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White Paper on Dish Stirling Technology

Path Toward Commercial Deployment

Charles E. Andraka
Ellen Stechel
Peter Becker, Stirling Energy Systems
Brian Messick, Stirling Energy Systems

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Charles E. Andraka
Ellen Stechel
Concentrating Solar Power Department 06123

Peter Becker
Brian Messick
Stirling Energy Systems

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS1127

Abstract

Dish Stirling energy systems have been developed for distributed and large-scale utility deployment. This report summarizes the state of the technology in a joint project between Stirling Energy Systems, Sandia National Laboratories, and the Department of Energy in 2011. It then lays out a feasible path to large scale deployment, including development needs and anticipated cost reduction paths that will make a viable deployment product.

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We acknowledge the long-term support of dish Stirling system development by the Department of Energy through Sandia National Laboratories. We also acknowledge the significant private funding of dish Stirling development by Stirling Energy Systems (SES) leading to the state of the technology referenced in this report.

This document was jointly prepared by Sandia and Stirling Energy Systems for audience with the Department of Energy, and was CRADA-protected for a period of 5 years from the date it was produced. SES proprietary information may have been contained as well, and was protected for a period of 3 years through an NDA.

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1. INTRODUCTION

1.1. Overview of Dish Stirling

The dish Stirling technology is a solar energy generating system that consists of a parabolic solar concentrator dish structure that supports an array of curved glass mirror facets. It is designed to automatically follow the sun via a dual-axis tracking system, and to collect and focus its solar energy onto the solar receiver of a power conversion unit (PCU). The PCU, which is powered by a Stirling engine, generates grid-ready, 3-phase alternating current (AC) electricity. A detailed description of the Dish Stirling technology is presented in Section 2.

Multiple companies are in the process of developing dish Stirling technologies for commercialization in solar power applications. In March 2010, Stirling Energy Systems (SES) became the first to deploy the dish Stirling technology in a commercial solar power plant, with 60 SunCatcher™ units installed at the privately-funded, 1.5 MW Maricopa Solar power plant (Maricopa Solar) in Peoria, Arizona. SES developed the modular 25 kW SunCatcher™ dish Stirling system as part of a long-term research & development (R&D) partnership with Sandia National Laboratories (Sandia) and the United States Department of Energy (DOE). This partnership has been valuable to all partners, providing Sandia and the DOE with direct developmental access to SES's working systems at the National Solar Thermal Test Facility (NSTTF) and Maricopa Solar, while helping provide resources and expertise for SES to advance the technology,.

1.2. Beneficial attributes of Dish Stirling technology

The revolutionary SunCatcher™ dish Stirling technology (Figure 1) offers a number of beneficial attributes, including:

- **High efficiency:** The SunCatcher™ technology has achieved a solar-to-grid conversion efficiency of 31.25%, the highest recorded efficiency for any field solar technology. Its annual average conversion efficiency is 24-27%.
- **Modularity and scalability:** The modular design makes it possible to easily scale from small groups of SunCatchers to large power plants and also contributes to high availability as units can be taken off-line as required for maintenance.

Figure 1. X1 SunCatcher™ Dishes at Maricopa Solar

- **Technically validated:** The SunCatcher™ has received over $500 million in private development and testing investment, has a proven testing record, and has accumulated over 168,300 hours of commercial operation at Maricopa Solar.
- **High capacity factor:** The SunCatcher™ technology can achieve a net annual capacity factor of 24 to 25% in high direct normal irradiance (DNI) areas without storage. The technology also possesses thermal inertia advantages that mitigate the impact of cloud transients.

- **Mass production:** The SunCatcher™ is designed for high volume and low cost automotive-style mass production, enabling high-precision, highly consistent quality manufacturing. This translates into higher reliability of system performance and lower cost.
- **Grid quality electricity:** The SunCatcher™ produces sinusoidal 3 phase AC power directly, which is easily integrated into the high voltage transmission system for solid grid stability and simple utility integration.
- **Zero water use for power production:** The SunCatcher™ technology uses no water for generation or cooling; water is only required for periodic mirror washing, which requires an estimated 4.5 gallons per MWh.
- **Readily available, environmentally-friendly material use:** All materials used in the SunCatcher™ are readily and abundantly available and no toxic raw materials are used.
- **Flexible siting and minimal land disturbance during installation:** SunCatcher™ units can be installed on sloping land with up to a 5% grade. Minimal grading requirements limit impact to the ground and sensitive species.

1.3. Summary of Path to SunShot

The DOE has established the SunShot Initiative, focused on reducing the total cost of solar energy systems so that they are cost competitive at large scale with other forms of energy without subsidies before the end of the decade. The goal is to reduce the cost for utility scale installations to 6 cents per kilowatt-hour (kWh). The dish Stirling technology, deployed for large-scale utility projects and taking advantage of advanced research & development, has a clear path to approach this DOE SunShot target.

1.3.1. Technology with promising opportunity to meet SunShot goal

The dish Stirling technology, which has been technically proven through a rigorous validation program, offers a promising opportunity to meet the SunShot target. Technological breakthroughs have already been achieved by the SES/Sandia partnership in the form of demonstrated world-record efficiency, engineering designs to overcome several historical reliability limitations of the Stirling engine, and development of a cutting edge optical alignment tool that aids performance and system reliability. SES has designed the SunCatcher™ to be manufactured in high volumes to meet a large scale deployment model, enabling it to take advantage of economies of scale for competitive cost while utilizing an existing industrial ecosystem and proven logistics. These factors and more have resulted in a competitive levelized cost of energy (LCOE) for the current product.

1.3.2. Barriers to achieving SunShot

The barriers to achieving the SunShot target with dish Stirling systems are primarily in the areas of financing, installed system costs, and operations and maintenance (O&M) cost. A critical success factor is the availability of reasonable financing for early market-entry projects to enable the ramp-up of high-volume production and to take advantage of economies of scale associated with its deployment model. The higher perceived financing risk associated with a newer technology typically results in higher cost of capital, imposing challenges for newer technologies to achieve market penetration.

The cost of the PCU, dish Structure, and BoP comprise the largest share of overall equipment cost. While SES has made some progress to date in reducing product part count and costly material, substantial cost reductions must occur for both the SunCatcher™ equipment, and BoP system.

Two key O&M cost drivers are heater head life and mirror washing cost. Research and operating experience have led to notable improvements in overall system and component reliability, yet with learning and R&D, additional enhancements are expected.

The revolutionary SunCatcher™ has already achieved breakthrough performance, with specific opportunities for further enhancements already identified. While not a primary barrier, added performance improvement through increased cycle temperatures without a compromise in collection efficiencies would further lower the LCOE.

1.3.3. Approaches & actions to overcome barriers

SES has a clear plan to overcome these barriers and position the SunCatcher™ technology to achieve the 6 cent per kWh SunShot target. While the gap to achieve the SunShot target is comparable to conventional leading solar technologies, the SunCatcher™ is early in its experience curve and thus will benefit from manufacturing continuous improvement and further step change activities for substantial cost reduction. Substantial cost reduction is also reasonable from identified short to medium term design enhancements and considering off-shore manufacturing for some of the components. Combined, these activities comprise a clear platform for significant cost reduction and will position the SunCatcher™ within 2 to 3 cents per kWh of the SunShot goal.

Advanced R&D activities in the areas of materials and engine architecture optimization, among others, can reasonably result in bridging the remaining LCOE gap for the SunCatcher™ to achieve the SunShot goal. Given that approaches to close the LCOE gap from today to reach SunShot have been identified and are primarily evolutionary, the SunCatcher™ complements the PV technology development path, while providing a lower risk development path to equivalent cost and market penetration goals. More revolutionary advances would then focus on getting heat off the dish to enable thermal storage. Finally, the dish concentrator sub-system of this technology has beneficial attributes that align well with other potential applications. Potential areas for future deployment of this technology include high temperature thermo chemical fuels, chemicals, and material manufacturing.

In the near term, overcoming financing challenges will require both continued support from the DOE Loan Guarantee program, as well as a mid-scale SunCatcher™ power plant. The latter will serve to mitigate investor concerns regarding the previously planned scale-up from a 1.5MW plant to 300MW plants and higher.

2. DISH STIRLING TECHNOLOGY

The DOE [1] has identified the dish Stirling technology as having potential for competitive low cost energy generation. The system is designed for high concentration of sunlight to a point, resulting in high temperature which enables the observed high engine cycle thermodynamic efficiency.

The heat to electricity conversion process in the PCU involves a closed-cycle, high efficiency four-cylinder, kinematic Stirling engine, in which hydrogen is the working gas that is recycled through the engine. The Stirling engine operates with heat input from the sun that is focused by the dish concentrator's mirrors onto the PCU solar receiver tubes, which contain the working gas. The PCU solar receiver is an external heat exchanger that absorbs the incoming solar thermal energy to heat and pressurize the hydrogen gas in the heat exchanger tubing. The volumetric changes in the working gas drive the Stirling engine, which in turn powers the PCU's generator. The rotating generator connected to the Stirling engine produces the AC electrical output. Balance of Plant (BoP) systems, comprised of standard electrical switchgear, cables, and transformers collect the electrical output from the dish Stirling systems for connection to utility power grids.

Waste heat from the engine is transferred to the ambient air via a radiator system similar to those used in automobiles. The gas is cooled by a radiator system and is continually recycled within the engine during the power cycle. The conversion and cooling process does not consume any water, setting it apart from other solar thermal-powered generating systems. This is significant in desert environments that are typically ideal for concentrating solar power (CSP) power plants, where water resources are scarce.

The Stirling cycle is well known as theoretically approaching the Carnot cycle, which means it can extract the most possible from a given temperature difference. In practice, Stirling cycles with good regenerators, such as the SES engine, can harvest over 75% of the Carnot efficiency. The shape of the thermodynamic cycle allows a greater capture than other cycles, such as Brayton or Rankine cycles. Further, practical kinematic Stirling engines (engines with a crankshaft) have been developed in a suitable size range, from 25 to 50kW, for an excellent match to practical dish sizes. The SES engine design originated in the DOE Automotive Stirling program, and was modified by Kockums for solar applications in the 1980's. SES obtained the rights to the solar engine, and substantially improved it for manufacturability, durability, and serviceability. The SES engine's four cylinders are interconnected and double-acting, as illustrated in Figure 2, maximizing the specific power capabilities of the engine.

The SES SunCatcher^{TM} holds the world record for sunlight to grid energy at 31.25% net system efficiency [2], measured in the field at Sandia with a 10-minute running average over a 1 hour test period. This high design performance, coupled with two-axis tracking, leads to a net annual efficiency of 24-27%, far exceeding the annual performance of competing solar power systems. It is important to note that this test is in real-world operating conditions, rather than controlled, transient laboratory conditions. High efficiency is a key driver of low LCOE costs, as it provides a higher utilization of the investment in materials, equipment, and land.

The dish provides a geometric concentration ratio of nearly 3,000, with a peak concentration of over 10,000 suns. This tightly focused beam, created through quality optics, allows decoupling of the thermal losses (re-radiation, convection, and reflection) from engine operation, and thus allows the engine to operate at ideal performance temperatures, limited primarily by cost-effective materials. The SES engine operates at peak heat exchanger surface temperatures around 780°C and cycle gas temperatures around 650°C.

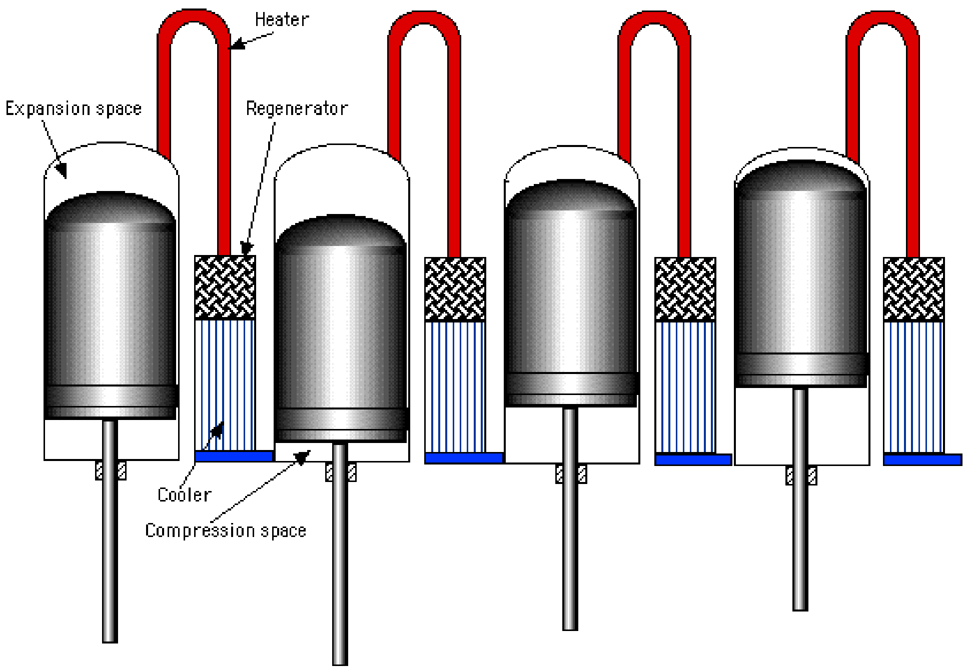

Figure 2. Stirling cycle schematic, showing double-acting piston geometry of the 4-cylinder SES engine

The two-axis tracking system allows the highest utilization of deployed glass. Unlike competing CSP technologies, the tracking dish system does not experience varying cosine losses throughout the day. In high rate production, the glass and supporting structure are a significant fraction of the power plant cost, so high utilization is important to LCOE reduction.

As part of the SunCatcher™ system, SES has developed a proprietary control system for optimal sun tracking and system operation. This control system enables autonomous and safe operation by initiating daily start up after sunrise, tracking the sun's diurnal and annual trajectories, and optimizing energy output against variations in environmental parameters. These environmental parameters include, but are not limited to: insolation; ambient temperature; wind speed; and transient shading due to clouds. The SunCatcher™ Control System also optimizes energy output against variations in thermal, mechanical and electrical parameters such as internal temperatures and pressures, and generator voltage and frequency.

The SunCatcher™ electric power generation process does not burn fossil fuels, emit greenhouse gases, or emit water. In addition, since individual dish systems are self-contained and not plumbed together, the footprint in potentially sensitive environments is minimal. The concrete-less foundation concept allows insertion of the pedestals with little ground disturbance and a complete lack of drilling spoils needing disposal. This concept allows installation even in areas with a notable slope or unevenness, without first leveling the terrain.

3. DEPLOYMENT MODEL

Unlike other dish Stirling technologies that are focused on small-scale distributed generation applications, SES has structured its business model for deployment of the SunCatcher™ in utility scale solar power plants. With targeted project sizes ranging from 25 Megawatts (MW) to several hundred MW, these large single point deployments establish economies of scale which offer significant opportunity for long-term cost competitiveness. Namely, the large project capacities facilitate high-volume manufacturing and they concentrate resources for field assembly, installation, and ongoing operations and maintenance activities.

SES applies a distributed manufacturing model, whereby the SunCatcher's major components will be produced at several supply partners' facilities, and subsequently transported to various solar generation project locations, where they will be fully assembled, installed, and commissioned by SES. This partnership based model of manufacturing has the benefit of leveraging existing manufacturing expertise and minimizing production risk. By using this model, SES is able to utilize suppliers' capability and capacity to allow for rapid and scalable production deployment, benefit from supplier's design, engineering, and manufacturing expertise, and utilize ongoing cost reduction processes.

Several key components of the SunCatcher™ closely resemble parts used in auto manufacturing, namely the 4-cylinder Stirling engine and mirror facets made from stamped steel similar to car hoods. As such, SES is leveraging the automotive industry's mature practices in the procurement and manufacturing of SunCatcher™ components. SES has identified automotive suppliers for high volume components as well as aerospace suppliers for certain parts such as heater heads and coolers. Supply chain partners in these industries have a demonstrated track record of moving from low-volume unit manufacturing to high-volume manufacturing in a short timeframe. Furthermore, SES's knowledge base has grown rapidly by engaging with world class suppliers at an early stage in the technology development process.

The distributed manufacturing model parallels that of automobile Original Equipment Manufacturers (OEMs). These companies generally do not manufacture body frames, engines, or electronics, but rather they integrate components from world-class suppliers. In this case, SES is integrating components in the form of mirrors/facets, PCU, SCADA System, and PCU Controls. The final assembly of the SunCatcher™ is executed directly by SES in temporary assembly facilities capable of high volume in-line assembly at the point of use. SES has developed substantial in-house expertise and detailed processes for this high throughput activity. Several specific areas of expertise include the mirror facet alignment processes, the dish structure build sequence and installation process, and packaging, transportation, and material handling equipment and processes. SES has developed processes and facility designs for assembly and commissioning of 50 units per day (1.25 MW) at each deployment site. Such rates of deployment are necessary to leverage manufacturing facility investments. Once commissioned, the units begin to produce power to the grid, rather than needing the complete plant before energy production begins.

4. PERFORMANCE

4.1. Overview of Current System Performance

Building on the record peak efficiency achievement, continued research has led to SunCatcher™ performance enhancements, particularly in the area of power throughput of the engine. These have enabled the system to produce 26 to28 kW of electrical energy to the grid under optimal conditions.

The primary research has been performed at Sandia, by a team of SES engineers working closely with Sandia laboratory scientists. Research areas have included, but not limited to: gas flow paths; regenerator design; controls enhancement; optical optimization; opto-structural interactions; hydrogen management; and cooling system parasitic optimization. Potential performance enhancements are applied to controlled systems, and then the system performance is monitored and compared to control cases. Once these improvements are proven at Sandia, they are rolled out en masse at Maricopa Solar. While each improvement has provided incremental performance enhancement, the breakthrough performance of the entire enhanced system is unmatched anywhere in the world.

The performance of a Dish Stirling system is typically a straight line from design point operation at a solar input of 1000W/m² to 0 power output at a solar input below 300W/m². The excellent turndown ratio (efficiency is maintained at part power) of the Stirling system means that utilization of off-peak insolation is maximized. The impact of ambient temperatures scales with Carnot, or roughly with the inverse of the lower (ambient) temperature. Some competing technologies are highly sensitive to ambient temperatures, for both performance and life. A typical performance curve for the dish Stirling system is illustrated in Figure 3, which demonstrates the considerable improvement achieved through partnership with Sandia, from the earlier MPP SunCatcher™ model to the current X1 SunCatcher™ model. This performance, coupled with two-axis tracking, leads to excellent energy availability during a typical meteorological year. Our studies [3] show that, in a desert climate such as Albuquerque or the Mohave, in a large field, including dish-to-dish shading, the systems can produce 2.2MW-hr AC per year per kW installed, or about 0.7MW-hr/m² of collector area, which is the highest energy production per Watt of any solar power generating system. With typical dish spacing, this translates to approximately 5.7 acres of land per MW of rated power.

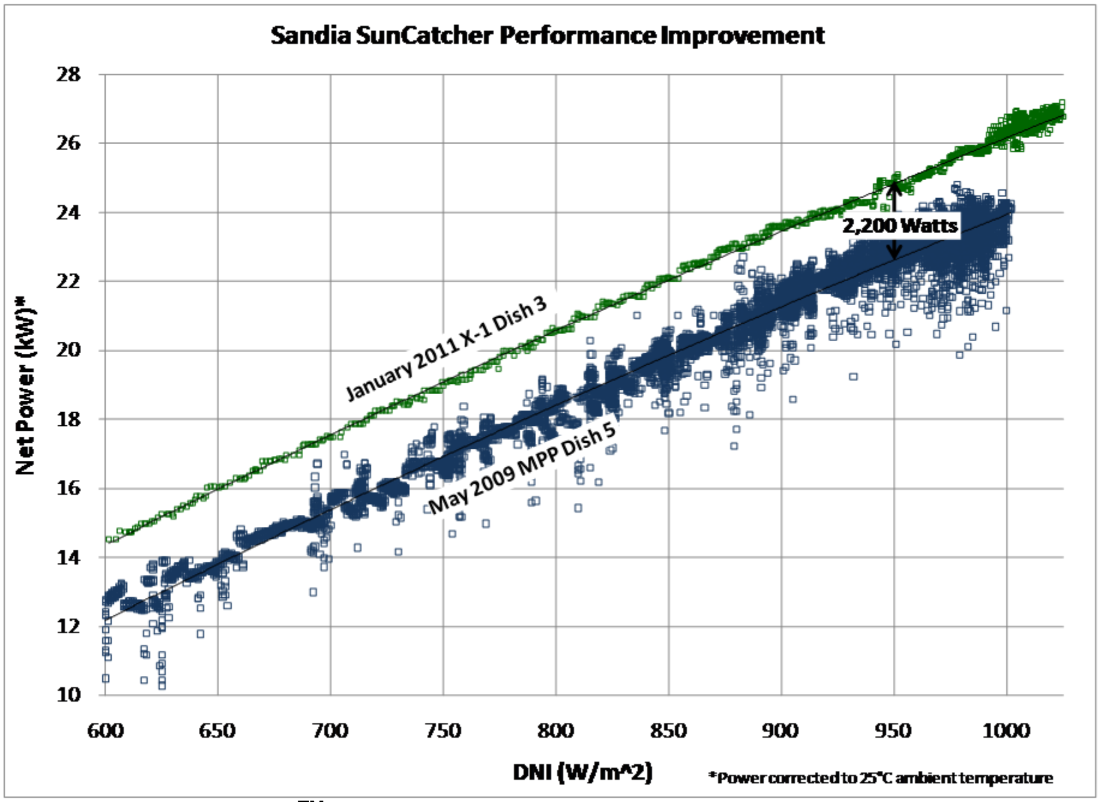

Figure 3. SunCatcher™ Performance Improvement from MPP Model to X1 Model

Studies of optical performance [4, 5] indicate a dramatic link between high optical and system efficiency and the cost or value of the system. SES and Sandia have developed substantial tools and approaches to optimize the optical performance. Design tools that couple the optical and structural model were pioneered on the SES project and are now becoming mainstream in the CSP program. These led to optimization of the structure such that about 6,000 pounds of steel were removed while delivering an equally optically stiff system. Characterization tools were deployed at the facet provider, and led to rapid 4-fold improvement in optical accuracy of the facets in less than 3 months, in preparation for the Sandia and Maricopa Solar deployments.

Studies by the facet manufacturer indicate that production tooling will enable further improvement to the facet shape and should result in as much as a 5% system performance improvement. Additional optical tools were recently deployed to Maricopa Solar after development on SES hardware at Sandia. These are providing a 7-fold improvement in alignment accuracy, as well as significant improvement in alignment speed. The alignment accuracy has a direct impact on the system performance. These tools provide unprecedented alignment accuracy, while providing the ability to align a dish at an on-site assembly plant in less than 20 minutes. This is a substantial time and cost savings in the assembly process, enabling the proposed assembly rate. Together, these tools provide the basis for high performance coupled to significant cost savings.

4.2. Annual Field Performance Profile

The key revenue driver for solar power plants is power output, which is determined by the solar resources at the site, the conversion efficiency, and availability of the installed technology. The SunCatcher™ Power Curve is a performance model developed by SES that computes the expected gross power output (prior to external losses) based on weather data and actual SunCatcher™ operating performance. The model uses three primary input variables: solar energy irradiation (measured by DNI), ambient temperature (°C), and wind speed (mph). The SunCatcher™ operates within the following ranges of these variables:

- DNI from 300 to 1015 W/m^2
- Ambient temperatures between -10°C and 50°C
- Wind speeds of up to 35 mph (15.6 m/s)

Key points of note when understanding SunCatcher™ power production:

- The expected energy production of each SunCatcher™ can be estimated through the Power Curve
- External factors are applied to account for losses not directly attributed to the SunCatcher™ that are predominantly site dependent, such as: field power, transmission, and transformer losses; soiling and shading losses; losses from variable weather days; and losses due to sudden high wind gusts, rain, and other environmental events
- Environmental conditions including ambient temperature, wind speed, wind direction and DNI are continuously sampled and logged, together with power output and other dish operating parameters

Results from Maricopa Solar are consistent with SES's Power Curve model assumptions. With sixty dishes deployed at Maricopa Solar, every minute of operation generates one dish-hour of operating data and experience. This has made a more thorough evaluation possible of areas such as dish to dish output variability, operation at elevated temperatures, and the effect of wind direction relative to dish orientation, among others. The modeled energy production that is based on historical weather (TMY3) data predicts that the production intent X1 model SunCatcher™ units at Maricopa Solar will produce 47,640 kWh/SunCatcher™/year after balance of plant and external losses are accounted for. Based on actual measurements taken at Maricopa Solar from March 15, 2010 to Jan 5, 2011, the annual production at 98% unit availability is calculated to be 51,063 kWh/ SunCatcher™/year, 7% higher than the modeled figure of 47,640 kWh/ SunCatcher™/year. Note that the energy production estimates are based on historically observed DNI levels in Peoria, Arizona, the location of Maricopa Solar. Higher DNI levels in areas such as the Mojave allow for production levels around 55,000 kWh/SunCatcher™/year.

Availability is a critical operating metric for all solar technologies. The total hours considered for the availability calculation are those that the SunCatcher™ operates within the equipment's operating limits and has the potential to produce power. SES availability target is 98% for a utility scale solar plant. The availability performance of Maricopa Solar between March 15, 2010 and January 5, 2011 has met the start-up target of 92% that was set by SES' Independent Engineer, an aggressive goal for a pre-volume production technology during its first commercial operating year. For the six month period between May and Oct 2010, a cumulative availability achieved was 97%. Since then, a strategic decision to perform additional testing to improve performance and reliability has caused a modest fall off in the availability figure. Given the promising availability results observed at Maricopa Solar and the inherent modularity of the technology, SES is confident that the SunCatcher™ can meet the 98% availability target in future utility scale projects.

4.3 Performance improvements in progress

SES continues to identify, evaluate, and implement additional improvements to the demonstrated breakthrough performance of the SunCatcher™ technology. Improvements to the performance have recently resulted in more than 3 percent improvement in energy production. Other near-term enhancements to the existing product design are expected to yield an estimated additional 5 percent increase in energy production. The activities are focused on optimizing certain components in the existing SunCatcher™ product. Within 5 years SES expects to achieve additional performance breakthroughs potentially resulting in another 10 percent enhancement in energy production. One focus of these longer term breakthroughs is optimization of the heat exchangers.

5. RELIABILITY

5.1. Advancements in reliability of SunCatcher™ & components

Historically, the three major reliability issues with the kinematic Stirling engine are the piston rod seals, the engine hot parts, and the balancing of thermal inputs. SES has made significant progress in addressing these challenges to enhance the reliability of the SunCatcher™ system and specific components.

The piston rod seal is a dynamic seal that seals the hydrogen at high differential pressures and should accommodate engine speed around 1800 rpm. The seal is historically a weak link for kinematic Stirling engines. In the early design stages for the SunCatcher™, the piston rod seal failed more than any other component. Careful scientific tests and analysis identified the mechanisms leading to premature failure. Solutions were proposed and tested on several test rigs at Sandia. SES design strategy targeted the most sensitive parameters for this component in order to successfully extend the life of the piston rod seals to 2 years, or approximately 7,000 operating hours. Accelerated validation testing data indicates that the revised seal design has exceeded this target.

The hot parts include the heater head, regenerators, gas cooler, and hydrogen gas circuits, which are connected to the heater head within the solar receiver. The heater head life is considered one of the main barriers in this group due to its material and manufacturing cost. The direct solar flux and thermal energy absorbed and re-radiated from cavity enclosure is transferred to heater header tubes which contains the high-pressure hydrogen gas working fluid. The typical failures are a low cycle fatigue /creep combined mechanism which results in tube failure. Additionally, potential hot spots due to uneven heat flux on the tubes can result in tube overheating and damage. Currently, heater head life is designed to 12 years of operation; however a hot spot resulting from unbalanced thermal loads could potentially present an earlier failure risk. The possibility of hot spots failure has been substantially decreased by the successful development of a production alignment tool. This was collaboratively developed by Sandia and SES to reliably align the facets in the dish, which results in a balanced heat flux distribution.

As a result of continuous design improvement efforts and collaborations with Sandia, the Mean Time Between Failure (MTBF) for the SunCatcher™ system has improved by approximately a factor of 10 from late 2008 to mid-2010. Recent design enhancements are expected to result in an additional 10 fold improvement in MTBF. This increase is expected to be validated in the field by the third or fourth calendar quarter of 2011.

5.2. Operations & maintenance for a SunCatcher™ power plant

From reliability data on components and the SunCatcher™ system, SES has developed a maintenance program for the SunCatcher™ units to ensure high plant availability is achieved. A key deliverable of the technology validation program is to identify regular maintenance requirements of certain components over a project lifetime of 20 years or longer. The analysis performed on each component establishes MTBF data which is utilized to predict the frequency of maintenance required. A typical and conservative preventive maintenance program for the PCU deployed at a commercial scale has been designed as illustrated in Figure 4. The hours required for each of the tier overhauls are based on operational experience at Maricopa Solar and

Sandia. The current engine design dramatically reduces the time for service compared to prior prototype engine designs.

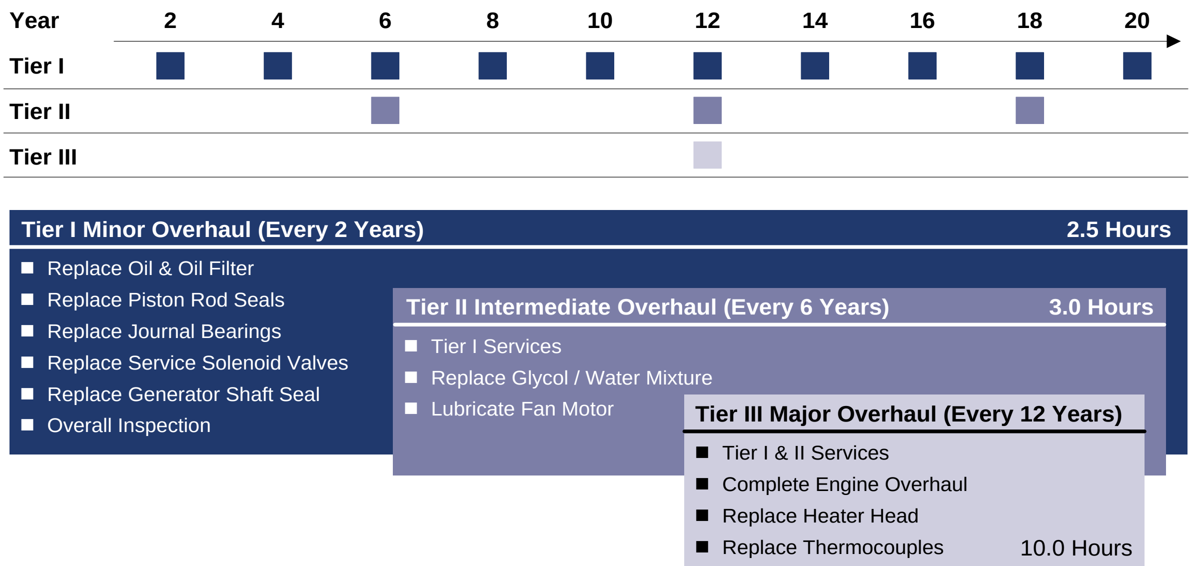

Figure 4. SunCatcher™ Preventative Maintenance Program

SES has developed a specific O&M model to predict maintenance requirements over a project lifetime based on component MTBF data. The timing profile of all plant operations and maintenance activities, labor requirements, and component costs are incorporated into this O&M model to provide a total O&M cost based on specified project conditions.

Through a structured validation and continuous improvement process, the key components impacting overall reliability are identified and serve to focus future design enhancements. Continuous reliability improvement for the entire system, reduced maintenance requirements, and enhanced operational performance are primary goals.

5.3. Approach to additional reliability enhancement for dish Stirling technology

Further breakthroughs in reliability and O&M cost can be attained through extending minor overhaul periods and overcoming critical expensive component life barriers. This would enable components to last for the entire useful cycle life of the system (20-25 years). Several research and development approaches are proposed to overcome these barriers, including:

- The development of low cost engineered material for high temperature reliability (low cycle fatigue, creep and aging resistance) utilizing low cost materials and manufacturing technologies will enable lower cost heater head with potential extended life to match the entire life cycle target.
- The development of coatings for dynamic seal surfaces capable of reducing wear rates while maintaining high capability of sealing will extend the time for the first maintenance schedule and will reduce the overall maintenance cost.
- The refinement of integrated multi-disciplinary system performance and life prediction tools will enable studies of system interactions and the mitigation of potential adverse events of the

system. The research work should quantify tradeoffs to gain higher reliability with minimal power sacrifices while optimizing the overall cost. This should include heat transfer, CFD, FEA, optical modeling, and non-linear analysis of elastomeric components in the system.

- Advancements in analytics and complex system optimization which encompasses: data mining algorithms; system trending; and real time automated reasoning and decision making techniques to integrate messages from a health management system, thus combining the results for risk assessment and adaptive operation.

6. INSTALLED COST & LCOE

The SES deployment model utilizes high-volume manufacturing for the SunCatcher™ product, which is designed for a commercial volume production level starting at 50 units per day (equivalent to 300MW per annum). Doing so enables SES to take advantage of cost efficiencies derived from mass production processes, particularly on the high-volume production of engines and facets. Since some SunCatcher™ components require specialized tooling, the mass volume production provides economies of scale to recoup tooling investment, enabling a competitive product cost. Furthermore, SES is utilizing the experience of its suppliers for cost reduction mechanisms. The deployment model also supports competitive costs through concentrating a high number of dishes for assembly, installation, and operations and maintenance over the life of the power plant. This enables a high-volume assembly facility on-site, which significantly saves assembly cost versus a model that would be based on in-field assembly.

6.1. Current production costs & drivers

The LCOE of the current SunCatcher™ design is approximately 14 cents per kWh. This is driven largely by installed system cost, O&M cost, performance (power production), as well as financing. For the purposes of this estimate and other LCOE estimates provided later in this section, several assumptions were used, including:

- No Investment Tax Credit (ITC)
- Weighted Average Cost of Capital (WACC) = 6.57% (Assumes 80% Debt, 20% Equity, Cost of Debt = 6.0%, Cost of Equity = 17.5%)
- MACRS Depreciation
- Tax Rate of 36%
- Project life of 20 years

The installed system cost includes: SunCatcher™ equipment; assembly and installation; BoP; and standard site, transaction, and contingency costs. Figure 5 illustrates the cost structure of the current SunCatcher™ equipment. This cost structure includes the cost associated with field installation, which consists of assembly on-site and installation of SunCatcher™ units in the field. The two largest cost drivers are the PCU and Dish Structure, areas which will be focused on in future design enhancements in order to further reduce cost.

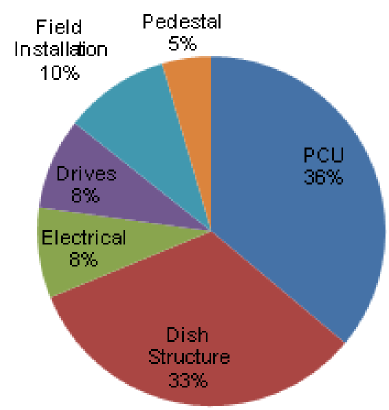

Figure 5. SunCatcher™ Cost Structure

6.2. Installed cost reduction approaches

The SunCatcher™ technology possesses significant cost improvement potential, given that it is early in the experience curve, and based on employing standard cost reduction levers that have already been used in part or full by other solar technologies. These levers include:

(1) **Re-design:** Currently a conservative design approach has been employed across all sub-systems; as a result, significant potential exists to reduce the cost at relatively low risk. For example, a long-term redesign of the engine architecture offers a substantial cost reduction opportunity which could exceed 10%.

(2) **Manufacturing continuous improvement:** The experience curve has historically proven that for every doubling of cumulative production of a given good, the cost of production goes down by a fixed percentage. For instance, the experience curve percentage for crystalline silicon PV module is established by academic papers as between 18% and 35% for each doubling of cumulative production. Young industries and products achieve cost reductions in a relative short time compared with a more mature product.

(3) **Optimized component sourcing/manufacturing:** Currently the majority of components for the SunCatcher™ are manufactured in North America. Substantial cost reductions (some estimates indicate as high as 30%) can be realized through manufacturing some components in other countries.

6.3. LCOE roadmap to SunShot target

Figure 6 depicts the current SunCatcher™ LCOE and provides estimated potential reduction in LCOE using several of the cost reduction approaches discussed in Section 6.2. The resulting roadmap depicts realistic potential for the SunCatcher™ dish Stirling technology to achieve the DOE SunShot target of 6 cents per kWh. Specifically, the estimated reduction in LCOE from design enhancements is based on a multitude of product enhancements concepts that have been identified with preliminary concept analyses completed. This is, in fact, a conservative estimate of the potential reduction in LCOE from various concepts that will have a net system impact in the form of enhanced power production, decreased installed cost, decreased O&M cost, or a combination of these.

Other categories contributing to potential LCOE reduction include continuous improvement in manufacturing operations and optimized component sourcing, both discussed in Section 6.2. These reasonable estimates, in combination with planned design enhancements, provide a low-risk path for the SunCatcher™ to potentially achieve approximately 8 cents per kWh on an LCOE basis. Given that some conservatism is built in these estimates, more upside may be realized, and some additional reduction in LCOE could result from margin reduction opportunities. Still, an approximate gap of only 2 cents per kWh must be overcome through advanced R&D to further enhance the SunCatcher™ product design, resulting in additional enhancements to performance, O&M cost, installed cost, or some combination, in order to achieve the DOE SunShot target. Overall, the path needed to reach the SunShot target requires lower investment and carries significantly less risk than other solar technologies.

The path to reach the SunShot target requires a reduction of approximately 50% in both installed cost and O&M cost, as well as an increase of 10% or greater in power production. The power production requirements will be met through already planned design enhancements, and the required reduction in installed cost and O&M cost are reasonable over the long-term, considering that the SunCatcher™ technology is in the early stage of its experience curve.

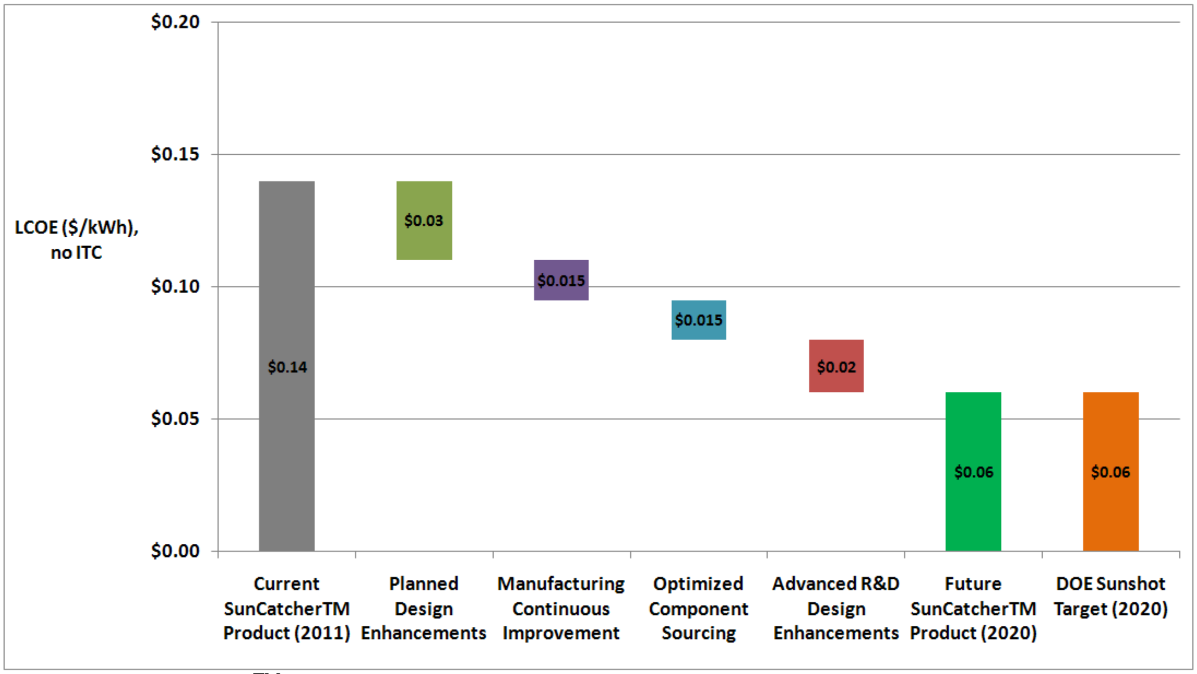

Figure 6. SunCatcher™ LCOE Roadmap to SunShot Target

7. ADVANCED R&D POSSIBILITIES

7.1. Heat pipe receivers

In the 1980's and 1990's, the DOE and Sandia identified Heat Pipe Receivers as both a performance and reliability enhancement for dish Stirling systems [6]. Sandia demonstrated a 20% improvement in system performance (efficiency and power throughput) for an identical system when the Direct Illumination Receiver (DIR) was replaced with a heat pipe. This was demonstrated on a Stirling Thermal motors (STM) engine on Sandia's Test Bed Concentrator. The STM engine has a very similar heater head layout to the SES engine, with 4 heater heads in a square pattern. The size of the engine is similar as well. The tested engine operated with a helium working fluid, as permeation of hydrogen into the heat pipe can cause difficulties. The difference in performance from hydrogen to helium, determined in the same period, was an increase of about 10%. Therefore, going from the current hydrogen DIR system to a helium heat pipe system would likely yield a 10% improvement in system output and efficiency.

The heat pipe works with a phase change heat transfer fluid, typically sodium, at the engine operating temperatures. The heat transfer fluid is distributed to the surface of an absorber dome with a capillary wick structure. The liquid is evaporated, and the vapor then travels to and condenses on the heater head tubes. Since the vapor can condense evenly around the entire tube, increasing heat transfer area as compared to the DIR, the tubes can be smaller, resulting in less passive gas volume and therefore a higher engine performance. In addition, the phase change is isothermal, so the peak temperature is the average temperature, and thus the gas temperature in the engine, proportional to the average receiver temperature, is higher. The peak temperature of the receiver tubes is usually limited by materials limitations, as reasonable-cost metals begin to lose their strength significantly above 800°C. Therefore, the heat pipe can raise the effective engine hot temperature without raising the material peak temperatures.

When the DOE heat pipe program ended, Sandia had performed substantial durability testing of heat pipe wicks, and identified several long term durability concerns. A separate government program designed for nuclear anti-proliferation through employment of former Soviet weapons engineers supported development of wick alternatives to address these concerns at Kiev Poly University [7]. Key approaches were identified, and wicks constructed, that appear to solve the known issues. However, long-term and accelerated testing on these wick structures has not commenced. Revived development and testing of these wick structures could lead to a dramatic breakthrough in cost and performance of the dish Stirling systems.

In addition, while Sandia tested the STM engine, the interface to the engine was less than ideal, in both complexity and durability. Integration of a heat pipe with a 4-cylinder engine will require detailed engineering, with potentially clever accommodation of differential thermal expansion issues. This could be integrated into the development of advanced engine configurations that SES is contemplating.

Initial work was also performed by STM on contract to DOE to identify coatings that could be applied to the heater head tubes to minimize hydrogen permeation. Such coatings, if successful, could allow hydrogen use with a heat pipe receiver, thereby attaining the full benefit of a heat pipe receiver, which could be 20% improvement in efficiency (6 points of efficiency on a 30% system) and 20% improvement in power throughput. Even without the heat pipe, control of hydrogen permeation to the atmosphere could provide a reduction in O&M costs for replacement of lost hydrogen gas.

The key to all of these possibilities is a robust high performance heat pipe wick, a clever mechanical interface to the Stirling engine, and ideally a hydrogen permeation prevention layer on the heater head tubes.

7.2. Phase change storage

The high temperature thermal processes used in dish engine systems lend themselves to highly efficient thermal storage. Thermal storage has been shown to provide up to 99% storage efficiency, compared to 76% typical of electrical storage, at a far lower cost per unit of storage [8]. Short term storage can be feasibly integrated with the engine package at the focus of the dish, providing cloud transient suppression on the order of 15 to 30 minutes of continued operation [9]. Off-board storage can be developed to provide unlimited storage capacity for evening and base load power generation [10].

The use of heat pipe receivers decouples the thermal input surface from the engine heater head. This allows independent optimization of the input surface for solar collection, and the heater head for engine operation. Further, this allows intermediate materials and objects between the input and output of the receiver component. This means that incorporation of some highly efficient thermal storage could be accomplished. Short periods of storage (around 30 minutes) could be incorporated at the focus of a dish, allowing smoothing of cloud transients, as well as enough time to negotiate changes in output with the transmission system operators. This storage would likely include phase change salts coupled directly or indirectly into the heat pipe working fluid. Storage of thermal energy has been shown by the DOE CSP program to have very high storage efficiency, as compared to competing technologies such as batteries, compressed air, or pumped water. In addition, heat pipe receivers could incorporate a second thermal input surface, opening the possibility of a practical hybridization with natural gas to firm up capacity.

Higher amounts of storage, equivalent to hours or even days, would require either advanced materials or off-board storage. A heat pipe or similar receiver could facilitate such storage, allowing incorporation of secondary heat exchangers to introduce and extract heat from storage, without compromising engine performance. The heat transfer and storage media could be high temperature molten salts, similar to processes pioneered for towers, or liquid metal compounds. It is likely that off-board storage, with high capacity factors, would combine the thermal inputs from several dish modules to power a single ground-mounted engine at a very high capacity factor. Storage could be sensible in either liquid or solid media, but would more likely be a phase change system, as the Stirling cycle incorporates an isothermal input well suited to the constant temperatures provided in phase change systems.

The development needed to bring about storage for dish Stirling, whether on-board short term or off-board high capacity factor, consists of materials identification and testing, and advanced configuration engineering to integrate the plumbing and storage features into the system without compromising performance.

7.3. Stirling engine architecture

SES is applying continuous improvement principles to optimize the existing SunCatcher™ design, further enhancing the cost competiveness of the dish Stirling technology. For its next generation design of the product targeted at breakthrough cost reduction with additional performance enhancement, SES plans a redesign of the PCU, including an optimization of the heat exchanger and a redesign of the Stirling engine architecture.

Optimization of the heat exchanger focuses on the gas circuit heat exchanger components, the cooler, the regenerator, and receiver tubes. Substantial gains can also be realized through a redesign to improve the engine configuration. The current SunCatcher™ engine design focus was on increasing durability and reliability, and simplifying maintenance procedures. Once the basic design was validated, performance optimization became the focus. This was performed in parallel with work to optimize the life of piston rings, piston rod seals, and regenerator, which is ongoing and will continue. A major redesign will entail a rigorous process consisting of:

1. Setting targets for power, speed, cost, life/service interval, market requirements, and competitive benchmarks
2. Performance simulation to determine displacement, bore/stroke ratio, and cylinder layout and timing
3. Thermodynamic component optimization for the solar receiver, regenerator, and cooler
4. Engine design specifying layout/configuration, system interaction, and component details

Advancements to the Stirling engine architecture for solar thermal power generation will result from a rigorous R&D program focused on engineering design, testing, and validation activities. Preliminary concept evaluation studies indicate that the activities described herein will likely result in an increase of approximately 10% in power production, reduction in installed cost of at least 5%, and reduction in O&M cost of greater than 5%.

7.4. Novel reflector systems

The reflector system is approximately one third of the cost of the SunCatcher™. Meanwhile, system performance is critically dependent upon accuracy of the reflector system. Prior observation suggests that accepting lower performance for lower cost is seldom advisable [6]. The approaches currently used by SES include automotive-like stamping and drawing of sheet metal, combined with laminating of thin glass reflector surfaces. This uses proven automotive technologies for a robust finished product.

Novel reflector systems, using manufacturing processes from other industries, may result in lower cost manufactured systems. In particular, we propose evaluating various composite structures, combined with either thin glass mirrors or potentially polymer reflector surfaces. Approaches such as Low Pressure Sheet Molding compounds, glass/resin composites, syntactic foams, and others may be cost effective. Particularly interesting would be the ability to apply glass mirrors "in the mold", eliminating an expensive bonding step later in the process. Preliminary evaluation of these approaches for mirror facets indicates that they could reduce reflector cost by more than 20%.

Further, with judicious use of composites, and novel structural combinations, it is conceivable that a significant portion of the steel structure could be removed, allowing the mirror facets themselves to become load-bearing members. A dish system is particularly suited to such a construction, due to the shorter focal lengths (than heliostats), which provides out-of-plane portions of the mirrors, lending to exceptional structural stiffness. Such an approach has the potential to save thousands of pounds of steel on each structure. Such integration, combined with the novel reflector surfaces, could potentially reduce the cost of the entire concentrator subsystem (the Dish Structure) by more than 20%.

8. NOVEL APPLICATIONS OF DISHES

While previous research and development efforts have focused on dish-Stirling technologies for electric production, the dish system provides very high concentration ratios, and therefore the potential for very high receiver temperatures. This uniquely positions the dish concentrator technology for other potential applications that require energy to be focused or require high temperature heat.

One such application is utilizing the dishes for high temperature thermo-chemical processes. Sandia is currently conducting R&D on a "Sunshine to Petrol" process. This uses high temperature reactions to split water, producing hydrogen, and to split CO_2, producing CO, which then can be combined to create liquid fuels for transportation. The temperatures required for these processes can be achieved through using the dishes, and the equipment currently conceived is well sized for the SunCatcher™ dish platform. Other high temperature chemical processes, including thermo chemical storage, are possible on the dish platform as well. Thermo chemical storage is usually based on high temperature processes, and would allow off-dish storage of large quantities of energy, in chemical form, that could lead to base load electrical production.

The application of a dish concentrator for production of high temperatures can potentially be useful for a number of material manufacturing processes that require high and ultra high temperatures. One such application is the production of aluminum via high temperature solar thermal. Other potential applications include using dish concentrators to generate heat energy for a high temperature furnace for sintering or brazing, and applying dish concentrators for ultra high temperature processing of ceramics and nanocomposites, among others.

Finally, the dish concentrator technology demonstrates potential for various other applications. Several of these include using the technology for process heat generation and for waste treatment, among others.

9. SUMMARY

The dish Stirling system is a breakthrough concentrated solar power technology with multiple beneficial attributes that, when combined with the SES deployment model, result in a LCOE that is currently competitive with other solar technologies. SES has a clear plan to position the SunCatcher™ technology to achieve the DOE SunShot target of 6 cents per kWh. Multiple design enhancements have already been identified that are technically feasible with little or moderate risk, which will substantially reduce LCOE through a combination of reduction in installed cost and reduction in O&M cost; benefits will also be realized from enhanced power production concepts. Furthermore, since the SunCatcher™ is early in its experience curve, substantial LCOE reduction can also be realized through manufacturing continuous improvement over the next five years and beyond, and through potentially sourcing some components outside North America. These reasonable steps will position the SunCatcher™ near the SunShot target, with the remaining gap to be overcome through advanced R&D activities. Finally, additional technical breakthroughs can enable storage for the SunCatcher™ as well as utilize technology components for other revolutionary applications, such as solar fuels.

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