to the steam generator. Various ideas have been proposed for maintaining the thermocline, and these represent an important research area. Some (but not all) studies of such thermocline tanks have suggested that over many charge and discharge cycles, slumping of the filler material might occur, causing high hoop stresses at the bottom of the tank and leading to tank failure. Further investigation is needed to determine the extent of this problem, and various means could be studied for mitigating it. Although thermocline tanks have typically been proposed for a direct system, they could also be used in an indirect design if it is decided that running molten salt in the collector field is too difficult. Even in an indirect design, the thermocline tank would offer the advantage of replacing high-cost molten salt with cheap filler material.

There is a general need to increase the stored energy density of thermal storage systems. One approach is to identify storage materials with lower costs and better thermal properties than those typically used for storage. NREL is using the FactSage software to evaluate the thermal properties and phase behavior of new salt formulations. NREL has identified a formulation that has a higher heat capacity and lower cost than solar salt that can reduce storage volume by about 20%. To complement this modeling effort, NREL has built a materials laboratory to measure and validate the thermophysical properties of such fluids.

The use of phase-change enthalpies to increase the stored energy density has potential to reduce the energy storage inventory by a factor of two or more. Implementation of phase-change storage requires innovative solutions to several practical barriers. Energy transfer due to phase change occurs at a single temperature and therefore does not match well to the sensible enthalpy of a single-phase HTF. This mismatch can be addressed by using a set of cascading phase-change materials with varying transition temperatures. NREL is modeling phase-change storage and using FactSage to identify salt formulations that possess similar physical properties and uniformly-spaced transition temperatures for efficient energy transfer in phase-change storage systems.

The most significant practical barrier to the use of phase-change storage is the solid-phase thermal conductivity, which limits heat transfer during discharge and the power density of the storage system. Many solutions to this issue are being investigated at NREL, Sandia, universities, and industry. One approach is the use of encapsulated phase-change particles or pellets. Their size range varies from nanometer, which is being investigated as an additive to storage fluids to increase heat capacity, to millimeter, which is being investigated as the storage medium for a packed bed, thermocline design. In any case, the size of the encapsulated phase-change material is such that heat transfer is not limited by the thermal conductivity of the solid phase. Another approach is to enhance the conductivity of the solid phase with heat pipe modules. Still another is to develop methods to prevent the formation of the solid phase onto the heat transfer surface or remove it as it forms. Variations of all of these approaches are currently being investigated.

Thermochemical energy storage perhaps offers the greatest improvement in storage energy density. This type of storage uses the enthalpy associated with a reversible chemical reaction.

The enthalpy can exceed the sensible enthalpies of storage materials by an order of magnitude. Research and development in this area is considered to be long term because there are several practical limitations to its implementation. The reactions tend to occur at temperatures (1,000°C) greater than those currently being used or considered in CSP technologies, and the substances that undergo reaction can be very corrosive. Lastly, even though the intrinsic reaction rates are appreciable and reversible, morphological changes in the solid phases of the reaction mixture tend to decrease surface areas and limit the mass transfer that is required to sustain the reactions at required rates. Currently, one company is performing research in thermochemical conversion for CSP thermal energy storage.

Various storage means have been explored in Europe, including concrete thermocline storage and phase change storage. The latter is especially well suited to trough systems that boil water in the collector field, as the phase-change temperature can be matched to the field operating temperature. (Where heat must be transferred over a temperature range, multiple phase change tanks having different phase-change temperatures can be employed; however, this increases the technical challenge as each phase-change system must be made to operate successfully.) Both concrete and phase-change storage have issues associated with conducting heat into and out of material in a solid state.

2.4 Overall Collector Design Improvements

Existing troughs rotate around an imaginary axis between the receiver and the collector. Other axes of rotation are possible, specifically around the receiver or around the torque tube. Rotating around the receiver would mean that the receiver is fixed and so many ball joints or flex hoses could be eliminated. Increasing the aperture width of the collector decreases the number of receiver tubes, pylons, and drive motors per square meter of collector. Sandia has proposed a 2X trough in which the aperture is doubled with the same receiver tube diameter, thus doubling the concentration ratio. Clearly there are potential cost savings associated with going with a larger aperture, although it is not clear that a factor of two increase in the aperture is the optimum or that it is optimum to double the concentration ratio. Lower concentration ratios result in lower parasitic pumping power due to larger receiver tube diameters, as described earlier, and modern receivers already have very low heat loss (at least when new). The module length can also be increased. When making the collector bigger, one must account for increased wind loads and potential difficulties associated with transporting the collector components and assembling them in the field. Detailed analysis by the laboratories covering the various degrees of freedom is critical to identify optimum designs.

2.5 O&M Improvement Opportunities

The estimated fixed O&M costs for a 100-MW plant in southwest Arizona were $8,500,000, (approx. $70/kW-yr) based on shifting the WorleyParsons analysis to that location [10]. Variable O&M costs (for utilities and water) are estimated at $2.5/MWh. Total O&M costs equate to about 1.5¢/kWh. This cost is consistent with the most recent data from the SEGS plants. At an LCOE of 14 cents per kWh, this represents 11% of the cost of the delivered electricity and is thus a very important item.

Of the $8.5 million annual O&M cost, most is for plant operation. However, solar field maintenance costs (labor plus materials) were estimated at $1.6 million, which is 19% of the O&M cost. Including mirror washing costs brings the total to $1.9 million or about 23% of the total plant O&M cost. O&M data from the latest plants is not available and so we currently must rely on results from the older SEGS plants. A 2009 review by NREL focusing on the SEGS plants assessed the various items affecting both maintenance costs and failure rates. The relative failure rates of different items are shown in Figures 2 and 3.

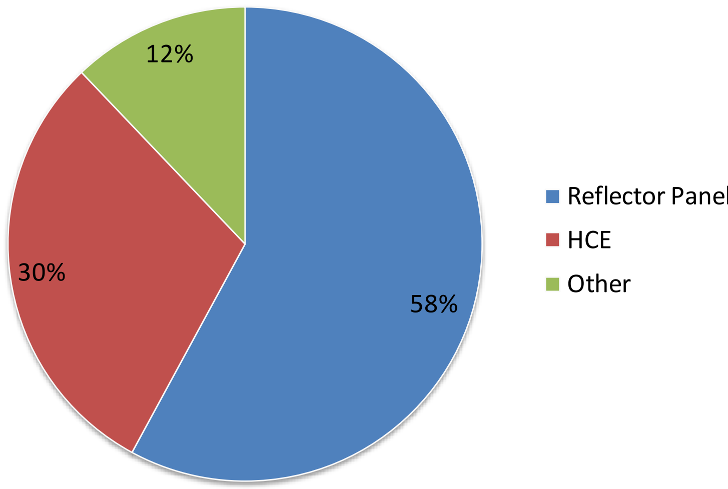

Figure 2. Percentages of total solar field component failure at SEGS III-VI, 1989-2005 average [8].

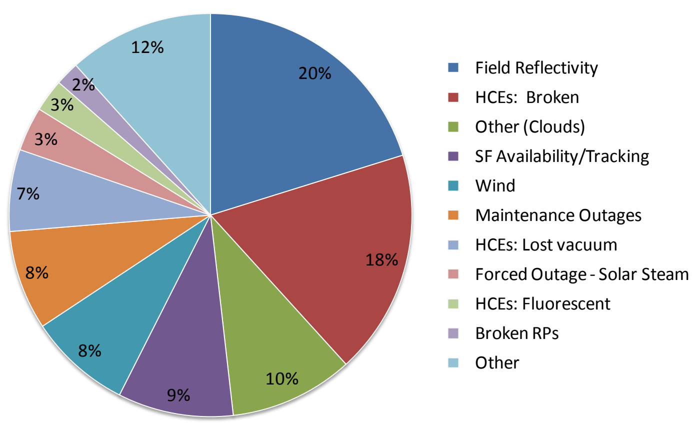

Figure 3. Causes of lost power production at SEGS III-VI, 1999-2001 average [9].

As shown in Figure 2, broken reflector panels have historically been the biggest problem. These involved panels cracking, breaking, and becoming separated from their mounting pads. The glass breakage and cracking was primarily due to wind damage, and the pad separation was primarily due to adhesive failure. Thermal expansion of the metal pads relative to the glass panels was a major contributor, causing Flabeg to change to ceramic pads. Wind damage was especially problematic on rows at the edge of a field, which were not sheltered by other rows. Figure 3 shows that loss of reflectance accounts for a significant fraction of lost power production.

Receiver breakage was another major failure item. Failures involved vacuum loss, hydrogen infiltration, glass envelope breakage, and degradation of the coating. All of these generate replacement costs—and until replacements are made, performance degradation. This is especially the case for broken glass receiver tubes, which can have high heat losses on windy days. The most recent data for SEGS indicated that receiver tube failures had decreased to 3.37% of the total field receivers per year. Of these failures, 55% were reported to involve broken glass and 29% involved loss of vacuum, in most cases due to the failure of glass/metal seals, but also due to bowing tubes. Tubes exposed to even just one sun can bow due to differential heating if they do not have heat transfer fluid flowing through them, and this problem has become even greater as receiver coatings have improved.

Mirror breakage can be addressed by using thin film reflectors, although issues such as buckling may need to be avoided. Also, laminated mirrors that allow mirrors to crack without falling off could maintain reflective performance. Wind breaks and reinforcing perimeter collectors can help prevent wind damage. To maintain high reflectance, lower-cost and more effective cleaning systems and anti-soiling coatings are being investigated. Developing an automated contact washing system, possibly integrated into the trough itself, could reduce cleaning costs and ensure continuous high performance.

A receiver tube breakage rate of 3.4% per year seems unacceptably high, given that the receivers themselves represent 30% of the solar field material cost and would require additional labor to replace. Data from the latest plants is needed to determine the current failure rate. In general, data collection is needed to investigate what the latest failure mechanisms are and identify potential means to prevent them. Loss of vacuum and hydrogen infiltration in receiver tubes can lead to significant performance losses and has been discussed in Section 2.2.2.

2.6 Parasitic Power Reduction Opportunities

Analyses by WorleyParsons indicate that the parasitic power as a percentage of gross turbine output ranges from 13% for a water-cooled plant to 15% for an air-cooled plant. Approximately half of the parasitic power is used to pump the heat transfer fluid. Runs of a piping model indicate that about half of this (or about one-quarter of the total parasitic power) results from the pressure drop in the receiver tubes. The pumping power required for the receiver tubes varies inversely with the diameter of the receiver tube raised to the fifth power. So a small increase in receiver tube diameter can result in a greatly reduced pumping power. The larger receiver can also compensate for optical inaccuracies in the mirrors and the mirror-receiver alignment.

This savings in pumping power must be weighed against an increase in the cost of the larger receiver and somewhat increased heat loss. Modern receivers have very high vacuums (<0.1 Pa) and their solar selective coatings have low emittance (<0.10) such that overall heat loss from them is very low, meaning that a small percentage increase in this heat loss will not necessarily have a significant impact on overall collector efficiency. Because the power required to pump the heat transfer fluid through the receivers represents 3%–4% of the plant gross power, it may make sense to evaluate the use of larger-diameter receiver tubes than the ones that have typically been used. (However, header pipe sizes must be carefully chosen to ensure adequate flow uniformity if the pressure drop in the collectors is reduced.) A larger aperture width collector also helps by reducing the number of receiver tubes in the field. Another opportunity for reducing parasitic power relates to the properties of the circulating HTF. Reducing HTF viscosity will reduce pumping power. Increasing the HTF volumetric heat capacity (ρC_p) will reduce fluid velocity within the receiver tubes and also reduce pumping power.

In air-cooled plants, fan power represents 24% of the parasitic power, or 3% of the gross power. Air-cooled condenser arrays typically use two-speed fans, and this was assumed in the WorleyParsons analysis. Because fan power is highly nonlinear as a function of air volumetric flow rate (it varies with the cube of flow rate), the use of a variable frequency drive could cut down considerably on fan power. Variable frequency drives (VFDs) are not typically used in conventional air-cooled power plants because of their cost, but for a parabolic trough collector system that is dominated by collector field capital costs, the use of VFDs to reduce fan power consumption may be worth considering.

2.7 Advanced Systems Concepts

2.7.1 Direct Steam Generation (DSG)

Current trough collector fields are limited to about 400°C outlet temperature because that is the upper temperature limit of the oil. Molten salt would allow higher temperatures but at the expense of a high freezing point. Another option is to run pressurized water in the collector field. An early study by Murphy and May at NREL showed that boiling water directly in a parabolic trough collector field was an attractive option for providing industrial process steam. Researchers from the German Aerospace Center (DLR) have analyzed direct steam generation in a trough field and found that there are some challenges involved in maintaining balanced steam pressures. There is also the issue of coming up with a suitable storage system for DSG designs. Nevertheless, because of the potential advantages associated with operating at higher temperatures, this remains a promising option.

2.7.2 Hybrid Designs

Recent changes in the natural gas industry make it more attractive to combine natural gas burning with solar electricity production. Large reserves of gas shales have recently become available. In addition, because the use of natural gas to produce electricity releases less carbon per MWh than a coal plant, the natural gas industry has taken the position of strongly supporting carbon reduction legislation. They see natural gas as an enabling technology for renewables. Natural gas is burned to provide up to 25% of the power at SEGS. Various studies have looked at integrated solar-combined cycle (ISCC) plants. NREL has been investigating a new configuration, and preliminary cost estimates look promising compared to typical ISCC configurations. A preliminary analysis has indicated that such a design could lower the real LCOE (compared to an all-solar parabolic trough plant) by about 5¢/kWh for a design that is about 46% solar/54% gas. (Note, however, that this lower cost is due in part to the fact that natural gas is being burned. Analysis is underway to separate out the solar-specific cost.)

Integration and transmission issues will be minimized with solar/fossil designs. While a reduced solar fraction may sound less attractive, it provides a path to support manufacturing of solar fields and familiarity for utilities that will lay the groundwork for dedicated CSP plants.

2.7.3 Supercritical Brayton Cycle

Consideration has also been given to the use of supercritical CO_2 Brayton cycles. The potential for s-CO_2 is longer term, because no one yet builds s-CO_2 turbines. Most references suggest the s-CO_2 cycle could be slightly more efficient than superheated steam cycles at roughly equal temperature and slightly higher pressure. The turbomachinery is projected to be 20% less expensive. Such a power cycle would be more compatible with molten salt storage than a steam cycle. In theory this could lower LCOE by about 1¢/kWh.

2.8 Environmental Issues

Water usage is a major concern with parabolic trough power plants because they are located in arid regions. A typical water-cooled plant uses 800 to 900 gallons of water per MWh. NREL has conducted analyses on the use of dry and hybrid (wet/dry) cooling to greatly reduce water consumption. Further analysis is needed to determine the impact of time-of-day electricity rates. Also, there is a need to study potential ways to recycle the water used for mirror washing and steam cycle make-up (needed to replace boiler blowdown water used to remove mineral build-up).

3 Recommended Activities

In this section we list the specific proposed activities needed to achieve the full range of cost reductions. These activities include some that are currently underway by the laboratories, FOA contractors, and industry, as well as proposed new activities. SAM computer simulations were made to determine the impacts of various improvements on the levelized cost of electricity. Figure 4 shows the results of a sensitivity analysis for the various cost reduction areas. This clearly shows that reducing collector field cost is a key activity. Table 4 shows scenarios for specific cost reductions using improvements that are "in the pipeline" (shown for the year 2015) as well as a combination of improvements which, if made by 2017, could achieve 2017 cost goals. Note that it is assumed that there will only be a 10% ITC in 2017. Thus today's costs are shown not only with today's 30% ITC but also what they would be with a 10% ITC so that the extent of needed improvement can be seen.

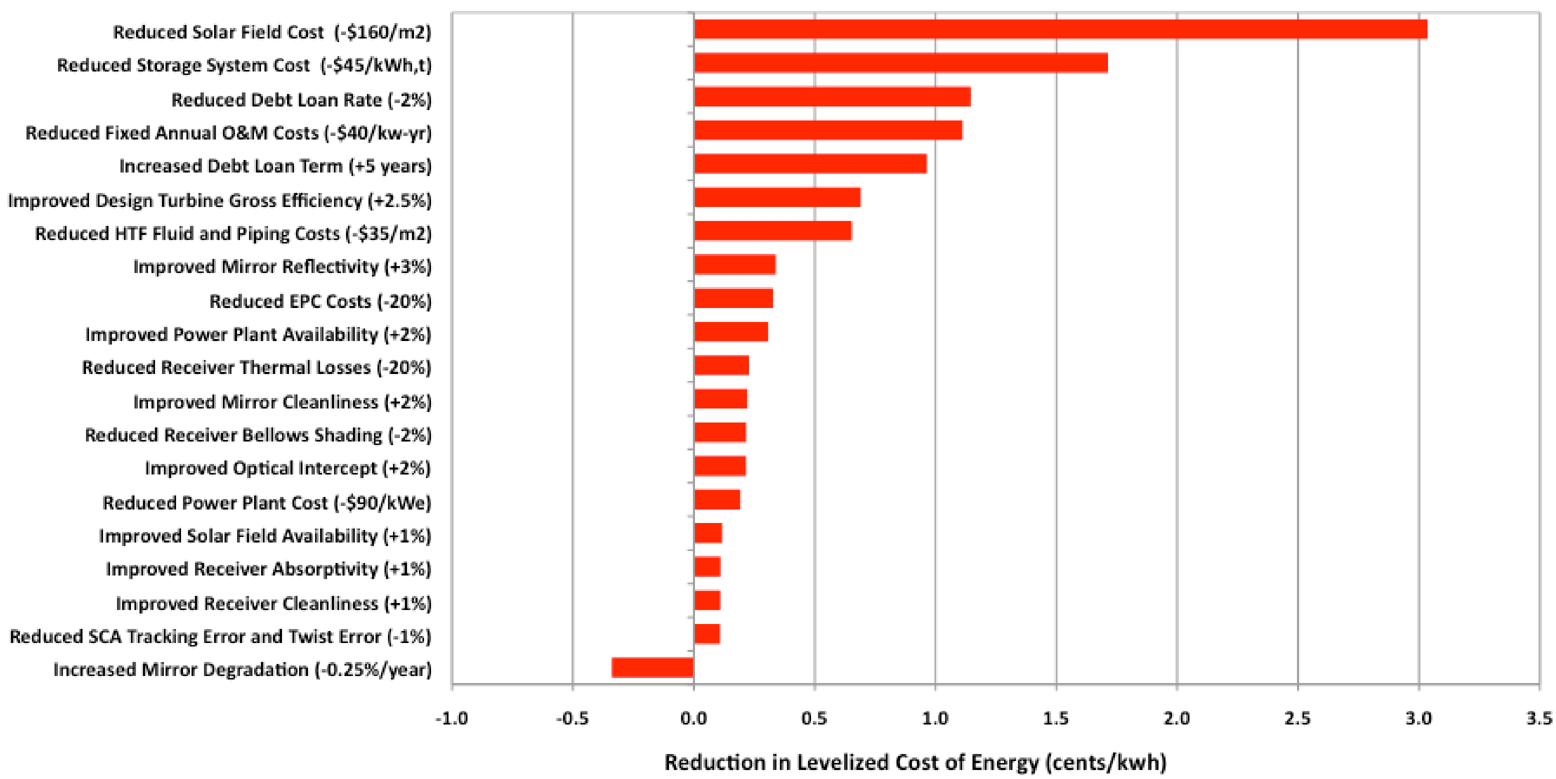

Figure 4. Sensitivity of LCOE to potential cost reductions in different areas.

Table 4. Estimated current and future costs for parabolic trough systems. Representative cases at 6 and 12 hours of storage are shown.

	2010	2010	2015	2015	2020
Design Inputs:					
Turbine MWe (gross/net)	111/100	110/100	280/250	110/100	280/250
HTF	Syn. Oil	Syn. Oil	Syn. Oil	Salt	Salt
Solar Field Temperature (°C)	391	391	391	450	500
Solar Multiple	1.3	2.0	2.0	2.0	2.8
Thermal Storage Hours	0	6	6	6	12
Cost & Performance Inputs:					
System Availability	94%	94%	96%	96%	96%
Turbine Efficiency (cooling method)	0.377 (wet)	0.377 (wet)	0.356 (dry)	0.379 (dry)	0.397 (dry)
Collector Reflectance	0.935	0.935	0.95	0.95	0.95
Solar Field ($/m2)	295	295	245	245	190
HTF System ($/m2)	90	90	90	50	50
Thermal Storage ($/kWh-t)	-	80	80	50	25
Power Block ($/kWe - gross)	940	940	875	1140	875
O&M ($/kW-yr)	70	70	60	60	45
Cost & Performance outputs:					
Capacity Factor	26%	41%	43%	43%	60%
Installed Cost ($/W)	4.6	8.0	7.9	6.6	6.5
LCOE (cents/kWh, real)	17.3	17.9	16.5	14.2	9.9

3.1 Items Affecting the Collector Field

3.1.1 Overall Collector Design

Industry is moving toward larger-aperture troughs, as these will reduce the number of collectors and receivers per megawatt with a corresponding reduction in overall piping and number of drives. The upper limit on size is probably based on survival wind loading, transportation issues, and installation difficulty. Sandia has proposed to double the aperture while maintaining the same diameter receiver tube. This increase in aperture size is a move in the right direction, but a detailed systems analysis study is needed to determine the optimum combination of parameters that minimizes the overall LCOE including initial costs, performance, and parasitics. Sandia and NREL should work together to investigate this, using contractor support to get the best cost information. Results should be shared with industry to obtain their feedback. Because some similar exercises are underway in the FOA contracts, the awardees should be urged to share their results on a confidential basis with the DOE labs. This information can then be used in a generic way. Higher concentration ratios may require a more accurate tracker, and Sandia should pursue its investigation of an improved closed-loop tracker.

3.1.2 Collector Structure Improvement/Wind Load Investigation

Considerable work is being done to improve the collector support frame by FOA contractors and other manufacturers. All of the main methods are being investigated: torque tube and torque box, space frame (or truss), and monocoque construction. DOE should continue to support these efforts and carefully monitor the progress in cost reduction. The cost evaluations shall provide detail on materials costs and content, assembly costs, and installation costs. The national labs will also help by providing test results to ensure that the structures meet optical and wind load requirements. Because wind loads tend to drive the structural requirements, the labs will measure wind loads in an actual collector field and investigate innovative ways to reduce those loads. Various ideas have been suggested for decreasing wind loads on trough fields, and the laboratories should work with industry to evaluate these. Finite element analysis will be used to study how wind and gravity loads affect the collector.

3.1.3 Receiver Tubes

Receiver tubes and fittings represent 30% of the collector field material cost. SAM simulations show that the LCOE from the plant can vary by more than ±2¢/kWh depending on how well the receivers absorb and retain the heat from the sun. Although great strides have been made in improving receiver performance, there is room for improvement in both the areas of new receiver tube performance and (especially) long-term performance.

3.1.3.1 Advanced Receiver Coating Development

SAM analysis demonstrates that a 10% improvement in the solar field performance for a parabolic trough system lowers the nominal LCOE for the 2009 baseline costs by 1.2¢/kWh, whereas a 10% cost reduction in the same solar field will reduce the nominal LCOE by 0.8¢/kWh. Thus performance improvements have a large impact on the overall economics. The overall objective of this activity is to develop new, more efficient selective coatings with both high solar absorptance ($\alpha > 0.96$) and low thermal emittance ($\varepsilon < 0.07$ at 450ºC) that are thermally stable above 550ºC, ideally in air, with improved durability and manufacturability and reduced cost. The resulting reduction in LCOE by moving to higher temperatures flattens out above 450°C, but a coating that is durable in air allows the receiver coating to be functional if the vacuum is breached in an evacuated tube for parabolic trough applications. In addition, a coating stable in air can be used in non-evacuated linear Fresnel receivers and in towers.

3.1.3.2 Hydrogen Mitigation

SAM analysis predicts that a parabolic trough plant with no hydrogen (no hydrogen-filled receivers) will generate electricity for 3¢/kWh less than the same plant that has hydrogen in 50% of its receivers. This is an enormous penalty, so it is no wonder that FPL Energy has replaced millions of dollars of receiver tubes due to hydrogen infiltration. Newer receiver designs incorporate more getter capacity and use hydrogen diffusion barriers. Nevertheless, the latest field results suggest that this problem is still occurring even in new tubes. Mineral oil heat exchanger fluids will likely continue to be used in new installations for a number of years until an alternative high-temperature fluid is developed and proven, and so addressing the hydrogen problem should be a high program priority. In addition to the changes that the manufacturers have made, potential solutions to be explored are:

- removing hydrogen centrally
- using a large-molecule inert gas like argon or xenon or nitrogen to block the motion of the hydrogen molecules
- improved hydrogen barrier coatings on the receiver tube

- developing a new heat transfer fluid that does not generate hydrogen.

3.1.3.3 Development of Lower-Cost Receivers

Use of an inert gas instead of a vacuum could eliminate the need for getters and reduce manufacturing cost. There are low-cost evacuated receivers manufactured abroad that could be suitable for trough application, and this would be worth exploring. A FOA or other means to stimulate more American manufacturers to enter this market will help spur competition and reduce cost.

3.1.3.4 Receiver Heat Loss Measurement

In order to evaluate the effectiveness of new receiver advances, receiver performance must be accurately measured. Results for the NREL test loop are very useful to manufacturers as they develop higher-performance improved designs. The tests also serve as an independent assessment of the technology, which can be given to investors and due-diligence engineers involved with plant financing, thereby aiding deployment. Technical reports that result from these tests show manufacturers the state-of-the-art and encourage other manufacturers to enter the market if they think they can make something that performs as well or better. This testing support should continue. NREL also uses an infrared camera system to rapidly measure and record heat loss from all receivers in the field to determine those that are losing too much heat and are in need of replacement. This technology has been transferred to FPL Energy and should be made available to other CSP industry members.

Figure 5 summarizes the results of Solar Advisor Model sensitivity runs that indicate the impact of receiver-related changes on the real levelized cost of electricity. DOE Program work is not only aimed at improving cost but also eliminating problems (such as hydrogen infiltration in receivers) that can decrease performance. Hence this graph shows the impact on costs that would occur if corrective measures are not taken, as well as the impact of improvements over the design values.

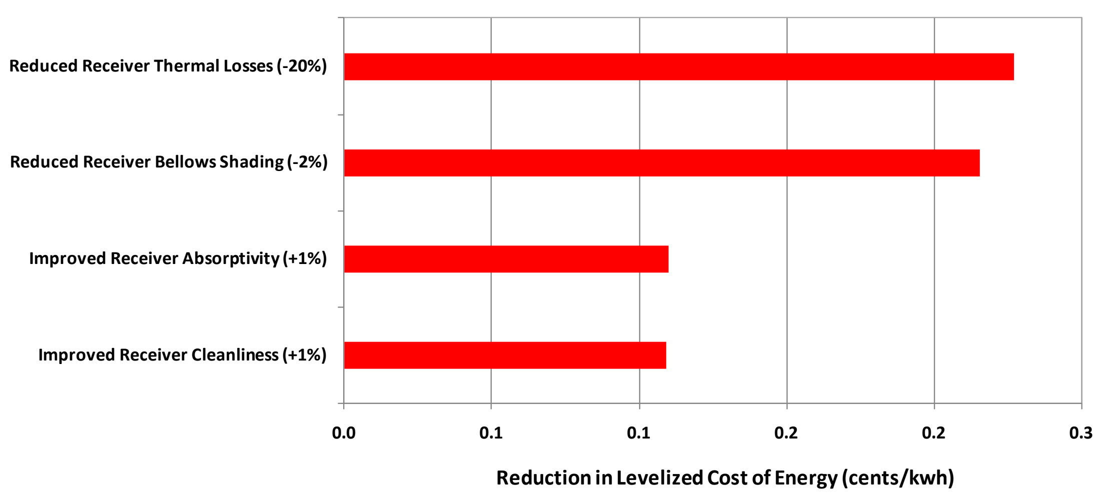

Figure 5. SAM results showing the impact of changes in receiver performance on the real levelized cost of electricity. 2009 costs are shown here.

3.1.4 Improved Mirrors

As discussed earlier, energy output is directly proportional to optical efficiency; therefore high optical performance is critical to minimizing the levelized cost of electricity. Work is needed to lower mirror costs, maximize reflectance, ensure long-term durability, and promote cleanability with minimal water use. Mirrors have a very high markup because of the limited number of suppliers, so efforts should be made to stimulate competition. Another reason glass mirrors are expensive is that there are not dedicated production lines for the low-iron glass needed for solar applications. There are costs incurred in switching back and forth between the production of regular green glass and low-iron glass. In other cases, dedicated plants may not be running at capacity, so the cost of manufacturing capability must be spread over a small number of sales. In any case, as mirror volume production increases, costs should drop significantly. Thus support for large, successful projects should help drive costs down. The Program should consider providing incentives for dedicated low-iron glass production. There are various efforts underway to develop lower-cost, higher-performing reflective surfaces, and these should all continue. These efforts are as follows:

- A collaborative NREL-industry effort has developed ReflecTech thin film reflector material that is applied to a thin aluminum substrate. Current efforts are aimed at further improvements.
- 3M is developing a silvered polymer reflective film as an improvement over its earlier ECP-305+ film and under a FOA is coating it with an anti-soiling hard coat.
- Abengoa has a FOA contract to develop a high-performance front surface mirror.
- PPG has a FOA contract to develop an encapsulated glass mirror.
- Alanod has developed an anodized aluminum mirror with enhanced reflectivity.
- The government has provided $38 million of economic stimulus funds to mirror manufacturers to reduce mirror costs.

Other industry efforts are aimed at developing thin glass, tempered glass, and laminated glass and improving the wet chemistry coatings. In the long run, it appears that thin film reflectors have the greatest chance of significantly reducing collector cost because they can serve as part of the structure and they eliminate the need to install individual glass facets. They also result in a much lighter-weight collector, which should lower installation and transportation costs. Improved mirror facets should be a top program priority. The dish/Stirling industry has adopted the use of structural facets involving a composite structure with thin glass mirrors. Structural or composite mirrors should be investigated for use in parabolic troughs.

3.1.5 Optical Materials Testing

The Program should continue to conduct tests of optical properties (specular reflectance, absorptance, and emittance), durability performance, and cost improvements of potential advanced solar mirrors and solar selective coatings. Maintaining a database of durability results for a wide variety of reflector and receiver materials is vital to ensuring high confidence on the part of project investors and successful long-term field operation.

3.1.6 Foundations and Support Structures

The specifications for these will depend on collector and site characteristics. Several FOA contractors are investigating this, and it is important that they report to DOE the details of the improvements being made and their impacts on cost. The laboratories should provide support in the form of finite element structural analysis for contractors that do not have this capability.

Figure 6 summarizes the potential impact on LCOE of changes in collector-related parameters. Mirror optical performance has a major impact on cost.

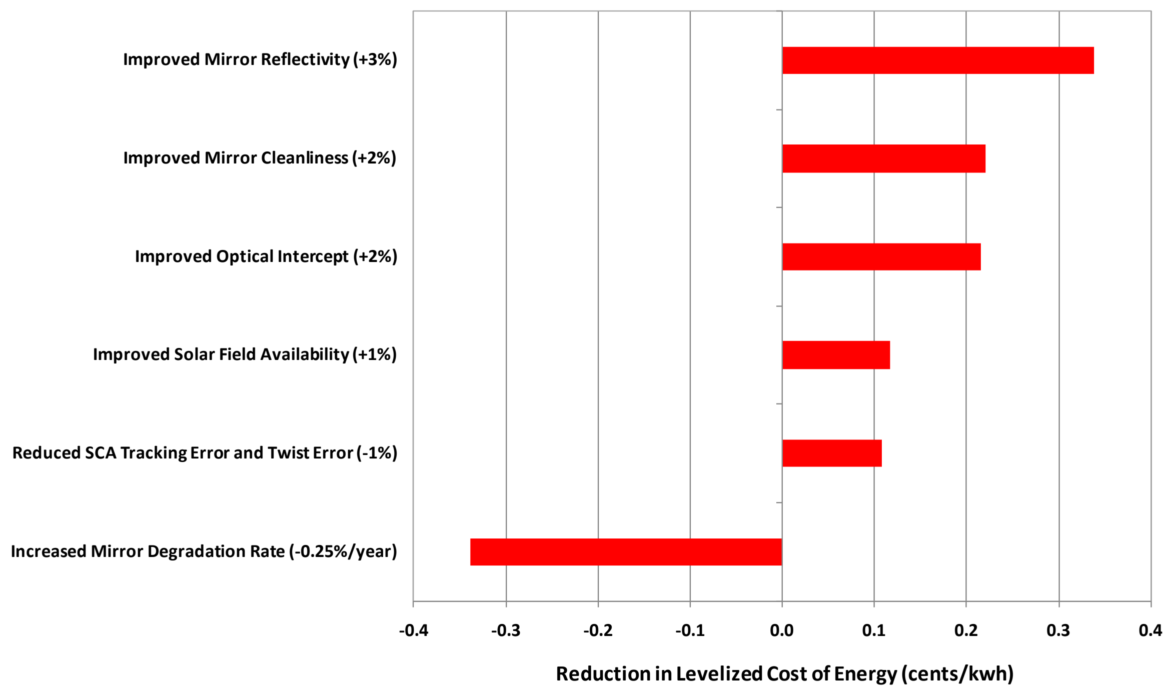

Figure 6. Impact of collector-related changes on the real levelized cost of electricity.

3.2 Heat Transfer Fluid

Currently the operating temperature of a trough field is limited to 400°C. Higher operating temperature would provide higher cycle efficiency, but it will also increase heat loss. The main advantage, however, is the smaller storage volume that would result. Advanced heat transfer fluids could also reduce parasitic pumping power, and because the fluid itself represents almost 2% of the total plant cost, research should also be aimed at identifying fluids with a higher heat capacity and a lower materials cost. Analyses by the laboratories and industry partners estimate that an HTF that operates at 500°C but requires freeze protection will reduce LCOE by $0.0125–$0.0175/kWh, depending on the amount of heat tracing. An HTF that is capable of operating at 500°C without freeze protection will reduce LCOE by $0.0225/kWh.

Using molten salt in the collector field is still a potential mid-term option. Sandia should continue its efforts to develop salts with a lower freezing point and continue to run tests to determine how frozen salt can be safely thawed. Their test results will also determine the compatibility of molten salt with various piping components. NREL intends to identify and test new materials for joint seals that are compatible with molten salt. Without such test results, loan rates will be much higher.

Long-term R&D at the labs should focus on modeling and experimental research to identify promising fluids and test promising formulations to evaluate their properties. Current work on nanofluids should be expanded to investigate nanomaterials that lower the melting point and increase the liquid temperature range for molten salts and other liquids. Other innovative approaches to developing an appropriate HTF should also be pursued.

3.3 Storage Cost Reduction

There are a number of FOA contracts that are working on storage cost reduction, including HTFs with improved properties, storage media with greater stored energy density, and advanced storage concepts. Work in this area should continue to focus on improved HTFs and storage media and advanced storage concepts. Development of improved storage media should be directed at increasing the stored energy density as well as the power density.

3.3.1 Storage Fluid

Near-term R&D should utilize computer modeling software to identify fluids and fluid combinations that have a high heat capacity, are low in cost, and are stable at temperatures up to 500°C. Long-term R&D should continue to investigate innovative approaches to dramatically increasing the heat capacity of storage fluids. Nanomaterials research has recently made progress in demonstrating the basic approach of increasing fluid heat capacity by adding phase-change nanoparticles to the fluid. This research is fundamental and requires the development of new methods to synthesize nanoparticles with the desired properties and stabilize these particles in the storage fluid. SAM analysis indicates that a two-tank storage system that uses a storage fluid with double the current heat capacity will reduce LCOE by $0.013/kWh.

3.3.2 Thermocline Storage

Thermocline tanks have the potential to greatly reduce the fluid inventory, but they present challenges in terms of hoop stress, thermocline control, and storage efficiency. Further computer modeling is needed to address these issues, and if the results are promising, a prototype tank should be built and tested. Laboratory work should be coordinated with FOA work to avoid duplication. Innovative variations of the basic thermocline design that eliminate thermocline spread and hoop stress should also be modeled initially to predict performance. Additionally, thermocline concepts that are based on encapsulated phase-change materials should also be modeled. Promising concepts should be validated with experimental prototypes. Several analyses by the laboratories and industry partners estimate that a properly performing thermocline will reduce LCOE by $0.009/kWh.

3.3.3 PCM Storage

PCM storage probably offers the best mid-term opportunity for significantly increasing stored energy density. The greatest barrier to this approach is the limited conductivity of the solid phase. This barrier limits the power density and performance of the storage system. Several FOA projects are currently investigating methods and geometries for overcoming this barrier. The laboratories should work with university and industry partners to provide support in the form of transport modeling and experimental testing and evaluation of PCM-based storage systems.

Completely new storage concepts based on PCMs should also be modeled and evaluated. SAM and industry analyses show that PCM storage will reduce LCOE by $0.008/kWh.

3.3.4 Thermochemical Storage

Thermochemical storage represents the best option for storage systems that possess very high stored energy densities. Improvement in stored energy density of an order of magnitude over current technologies is possible. Development of thermochemical storage as a reversible process requires the solution of several practical problems. The reversible reactions typically occur at temperatures higher than those achieved by current CSP technologies. Reactants may be corrosive to reactor walls at the operating temperature. Changes in the morphology of the solid reactant phases may result in long-term degradation of reaction rates and power performance. All of these issues are fundamental to the process, so solutions to these barriers will require a long-term R&D effort.

3.3.5 Other Advanced Storage Concepts

Work in Europe and FOA contracts are covering phase-change storage and the use of solid media including concrete, ceramics, and sand. An overall systems analysis evaluation is needed to determine which of these methods holds promise for significant cost reduction. This analysis should utilize cost estimates generated in the FOA awards. Laboratory testing should be performed on the most promising concepts.

3.4 Parasitic Power Reduction

Electric power is an expensive, high-value form of energy. Any electric power used to move heat transfer fluid or perform other functions directly robs high-value solar-generated power and so must be reduced to an absolute minimum. Losing 13%–15% of gross generated power to parasitics as indicated in a recent WorleyParsons study (resulting in an equivalent increase in the cost of generated electricity) seems excessive and presents a major opportunity for improvement. (Some in industry believe this number is only 10%, but even that means there is considerable opportunity for improvement.) A thorough analysis of all parasitic power consumption should be performed to identify where parasitic losses occur and where the greatest opportunities for reductions are. The ways of reducing each of those should be explored and their costs weighed against the cost of electricity saved. The use of larger-diameter receiver tubes should be considered as part of a broader trough and trough field optimization effort. Attention should be focused on minimizing pipe elbows, valves, and other minor losses. Variable speed drives should be considered in place of throttling valves and single-speed or two-speed fans. This analysis should be performed by the laboratories, possibly in conjunction with a company having experience in plant energy efficiency studies (e.g., RMI). HTFs with lower viscosities and greater volumetric heat capacities should also be developed as part of the advanced HTF development effort.

3.5 O&M Cost Reduction

Because O&M costs represent about 20% of the delivered electricity cost, this should also be a high-priority area. Larger system sizes and the development of power parks will decrease the man-hours of operating labor needed per megawatt. It is also worthwhile to investigate potential areas for automation, such as mirror cleaning, where a trough-integrated system might be considered. Because keeping mirrors clean is critical, a system that automatically monitors mirror reflectance could help ensure that cleaning occurs only when it is most needed. Mirror breakage can be addressed by developing laminated glass mirrors or thin film reflectors. The latest SEGS data indicated that approximately 2% of the receiver glass breaks each year. This seems unacceptably high and should be studied. Prevention of breakage might require improved operating procedures. In any case, DOE should work with industry to collect the latest O&M data so that failure modes can be avoided or reduced.

3.6 CSP Environmental Impact

Environmental concerns have become a significant issue for CSP. The labs should continue to support the BLM PEIS effort by developing best practices for siting on BLM land. In addition, the life-cycle impact of trough systems needs to be assessed. This will remove barriers to deployment by reducing indirect costs such as the development of environmental impact statements. The specific cost savings need to be evaluated as part of this work.

A particularly important issue is water use. Analysis of dry- and hybrid-cooled plants indicates that water use can be reduced from 800 gal/MWh to 80 gal/MWh. A dry-cooled plant increases the LCOE from 3% to 8%, depending on location. Hybrid cooling systems will have a somewhat lower impact on the LCOE, depending on the ratio of dry to wet cooling, but they save less water. Further analysis will be conducted to determine the impact of time-of-day electricity rates on the cost effectiveness of air and hybrid cooling systems. Of the 80 gallons, 20 are used for mirror washing and 60 for steam cycle make-up water. A commercial product that spins water to remove particulates can possibly be used to recycle wash water and will be investigated. Removing dissolved solids from steam make-up water is more costly, but options will be evaluated.

3.7 Collector and System Performance Assessment

Any improvements made in the collector field must be checked via testing. A comprehensive testing program is needed to support cost reduction efforts. As described earlier, this type of support is needed to ensure success in the field, as it fosters economies of scale and learning-curve improvements.

Modern parabolic trough collectors have high-performance receivers with minimal heat loss and thus have very flat efficiency curves. This means the performance is strongly dictated by the optical efficiency. A 1% drop in optical efficiency translates into a 1% increase in the cost of electricity. As a consequence, ensuring that deployed collectors have and maintain the highest optical performance is critical to success. It is also important that new, lower-cost collector concepts get the full benefit of both experimental characterization tools and optical models to achieve the highest possible performance. While secondary to optical performance, it is also important to measure thermal performance to ensure that cost reduction efforts do not unduly compromise performance at operating temperatures.

The following activities support a robust testing effort.

3.7.1 Mirror Measurement Methods

NREL has been utilizing the VSHOT method for determining slope error of mirrors. This has been the gold standard used by Acciona, SkyFuel, Abengoa, and Alcoa for determining mirror slope error and identifying where improvements are needed. Optical efficiency improvements of over 20% have been achieved using VSHOT to help develop new collectors. SAM runs indicate that for a 100-MW LS2 parabolic trough plant without storage in Daggett, CA with a 30% ITC, a 20% improvement in optical performance results in a drop in LCOE of approximately 2¢/kWh. In fact, both Acciona and SkyFuel were able to make major improvements in their designs, and hence lower their costs of electricity, as a result of VSHOT testing. Because performing VSHOT tests is time-consuming and NREL cannot meet all the demands for new testing, an effort is needed to increase the speed of VSHOT testing and identify other optical techniques, such as deflectometry and a Distant Observer technique, that have the potential to take data more rapidly. This task will allow more collectors to be tested more quickly so that performance in the field can be ensured. SOFAST, a new system developed at Sandia for use with parabolic dishes, uses a digital video camera and a projected fringe pattern to produce the same data as VSHOT with much higher resolution as well as other information such as mirror twist. It is also faster to set up (about 1 hour), and the data can be processed in only about 10 seconds. Its extension to parabolic troughs will be investigated.

The TOPCAT alignment system developed by Sandia can be used at an installed collector field or at the end of production to determine the extent to which mirrors are out of alignment and allow mirrors to be realigned to restore proper performance. As is the case with VSHOT, work is needed to increase the operational speed. A loop at SEGS VIII was aligned with a 5°C increase in its operating temperature as compared to before alignment.

The distant observer technique being developed by NREL involves the use of a camera from an aerial platform to determine the optical intercept factors and other optical information (such as surface errors and misalignments) for each collector in an entire field. If proven viable, this would greatly increase measurement speed compared to VSHOT and would allow an entire field to be measured in a short period of time. It is expected that using this tool to identify the main causes of optical errors at parabolic trough power plants will enable the plant operators to address those optical errors and thus improve their optical efficiency in the range of 2%–5%, resulting in a decrease in LCOE of about 0.5¢/kWh. Distant observer can also be used to determine the impact of operational wind speeds on collector field optics. It can also include an infrared camera allowing rapid measurement of an entire field of receiver tubes and identifying those in need of field repair or replacement. An NREL analysis indicated that if 60% of the receivers in a collector field suffer from hydrogen infiltration, receiver replacement will reduce the LCOE by about 3¢/kWh.

NREL and Sandia are both developing expanded laboratory space to develop and test new optical characterization concepts, including new facets. This includes the capability to apply loads to determine how collector shape is affected. Because optical testing is vital to the success of new collector concepts, lab development should be a high priority.

3.7.2 Collector Testing

NREL measures collector overall optical efficiency at an outdoor test loop. The measurement accounts for mirror reflectance, mirror slope error, intercept factor, receiver glazing transmittance, and receiver absorptance. Tests of the SkyFuel SkyTrough collector revealed areas for improvement, which was very helpful in their final design. Test results are obtained at normal incidence and at several different angles. Sandia's outdoor rotating platform is used to measure the overall efficiency of parabolic trough collectors (including optical efficiency) at a range of operating temperatures and can be used to generate an efficiency curve. It can measure the performance improvement resulting from such changes as an improved tracking system. All new collectors should undergo one or both tests before being deployed in the field. Testing in FY10 should indicate the extent to which efficiency curves developed by the two different approaches agree. The data collected from these tests allow DOE to assess the optical and thermal performance of advanced collector designs funded by the CSP program. Developers need the data to predict solar field performance associated with advanced collector designs. The data is also critical for attracting the debt and equity necessary to finance projects based on advanced designs.

3.7.3 Model Development

Modeling plays a pivotal role in cost-effectively developing efficient, low-cost parabolic trough system designs. Without a suite of modeling tools, the development path and time would be considerably longer and more costly. The CSP industry has access to and uses a variety of commercial or public (laboratory-developed) models designed to assess component and overall system performance. These vary in scope from simplistic models used for scoping analysis to more sophisticated tools for detailed engineering design and analysis. Many commercially available models are prohibitively expensive and/or are not conducive to CSP-specific applications. It is important that DOE continue to support the development of detailed component models (e.g., collector, receiver, storage, power plant) that allow both public and private researchers to understand and improve the performance of these subsystems. These models can be used in conjunction with system-level tools (e.g., Solar Advisor Model, IPSEpro, Gate Cycle) to better understand how various subsystems affect the overall system performance and to accurately predict the annual performance and levelized cost of energy of current and future parabolic trough systems. This information not only supports R&D efforts within the solar community, but is used heavily by the financial community in assessing the viability of commercial projects.

Optical models are important for developing new collector ideas. NREL's SolTrace should be improved to increase its speed and improve its user interface. Sandia's CIRCE also provides valuable optical modeling capability. Both tools should be kept available and improved.

3.7.4 Plant Performance Data Collection and Model Validation

This activity evaluates the total performance of operating plants and uses the data to validate performance models. This effort involves the development of a non-invasive test capability to measure fluid flow rates and temperatures in order to evaluate overall field performance. It can also include training a company to take a wide range of collector field measurements.

3.7.5 Test Standards

The development of an acceptance test standard for parabolic trough systems will increase confidence among members of the financial community and thus support financing. NREL should continue to develop this while supporting a parallel (but longer-term) effort underway by ASME. Work is also needed on mirror durability methodology development and standards development at the material, collector, and system levels. Work should also be done in conjunction with SolarPACES to develop a uniform receiver heat loss test standard.

3.8 Advanced Concepts

3.8.1 Hybridization

This task takes advantage of the strong interest expressed by the natural gas industry to partner with renewable energy. The laboratories should perform the systems analysis needed to find those combinations that maximize the efficiency of both solar energy collection and natural gas combustion and yield the highest rate of return for new trough installations. By combining solar with storage and natural gas, CSP has the potential to directly displace base load coal plants, thereby making an enormous contribution to carbon emissions reductions. It is recommended that the DOE laboratories develop partnerships with EPRI and the natural gas industry to accelerate this work. NREL has already identified a promising hybrid (solar/natural gas) concept and has filed a record of invention.

3.8.2 Direct Steam Generation

The Europeans have taken the lead on direct steam generation, but the laboratories should thoroughly evaluate the potential for this approach. While it allows for higher operating temperatures, coupling direct steam generation with thermal storage is a challenge. Direct steam generation also requires higher pressure, thick-walled receivers, affects solar field assembly due to the ASME standards for high pressure or boiler piping, and has other technical issues in its implementation. The labs should evaluate the European work on direct steam generation and decide if DOE-funded work in this area is warranted.

3.8.3 Supercritical CO_2 Cycle

As stated previously, a Brayton cycle using supercritical CO_2 could potentially lower LCOE by about 1 ¢/kWh. Systems analysis modeling will be directed at providing a thorough investigation of the potential for this concept. Issues such as increased piping cost, parasitic pumping power, and reduced heat transfer coefficients should be considered.

3.8.4 Low-Cost Collector Concepts

The laboratories should consider exploring long-term line-focus collector options. SkyFuel currently has a FOA to investigate high-temperature linear Fresnel collectors using molten salt heat transfer fluid. Compared to troughs, this technology has a smaller number of receivers and the receivers are fixed, thus making easier the prospect of running molten salt in the collector field. The second phase of the SkyFuel study should determine whether this is a concept worth pursuing. If it is, the laboratories should consider providing further support for the development.

Stretched membrane and inflated concepts have been proposed in the past. A study of these kinds of ultra-low-cost ideas is warranted as a high-risk but potentially high-return complement to the near-term development emphasized by the Program.

3.9 New FOAs

Because of the success of FOA contracts to date, this plan supports a new round of FOAs. These will include next-generation line-focus collectors with special emphasis on manufacturability, low-cost receivers (aimed primarily at encouraging new players to enter the market), high-temperature fluids and components (primarily to allow smaller storage volume), and advanced storage (to lower storage costs). NREL and Sandia will work with DOE to develop the detailed solicitations and then provide technical advisor support to the FOA winners.

3.10 Laboratory Support to FOA Contractors

NREL and Sandia staff serve as technical advisors on the FOA contracts in the areas of Collectors, Storage/Heat Transfer Fluid, Advanced Reflector, and Baseline Power. This activity serves as a vital link between the DOE laboratories and industry and helps ensure high quality in the work being performed. It is a vehicle for providing various modeling and testing support. It also helps keep laboratory staff up-to-date on the latest status of the technology. Funding for this needs to be increased to promote success and be continued with the new FOAs.

4 Spending Plan

A proposed spending plan is shown in Table 5 (available as an Excel spreadsheet). It covers FY10 through FY16, the year at the end of which the 30% investment tax credit is currently scheduled to expire. Table 5 includes for each activity:

- the activity title
- the activity participants
- whether it is new (N) or existing (E)
- the relevant section of this plan
- the priority of the activity: high (H), medium (M), or low (L)
- an appropriate metric for the activity
- the potential improvement in that metric
- the potential impact on the levelized cost of electricity (LCOE)
- the time frame
- the needed funding for each fiscal year through FY16 (including the funding, if any, in FY10)
- a description of the activity.

It should be noted that each activity is evaluated individually. In reality, there would be overlaps in contributions from the various activities, so the potential improvements in the metrics and LCOE cannot be added together. Staff at NREL and Sandia and industry members were asked to rank the various activities. These rankings were used to identify task priorities as high (H), medium (M), and low (L), with industry input being given somewhat more weight. These priorities are shown in Table 5 to aid DOE in allocating a finite budget. There was general agreement among industry members, however, that because reducing the cost of electricity generated from line-focus solar collectors by 50% is an ambitious goal, all of the activities described in this document can make important contributions to that effort.

Overall, we propose a near-term funding surge to maximize the chances of achieving the cost goal and to ensure that products and projects being built perform successfully, thus encouraging additional financing and greater deployment. New projects include overall collector design and frame improvement, development of low-cost receivers, field wind load measurement and mitigation, efforts to reduce parasitic power and O&M costs, expanded emphasis on reducing total plant water consumption, development of advanced hybrid system concepts, and investigation of ultra-low-cost collector concepts.

5 Conclusions

Achieving a roughly 50% reduction in LCOE in six years is clearly recognized as a considerable challenge by most of the CSP industry. To reach that goal, it is important and necessary to simultaneously pursue all available avenues. This includes R&D to improve performance and lower costs of all components, studies to reduce labor and maintenance costs, encouragement of additional manufacturers and product sources, reduction of parasitic power requirements, analysis to explore new overall system design approaches, lower-cost collector designs, innovative financing options, and testing to ensure high quality in new systems.

Fortunately, the Program is already fairly well focused on most of these activities, so a major change in direction is not needed. FOA projects have made significant progress, so these should be completed, and a new round of FOAs focusing on collector development, lowering of receiver costs, and storage is warranted. Recognizing the importance of maintaining high optical performance, optical characterization work will continue but be consolidated and transferred to industry as it is developed.

There are a number of circumstances that would appear to increase the chances of success. Renewable portfolio standards and government solicitations have encouraged the development and deployment of new products. The line-focus industry has a good track record and significant engineering talent. A close partnership between industry and the DOE laboratories can lead to the successful deployment of large-scale systems, which will achieve economies of scale and foster learning curve cost reductions. One challenge will be to find the right balance between protecting individual commercial interests while at the same time sharing information that is valuable to the industry as a whole. Along these lines, DOE should consider establishing an industry-laboratory working group to promote mutually collaborative activities and information sharing.

Table 5. Multi-year activities and budgets.

AOP Parabolic Trough R&D Activity	Participant(s)	New/ Exist.	Plan ID	Priority	Metric	Metric Impact	LCOE Impact	Time-frame	FY10	FY11	FY12	FY13	FY14	FY15	FY16	Description
Collector Development									2445	3890	3075	2010	1600	1150	1150	
Overall Collector Design	Sandia/NREL	N	3.1.1	H	$/m²	-45%	-3 ¢/kwh	Near	0	300	150	100	50	50	50	Parametric study of aperture, receiver sizes, focal length, piping needs
Collector Structure Improvement/Wind Load Investigations	Sandia/NREL	N	3.1.2	H	$/m²	-20%	-1.0 ¢/kwh	Near	0	300	150	100	150	50	50	Comparison of different frame concepts: torque tube, torque box, space frame, monocoque
Collector Optical Measurements	NREL	E	3.7.1	H	Optical Efficiency, Reliability	+2%	- .2 ¢/kwh	Near/Mid	300	400	300	300	300	200	200	VSHOT or similar measurements to determine reflector accuracy
Field Optical and Heat Loss Measurements	NREL	E	3.7.1	H	Optical and Thermal Efficiency, Reliability	+2%	- .2 ¢/kwh	Near/Mid	295	350	350	0	0	0	0	Distant observer development and application
Receiver Heat Loss Measurement	NREL	E	3.1.3	H	Thermal Efficiency, Reliability	- 20%	- .25 ¢/kwh	Near/Mid	380	250	200	150	150	150	150	Heat loss measurement of latest receivers and investigation of means to improve it
Optical/Load Test Laboratory	NREL	E	3.7.1	M	Optical Efficiency, Reliability	+2%	- .2 ¢/kwh	Near/Mid	240	240	0	0	0	0	0	Measuring the impact of loads on collector structures to help in developing more efficient designs
Outdoor Test Loop	NREL	E	3.7.1	H	Optical Efficiency, Thermal Efficiency, Reliability	+2%	- .2 ¢/kwh	Near/Mid	270	270	270	200	200	150	150	Measuring overall optical efficiency of trough modules to identify impacts of improvements
Rotating Platform Collector Tests	Sandia	E	3.7.1	H	Optical/Thermal Efficiency	+2%	- .2 ¢/kwh	Near	100	270	270	200	200	150	150	Measuring total efficiency of troughs to identify adequacy of design
Topcat Alignment System	Sandia	E	3.7.1	H	Optical Efficiency	+1%	- .1 ¢/kwh	Near	375	375	300	300	150	0	0	Determining mirror alignment inaccuracies and correcting them in the field
Trough Tracking Sensor	Sandia	E	3.1.1	L	Optical Efficiency	+1%	- .1 ¢/kwh	Near	50	100	50	25	0	0	0	A higher-accuracy sensor to support the increased demands of higher concentration ratios
Optical Model Development	NREL	E	3.7.3	M	Optical Efficiency	+2%	- .2 ¢/kwh	Near/Mid	250	150	150	50	50	50	50	Increase speed and improve usability of SolTrace
Plant Performance Data	NREL	N	3.7.4	H	Collector Field Efficiency	+2%	- .2 ¢/kwh	Near/Mid	0	300	300	150	150	150	150	Involves the development of a non-invasive collector field performance measurement platform. Can also include training of an industry partner
Test Standards	NREL	E	3.7.5	H	Risk/Reliability	+/- 2%	+/- 1.2 ¢/kwh	Near/Mid	185	185	185	185	50	50	50	Development of a collector field acceptance test standard to promote investor confidence. Also standardized receiver and mirror tests to ensure quality and the ability to compare results
Low-Cost Receivers	NREL	N	3.1.3.3	H	Receiver Cost, $/m	-30%	- .2 ¢/kwh	Near/mid	0	100	100	50	0	0	0	To support a FOA or other means to stimulate lower cost receivers
Wind Load Measurement and Mitigation	NREL	N	3.1.2	H	Collector Cost, $/m²	-20%	-1.0 ¢/kwh	Mid	0	300	300	200	150	150	150	In response to identified industry need
NREL/SNL Balance of Plant									325	950	800	450	250	100	100	
Hydrogen Mitigation	NREL	E	3.1.3.2	M	Thermal Efficiency, Receiver Cost, Reliability, Risk	+/- 20%	+/- .2 ¢/kwh	Near	185	200	150	50	50	0	0	Working with industrial partner to implement system for removing hydrogen in operating plants
Detailed Plant Modeling/SAM	NREL	E	3.7.3	M	Analysis, Water Usage			Near/Mid	140	300	250	200	100	50	50	Developing detailed trough, cooling system, and other models for parametric studies and use in SAM
Parasitic Power Reduction	NREL/Sandia	N	3.4	L	Percent of Net Power	- 20%	+/- .2 ¢/kwh	Near	0	150	100	50	0	0	0	Identify all the various ways to reduce parasitic power consumption
O&M Cost Reduction	NREL/Sandia	N	3.5	L	$/kWh	- 25%	- .8 ¢/kwh	Near/Mid	0	150	150	50	50	50	50	Collect latest O&M data and develop lower cost procedures such as mirror cleaning
Reducing Plant Water Consumption In Dry-Cooled Plant	NREL	N	3.6, 3.1	H	gal/MWh Water Usage	-75%	NA	Near/Mid	0	150	150	100	50	0	0	Even dry-cooled plants require some water for steam make-up and morror washing. This investigates means to recycle this water

NREL/SNL Advanced Heat Transfer Fluids									1250	1450	1450	950	950	950	1050
Develop and Test Salt-in-the-Field Components	Sandia/NREL	E	3.2	H	Storage Cost, Cycle Efficiency	30%	- 1.75 ¢/kwh	Near	350	500	500	150	150	150	150 Develop and evaluate salt in the field components including valves, joints, seals, pumps
Identify, Model, and Test Freeze Recovery Methods	Sandia	E	3.2	H	Storage Cost, Cycle Efficiency	30%	- 1.75 ¢/kwh	Near	250	300	300	150	150	150	150 Develop and test methods for recovering a collector loop(s) from a salt freeze
Identify amd Characterize Low-Melting Salts for HTF to 500°C	Sandia	E	3.2, 3.4	H	Storage Cost, Cycle Efficiency	30%	- 1.75 ¢/kwh	Mid	350	350	350	350	350	350	350 Identify and characterize salts that melt at <100°C and are stable at 500°C
Develop HTFs with Liquid Temperature Range from 0°-500°C	NREL	N	3.2, 3.4	M	Storage Cost, Cycle Efficiency	30%	- 2.25 ¢/kwh	Long	300	300	300	300	300	300	400 Develop research directions for obtaining a HTF that has a liquid temperature range from 0°C-500°C
NREL/SNL Trough Storage Components and Systems									2200	2200	2200	2200	2200	2250	2700
Identify, Model, and Test PCMs for Storage	NREL/Sandia	N	3.3.3	H	Storage Cost	25%	- 0.82 ¢/kwh	Mid	450	450	450	450	450	450	450 Identify, model, and test PCM candidates for various TES systems
Model Full Plant Performance (Powerblock/Storage Interactions)	NREL/Sandia	E	3.3	H	Storage Cost, Cycle Efficiency	10%	- 0.30 ¢/kwh	Long	400	400	400	400	400	400	400 Ongoing performance modeling of thermal storage systems and storage systems integrated into complete plant models
Develop Alternative Liquid Storage Media (Salt Formulations)	Sandia/NREL	E	3.3.1	H	Storage Cost	40%	- 1.32 ¢/kwh	Mid	400	400	400	400	400	400	400 Develop storage fluids with enhanced volumetric heat capacity and low cost
Develop Storage Fluid Property Enhancement (Nanomaterials)	NREL	E	3.3.1	M	Storage Cost	40%	- 1.32 ¢/kwh	Long	350	350	350	350	350	350	350 Develop composite storage fluids with enhanced volumetric heat capacity
Model and Test Novel Thermocline Designs	Sandia/NREL	E	3.3.2	M	Storage Cost	30%	- 0.87 ¢/kwh	Mid	150	150	150	150	150	150	150 Develop and model current and new thermocline designs
Outreach to Potential Suppliers (Salt, Tank Fab, etc.)	Sandia/NREL	N	3.3	M	Storage Cost	20%	- 0.81 ¢/kwh	Mid	75	75	75	75	75	75	75 Marketing effort to increase the number of suppliers of critical storage components and materials
Analyze and Model Novel Tank Design (Below Grade,Taller)	Sandia	N	3.3	M	Storage Cost	10%	- 0.30 ¢/kwh	Mid	75	75	75	75	75	75	75 Analyze novel storage tank designs to decrease the number of tanks for large storage applications
Model and Test Salt/Oil HXC Designs	Sandia/NREL	N	3.3	L	Storage Cost, Cycle Efficiency	40%	- 1.32 ¢/kwh	Near	75	75	75	75	75	0	0 Model and test novel salt/oil heat exchanger designs
Identify and Model Thermochemical Storage Cycles	Sandia/NREL	N	3.3.4	L	Storage Cost	40%	- 1.32 ¢/kwh	Long	75	75	75	75	75	75	300 Identify and model thermochemical storage cycles to support on-going work in this area
Model and Test Solid Particle Storage Systems and Heat Exchangers	Sandia	E	3.3.5	L	Storage Cost	30%	-1.0 ¢/kwh	Long	75	75	75	75	75	75	300 Model and test solid particle storage and heat exchangers to support on-going work in this area
Identify and Test Low-Cost Insulation (Aerogels)	Sandia	N	3.3	L	Storage Cost, Cycle Efficiency	-10%	- 0.30 ¢/kwh	Mid	75	75	75	75	75	200	200 Identify and test low-cost insulation for CSP applications
NREL Advanced Reflector Materials									1235	1405	1405	790	550	550	550
Advanced Reflector Coatings Development	NREL	E	3.1.4	M	Solar Field Cost, Optical Efficiency	+/- 3%	+/- .35 ¢/kwh	Mid	240	240	240	240	100	100	100 Development of coatings to provide better abrasion resistance
Antisoiling Coatings and Low-to-No H_2O Cleaning	NREL	E	3.1.4, 3	H	Optical Efficiency, O&M	+/- 2%	+/- .2 ¢/kwh	Mid	165	200	200	100	50	50	50 Development of means to minimize cleaning frequency and amount of water use
Optical Materials Service Lifetime Prediction	NREL	E	3.1.5	H	Reliability/Risk	-.25%/yr	+ .4 ¢/kwh	Near/Mid	145	200	200	100	100	100	100 Better lifetime prediction to provide greater investor confidence
Mirror Characterization and Durability Testing	NREL	E	3.1.5	H	Reliability/Risk	-.25%/yr	+ .4 ¢/kwh	Near/Mid	520	600	600	300	300	300	300 Expand and maintain reflector performance data base for industry
Reflector and Durability Standards Development	NREL	E	3.7.5	H	Reliability/Risk	-.25%/yr	+ .4 ¢/kwh	Near/Mid	165	165	165	50	0	0	0 Develop standardized test approach
NREL Advanced Absorber Materials									250	250	250	250	100	50	0
Schott Advanced Selective Coating Development CRADA	NREL	E	3.1.3.1	M	Optical Efficiency, Thermal Efficiency, Receiver Cost	+/- 1%, +/-20%	+/- .25 ¢/kwh	Mid	100	100	100	100	0	0	0 Low-e coating that can operate at 500°C and is resistant to oxidation. High temperature allows for smaller, lower-cost storage
Advanced Solar Selective Coating Development	NREL	E	3.1.3.2	M	Optical Efficiency, Thermal Efficiency, Receiver Cost	+/- 1%, +/-20%	+/- .25 ¢/kwh	Mid/Long	150	150	150	150	100	50	0 New high-performance coatings to reduce storage size

NREL/SNL Advanced Concepts									455	1355	1355	1105	550	150	150	
Advanced Power Cycles	NREL	E	3.8.3	L	Cycle Efficiency	10%	-.7 ¢/kwh	Mid/Long	255	255	255	255	100	50	50	Investigation of supercritical CO_2 and other advanced power cycles
Higher Concentration Trough	Sandia	E	3.1.1	M	Solar Field Cost	10%	-.75 ¢/kwh	Mid	200	300	300	150	50	0	0	Investigation of a trough with double the aperture and concentration ratio
Optical Facet Design Center	Sandia	E	3.7.1	M	Solar Field Cost, Optical Efficiency	+/-2%	+/-.2 ¢/kwh	Near/Mid	0	200	200	200	100	0	0	Apply dish facet experience to line-focus collectors
Hybridization	NREL	N	3.8.1	L	Capacity factor	50%	NA	Mid	0	200	200	200	100	0	0	Investigation of low-cost ways to combine CSP with natural gas
Direct Steam Generation	NREL	N	3.8.2	L	Plant LCOE	15%	-2 ¢/kwh	Mid/Long	0	200	200	200	100	0	0	Investigate ways to combine direct steam generation with storage
Low-Cost Collector Concepts	NREL/Sandia	N	3.8.4	L	$/m2	30%	-1.5 ¢/kwh	Long	0	200	200	100	100	100	100	Investigate various low-cost alternatives like linear Fresnel and variations
FOAs									14199	32931	41874	35000	38000	25000	16000	
CSP Industry Collector Development Projects									6927	6532	5148	0	0	0	0	
A-Linear Fresnel Reflector	SkyFuel	E	3.8.4		Solar Field Cost, TES Cost, Cycle Efficiency			Mid	850	589	553	0	0	0	0	Development of a low-cost, high-temperature linear Fresnel system
T-Next Generation Trough	Abengoa	E	3.1.1		Solar Field Cost			Mid	3049	2745	1558	0	0	0	0	Development of a next-generation lower-cost trough
T-All Aluminum Trough	Alcoa	E	3.1.1		Solar Field Cost			Mid	739	169	0	0	0	0	0	Development of an all-aluminum trough using monocoque construction
T-High Temp Trough Collector	Solar Millennium	E	3.1.1		Solar Field Cost, TES Cost, Cycle Efficiency			Mid	727	365	366	0	0	0	0	Development of a high-temperature trough
S-Molten Salt in the Field	Abengoa	E	3.2		Solar Field Cost, TES Cost, Cycle Efficiency			Long	1562	2664	2671	0	0	0	0	Investigation of the use of molten salt heat transfer fluid in the collector field
CSP Industry/University Advanced Storage Development Projects									6642	7899	2426	0	0	0	0	
Direct HTF Thermocline for Troughs	Acciona	E	3.3.2		Storage Cost			Mid	50	199	200	0	0	0	0	Reduces storage cost by displacing expensive molten salt
Low Melting Point Molten Salt	U. Arkansas	E	3.2		Storage Cost, Cycle Efficiency			Long	500	0	0	0	0	0	0	Allows molten salt to be used in field to eliminate heat exchanger penalty and costs
Concrete - High-Temp Thermocline	U. Arkansas	E	3.3.3		Storage Cost			Mid	162	0	0	0	0	0	0	Low-cost storage alternative to molten salt
Phase Change - Embedded Heat Pipes	U. Connecticut	E	3.3.3		Storage Cost			Mid	494	348	0	0	0	0	0	High storage density reduces storage volume and cost
CO_2 - High Temp Heat Transfer	C.U. New York	E	3.3.3		Storage Cost, Cycle Efficiency			Long	407	437	38	0	0	0	0	Allows for lower-cost powerblock
Thermochemical Cycles for Solar	General Atomics	E	3.3.3		Storage Cost, Cycle Efficiency			Mid/Long	584	416	0	0	0	0	0	Reduces storage volume and cost
Phase Change - Zinc Mag/Cl Salt	Lehigh	E	3.3.3		Storage Cost			Mid	428	304	0	0	0	0	0	Reduces storage volume and cost
Molten Salt - Carbon Nanotubes	Texas A&M	E	3.3.3		Storage Cost, Cycle Efficiency			Long	472	485	0	0	0	0	0	Increases heat transfer rate in solid phase to enable phase change storage
Phase Change - Salt Mixtures	Terrafore	E	3.3.3		Storage Cost, Cycle Efficiency			Mid	567	378	0	0	0	0	0	Increases storage density to lower volume and reduce cost
Optimal Heat Transfer Fluid	Symyx	E	3.3.3		Storage Cost, Cycle Efficiency			Mid/Long	500	500	0	0	0	0	0	Reduces parasitic pumping power
Demo - High-Temp CO_2 for Trough	Abengoa	E	3.3.3		Storage Cost, Cycle Efficiency			Long	879	3543	2076	0	0	0	0	Reduces power block costs
Demo - Indirect Storage at NSO	Acciona	E			Storage Cost			Mid	1198	0	0	0	0	0	0	Demonstrate thermal storage at commercial plant to provide revenue during evening peak
Demo - Thermocline & Sand @ Saguaro	US Solar Hold	E	3.3.2		Storage Cost			Mid	401	1289	112	0	0	0	0	Demonstrate the performance of advanced storage concepts
CSP Industry Advanced Reflector Development Projects									630	0	0	0	0	0	0	
A-High Value Mirrors	PPG	E	3.1.4		Solar Field Cost			Near	344	0	0	0	0	0	0	Lower-cost, high-performance mirrors
A-Hardcoats for Polymeric Mirrors	3M	E	3.1.4		Solar Field Cost, O&M			Mid	0	0	0	0	0	0	0	Will allow lower-cost reflectors to be kept cleaner in the field
T-Advanced Polymeric Reflector	Abengoa	E	3.1.4		Optical Efficiency, Solar Field Cost, O&M			Mid	286	0	0	0	0	0	0	Higher-performance, highly cleanable thin-film reflector with potential for low cost

Baseload FOA		E							0	15000	15000	15000	10000	7000	0	
New FOAs		N							0	3500	19300	20000	28000	18000	16000	
Collector Manufacturing Development FOA (Current and High-Temp)		N	3.9	H	Solar Field Cost			Mid	0	0	7,000	7,000	7,000	0	0	Manufacturing of state-of-the-art line focus collectors
Collector Manufacturing Development FOA (Manufacturing of High-Temp)		N	3.9	H	Solar Field Cost			Mid	0	0	0	0	10,000	10,000	10,000	Manufacturing of high-temperature (500°C+) line focus collectors
Low-Cost Receiver Manufacturing		N	3.9	H	Receiver Cost			Mid	0	3,000	3,000	3,000	0	0	0	Stimulates more receiver manufacturing
New Storage FOA Projects		N	3.9	H	Storage Cost			Mid	0	0	7,000	7,000	7,000	4000	4000	Focuses on reducing storage volume
High-Temperature Fluids FOA		N	3.9	H	Max. Operating Temperature and Other Properties			Long	0	100	1,000	1,000	1,000	1000	0	Increases operating delta T to allow smaller storage volume
High-Temperature Components FOA		N	3.9	M	Max. Operating Temperature			Long	0	100	1,000	1,000	1,000	1000	0	Develops components that can tolerate higher operating temperatures
Advanced Cycles and Configurations FOA-Analysis		N	3.9	L	LCOE			Long	0	300	300	0	0	0	0	Includes thermodyamic cycles, hybridization (with fossil or renewables)
Advanced Cycles and Configurations FOA-Testing		N	3.9	L	LCOE			Long	0	0	0	1000	2000	2000	2000	Small-scale testing of concepts
FOA Support									1385	2340	2990	2550	2400	1000	600	
Trough FOA Support	NREL/Sandia	E	3.10, 3	H	Solar Field Cost, Optical Efficiency	-25%	- 1 ¢/kwh	Near/Mid	485	800	800	800	500	400	0	Providing technical support to trough FOA awardees
Storage FOA Support	NREL/Sandia	E	3.1	H		-30%, +5%	- 1.5 ¢/kwh	Near/Mid	400	200	200	0	0	0	0	Provides technical support for storage FOA participants
Reflector FOA Support	NREL	E	3.10, 3	H	Optical Efficiency, Reflector Cost		+/- .5 ¢/kwh	Near/Mid	340	340	340	0	0	0	0	Development of lower-cost reflectors
Follow-On Collector FOA Support (Manufacturing of Current/Advanced)	NREL/Sandia	N	3.10	H	Solar Field Cost			Mid	0	100	400	400	400	0	0	NREL/Sandia support for new collector FOAs
Follow-On Collector FOA Support (Advanced)	NREL/Sandia	N	3.10	H	High-Temperature Systems			Long	0	0	0	100	600	600	600	Supports high-temperature manufacturing
Baseload FOA Support	NREL/Sandia	E	3.10	H	Solar Field Cost and Storage Cost			Mid/Long	60	300	300	300	300	0	0	Baseload designs are aimed at major cost reductions
Receiver FOA Support	NREL/Sandia	N	3.10	H	Solar Field Cost			Mid	100	400	400	400	0	0	0	NREL/Sandia support for new receiver FOA
New Storage FOA Support	NREL/Sandia	N	3.10	H	Storage Cost			Mid	0	100	400	400	400	0	0	NREL/Sandia support for new storage FOA
High-Temp Fluids FOA Support	NREL/Sandia	N	3.10	H	Primarily Storage Cost			Long	0	50	50	50	50	0	0	Supporting development of high-temperature fluids
High-Temp Component FOA Support	NREL/Sandia	N	3.10	M	Primarily Storage Cost			Long	0	50	50	50	50	0	0	Supporting development of high-temperature components
Advanced Cycle FOA Support	NREL/Sandia	N	3.10	L	LCOE			Long	0	0	50	50	100	0	0	Supporting advanced cycles development
TOTALS									23744	46771	55399	45305	46600	31200	22300	

Acknowledgments

The authors would like to thank Greg Kolb of Sandia National Laboratories for his input as well as the following industry members: Gilbert Cohen, Randy Gee, Ulf Herrmann, Chris Jensen, Dave Kearney, Bruce Kelly, Andrew McMahan, Alex Marker, Paul Nava, Hank Price, Adam Schaut, and David White. Finally, we appreciate the input from our colleagues at NREL. However, the authors are solely responsible for the final contents of this document.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
December 2010	Milestone Report	

4. TITLE AND SUBTITLE
Line-Focus Solar Power Plant Cost Reduction Plan

5a. CONTRACT NUMBER
DE-AC36-08GO28308

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Charles Kutscher, Mark Mehos, Craig Turchi, and Greg Glatzmaier
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5d. PROJECT NUMBER
NREL/TP-5500-48175

5e. TASK NUMBER
CP09.1001

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/TP-5500-48175

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
Line-focus solar collectors, in particular parabolic trough collectors, are the most mature and proven technology available for producing central electricity from concentrated solar energy. Because this technology has over 25 years of successful operational experience, resulting in a low perceived risk, it is likely that it will continue to be a favorite of investors for some time. The concentrating solar power (CSP) industry is developing parabolic trough projects that will cost billions of dollars, and it is supporting these projects with hundreds of millions of dollars of research and development funding. While this technology offers many advantages over conventional electricity generation—such as utilizing plentiful domestic renewable fuel and having very low emissions of greenhouse gases and air pollutants—it provides electricity in the intermediate power market at about twice the cost of its conventional competitor, combined cycle natural gas. The purpose of this document is to define a set of activities from fiscal year 2011 to fiscal year 2016 that will make this technology economically competitive with conventional means.

15. SUBJECT TERMS
CSP; solar collector; line focus; development plan; costs; cost reduction

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPHONE NUMBER** (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(10/2008)