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Dish-Stirling Systems: An Overview of Development and Status

Dish-Stirling systems have demonstrated the highest efficiency of any solar power generation system by converting nearly 30% of direct-normal incident solar radiation into electricity after accounting for parasitic power losses [1]. These high-performance, solar power systems have been in development for two decades with the primary focus in recent years on reducing the capital and operating costs of systems. Even though the systems currently cost about $10,000 US/kW installed, major cost reduction will occur with mass production and further development of the systems. Substantial progress has been made to improve reliability thereby reducing the operating and maintenance costs of the systems. As capital costs drop to about $3000 US/kW, promising market opportunities appear to be developing in green power and distributed generation markets in the southwestern United States and in Europe. In this paper, we review the current status of four Dish-Stirling systems that are being developed for commercial markets and present system specifications and review system performance and cost data. We also review the economics, capital cost, operating and maintenance costs, and the emerging markets for Dish-Stirling systems. [DOI: 10.1115/1.1562634]

I Introduction

With restructuring of utility markets, the emergence of green-power markets, and the increased worldwide demand for distributed generation, the opportunities for small power systems ranging in size from a few kW to several MW are increasing at a rapid rate. This increased demand is largely being met by existing internal combustion and gas-turbine power generators, but it is also the motivation for new technology development such as micro-turbines, fuel cells, and other alternative power generators. One solar power generation system that is targeted for application in these emerging markets is Dish-Stirling technology. In fact, Dish-Stirling systems are being deployed in pre-commercial applications and as demonstration systems at locations in the U.S. and Europe.

Solar thermal power systems, which are also sometimes referred to as concentrating solar power systems, utilize the heat generated by concentrating and absorbing the sun's energy to drive a heat engine/generator and produce electric power. Three generic solar thermal systems, power tower, trough, and dish-engine systems, are capable of producing power [2]. Trough systems use linear parabolic concentrators to focus sunlight along the focal lines of the collectors. In a power tower system, a field of two-axis tracking mirrors, called heliostats, reflects the solar energy onto a receiver that is mounted on top of a centrally-located tower. Dish-engine systems, the third type of solar thermal system, comprise a parabolic dish concentrator, a thermal receiver, and a heat engine/generator located at the focus of the dish to generate power.

Of the three solar thermal technologies, trough-electric systems are the most mature, 354 MW are installed in the Mojave Desert

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of Southern California [3], and the first commercial power towers are currently being designed for installation in Spain [4]. Dish-Stirling Systems, which are the least developed of the three technologies, are being deployed as demonstration units and some pre-commercial plants are in the planning stages [5]. Trough systems produce about 75 suns concentration and operate at temperatures of about 400°C at an annual efficiency of about 10%. Power towers operate at a concentration of about 800 suns, produce temperatures of about 560°C and have annual efficiencies of about 15%. Dish-Stirling systems have demonstrated the highest efficiency of any large solar power technology, producing more than 3000 suns concentration, and operating at temperatures of 750°C at annual efficiencies of 23% [6,7].

Dish-Stirling systems track the sun and focus solar energy into a cavity receiver where it is absorbed and transferred to a heat engine/generator. Figure 1 is a representation of a Dish Stirling System with the major system components, the dish, the power conversion unit (PCU), etc. identified. Although a Brayton engine has been tested on a dish [8] and some companies are considering adapting micro-turbine technology to dish engine systems, kinematic Stirling engines are currently being used in the four Dish-Stirling Systems being developed today. Stirling engines are preferred for these systems because of their high efficiencies (thermal-to-mechanical efficiencies in excess of 40% have been reported), high power density (40–70 kW/liter for solar engines), and potential for long-term, low-maintenance operation. Dish-Stirling systems are modular, i.e., each system is a self-contained power generator, allowing their assembly into plants ranging in size from a few kilowatts to tens of megawatts. The near-term markets identified by the developers of these systems include remote power, water pumping, grid-connected power in developing countries, and end-of-line power conditioning applications.

In the following sections, we describe some of the background of Dish-Stirling Systems and present design and performance details for the four pre-commercial, prototype systems, currently being developed in the U.S. and Germany. We also present some of the details about advanced components under development for dish systems. Last, we present an overview of the current and potential cost of electricity from Dish-Stirling technology and the emerging markets for solar dish power generation systems.

II Background of Dish-Stirling Systems

Over the last 20 years, eight different Dish-Stirling systems ranging in size from 2 to 50 kW have been built by companies in the United States, Germany, Japan, and Russia [7]. In this section of the paper, we present detailed background information that directly pertains to the four systems under development today The first of the historical systems, the 25-kW Vanguard system built by ADVANCO in Southern California, achieved a reported world record net solar-to-electric conversion efficiency of 29.4% [1]. The Vanguard Dish-Stirling system utilized a glass-faceted dish 10.5 m in diameter, a direct insolation receiver (DIR), and a United Stirling 4-95 Mark II kinematic Stirling engine. In 1984, two 50-kW Dish-Stirling systems were built, installed, and operated in Riyadh, Saudi Arabia, by Schlaich-Bergermann und Partner (SBP) of Stuttgart, Germany [9]. The dishes were 17-m dia, stretched-membrane concentrators, formed by drawing a vacuum in the plenum space formed by the dish rim and front and back steel membranes. The optical surface of the dish was made by bonding glass tiles to the front membrane. The receivers for the SBP dishes were DIRs and the engines were United Stirling 4-275 kinematic Stirling engines.

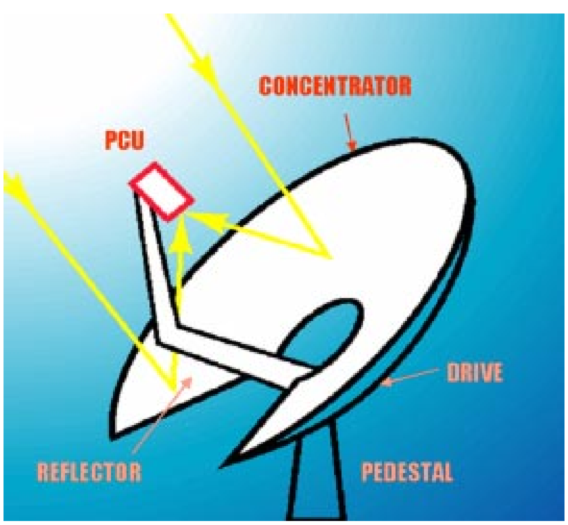

Fig. 1 Dish Stirling system components

A third Dish-Stirling system was built by McDonnell Douglas Aerospace Corporation (MDAC) in the mid 1980s and, when MDAC discontinued development of the technology, the rights to the system were acquired by the Southern California Edison Company (SCE) [10,11]. The parts for eight systems were built, and three systems were tested in the early 1980s. The MDAC/SCE dish was the first Dish-Stirling system designed to be a commercial product. It built on the design of the Vanguard Dish-Stirling system, using the same DIR and the USAB 4-95 Mark II engine. SCE operated the system from 1985 to 1988. Stirling Energy Systems (SES) of Phoenix, Arizona, acquired the technology rights and system hardware in 1996 and have continued development of the system.

In 1989, the Schlaich Bergermann und Partner built their first 7.5-m stretched membrane concentrator equipped with a SOLO V160 Stirling engine. First, in polar tracking configuration and later in an azimuth/elevation tracking configuration, the systems were operated for more than 30,000 hr on sun.

In 1991, Cummins Power Generation, working under cost-shared agreements with the U.S. Department of Energy and Sandia National Laboratories, started development of two Dish-Stirling systems—a 7-kW system for remote applications and a 25-kW system for grid-connected power generation [12,13]. Cummins was innovative in its Dish-Stirling systems, incorporating advanced technologies into the designs, such as: a solar concentrator with a polar-axis drive and polymer, stretched-membrane facets, heat-pipe receivers, and free-piston Stirling engines. The heat-pipe receiver transfers the absorbed solar heat to the engine by evaporating sodium and condensing it on the tubes of the engine heater head. The receiver serves as a thermal buffer between the concentrator and the engine, and because it transfers heat to the engine by condensation, it allows the engine to operate at a high average temperature and efficiency [14,15]. The two Cummins programs made progress, but were terminated in 1996 when Cummins' parent company, Cummins Engine Company, realigned business along its core area of diesel engine development. The assets of the Cummins solar operations were sold to Kombassan, a holding company in Alanya, Turkey.

Dish-Stirling systems have demonstrated that they are capable of producing electricity for the grid and for remote power applications. Technology development needs are for low-cost components and systems that can operate unattended at very high levels of reliability. Current efforts are focused on establishing reliability and, through break-and-repair approaches, identifying the components that require improvement, redesign, and replacement. In a parallel approach, advanced components, such a heat-pipe receivers, controls, and optical surfaces, that promise higher reliability and lower cost are being designed and tested.

III Descriptions of Dish-Stirling Systems

In this section, we present descriptions of the four Dish-Stirling systems that are currently being developed for commercial applications. For each system, we provide a photograph of the system, background information on the system, descriptions of the system

Table 1 Definitions of specifications and terms listed in Table 2

Concentrator	The solar concentrator is the system component that tracks the sun, collects the solar energy, and focuses it into the thermal receiver.
Type	All of these concentrators have reflective surfaces made from individual pieces of highly reflective glass. The dishes may comprise many facets arranged in such a manner as to approximate a paraboloidal shape (approximate) or the facets may be laid out and contoured so that the dish shape is intended to be a paraboloid of revolution (paraboloid).
No. of Facets	The total number of distinguishable facets, not the number of glass pieces that comprise the dish.
Glass Area (m^2)	The total glass area on the surface of the dish.
Proj. Area (m^2)	The total glass area projected in the plane of the collector aperture.
Reflectivity	The new, clean reflectivity of the glass as measured in a standard laboratory.
Height (m)	The distance from the ground to the highest point on the collector when it is oriented at its highest profile position, generally when facing the horizon.
Width (m)	The maximum width presented by the collector.
Weight (kg)	The weight of the collector, including the pedestal, support structure, glass, drives, and PCU support.
Tracking Control	The control methodology for the collector. An open-loop control tracks by aiming the collector at the sun's calculated position in the sky. A closed-loop control measures a parameter at the collector or receiver (usually solar energy or temperature) and tracks the collector in response to the measured variable.
Focal Length (m)	The measured focal length of the solar collector.
Intercept Factor	The fraction of the solar energy collected that is reflected through the receiver aperture. This is based on actual, clear day measurements.
Peak Conc (suns)	Measured peak concentration of the collector normalize to DNI of 1000 W/m^2.
Power Conversion Unit	The power conversion unit (PCU) comprises the receiver, the engine, and the generator.
Aperture Dia. (cm)	The receiver aperture diameter.
Engine Manf/Type	Engine manufacturer and type of engine.
No. of Cylinders	Number of cylinders.
Displacement (cc)	Total displacement of the engine.
Op Speed (rpm)	Engine operating speed.
Working Fluid	Engine working fluid.
Power Control	Means by which the engine output is controlled in response to the changing solar input.
Generator	Type of generator used in the system.
System Information	The following system information is actual, measured performance (indicated by bold letters) or system performance estimates (indicated by normal italics type.)
No. Systems Built	The total number of complete systems that have been built and operated.
On-Sun Op (hrs)	The total number of on-sun and hybrid operational hours for the systems listed above.
System Rating (kW)	The system nameplate rating.
Peak Net Output (kW)	Peak, net measured system output for a minimum of 5 minutes of continuous operation and normalized to a DNI of 1000 W/m^2, clean mirrors, and at an ambient temperature of 288°K.
Peak Net Effic (%)	Peak, net measured system efficiency for a minimum of 5 minutes of continuous operation and normalized to a DNI of 1000 W/m^2, clean mirrors, and at an ambient temperature of 288°K.
Ann Net Effic (%)	Annual, net efficiency estimate based on the reported performance curves and reported operating wind speeds calculated using TMY2 data for Albuquerque, NM, USA. Assumes 100% availability.
Annual Energy Production (kWhrs)	Predicted annual performance in Albuquerque, NM, USA, based on TMY2 data, the measured system performance curves, specifications for wind speed, and an assumed availability of 90%.

components, and a paragraph describing the corporate business development plans. Table 1 lists the parameters and detailed descriptions of the specifications and performance parameters listed in Table 2. The information presented in Table 2 is system information collected through February 2002 that has been documented by test and measurement. In those cases where information is not available, the corresponding table entry has been left blank.

There are a number of parameters that are similar for the four systems including: tracking (all four systems utilize elevation-over-azimuth tracking approaches) all systems use direct-illumination receivers (DIR); cooling systems (the fan/radiator type, similar to automotive cooling systems); lubrication systems (which use motor oil); and the operating temperature range for the receivers (700–750°C).

SAIC/STM SunDish System

Background. Science Applications International Corp. (SAIC) and STM Power, Inc. have been developing a Dish-Stirling power system for utility applications since November 1993. The development of the SunDish system followed many years of separate development of the stretched-membrane solar concentrator by SAIC and the development of the kinematic Stirling engine by STM. After testing an initial prototype system in 1995 [16], a second-generation Dish-Stirling system was designed and four systems were tested starting in 1997. Major features of the second-generation system included the following: face-down stow to protect mirrors and keep them cleaner; staggered facet arrangement to reduce wind loads; increased mirror area to increase power output; upgraded dish control system; non-pressurized engine crank case to reduce cost; gearbox between engine and generator to increase system capacity; and hybrid (fuel) operation capability for electricity dispatchability and enhanced energy production [17]. Figure 2 is a photograph of the SunDish Dish-Stirling system, which is installed at the Salt River Project near Phoenix, Arizona.

Four second-generation systems are operating today. System 1, fielded in April 1998 at the Pentagon in Washington, DC, was moved in January 1999 to the Arizona Public Service Solar Test and Research (APS STAR) site. At the Pentagon, the system operated at half power due to poor optical beam quality resulting from structural deflections. This issue was addressed prior to installing the system at the APS STAR site, where the dish ran on solar energy and in the hybrid mode on natural gas and hydrogen. System 2 was fielded in October 1998 at Golden, Colorado. It is used to evaluate beam optical quality and the changes in beam quality that can occur with time. This dish is in use today as a test bed for engine performance and alternative converter testing. Sys-

Table 2 Comparative specifications and performance parameters for DS systems

Concentrator	SAIC/STM System	SBP System	SES System	WGA (Mod 1) ADDS System	WGA (Mod 2) Remote System
Type	Approximate	Paraboloid	Approximate	Paraboloid	Paraboloid
No. of Facets	16	12	82	32	24
Glass Area (m^2)	117.2	60	91.0	42.9	42.9
Proj. Area (m^2)	113.5	56.7	87.7	41.2	41.2
Reflectivity	0.95	0.94	0.91	0.94	0.94
Height (m)	15.0	10.1	11.9	8.8	8.8
Width (m)	14.8	10.4	11.3	8.8	8.8
Weight (kg)	8172	3980	6760	2864	2481
Track Control	Open/Closed Loop	Open Loop	Open Loop	Open/Closed Loop	Open/Closed Loop
Focal Length (m)	12.0	4.5	7.45	5.45	5.45
Intercept Factor	0.90	0.93	0.97	0.99+	0.99+
Peak C R (suns)	2500	12,730	7500	>11,000	>13,000
Power Conv. Unit	**SAIC/STM**	**SBP**	**SES**	**WGA ADDS**	**WGA Remote**
Aperture Dia. (cm)	38	15	20	14	14
Engine Manf/Type	STM 4-120 double acting kinematic	SOLO 161 kinematic	Kockums/SES 4-95 kinematic	SOLO 161 kinematic	SOLO 161 kinematic
No. of Cylinders	4	2	4	2	2
Displacement (cc)	480 cc	160 cc	380 cc	160 cc	160 cc
Op Speed (rpm)	2200	1500	1800	1800	800–1890
Working Fluid	hydrogen	helium	hydrogen	hydrogen	hydrogen
Power Control	Variable Stroke	Variable Pressure	Variable Pressure	Variable Pressure	Variable Pressure
Generator	3 φ/480v/Induct	3 φ/480v/Induc	3 φ/480v/Induct	3 φ/480v/Induc	3 φ/480v/synch
System Information	**SAIC/STM**	**SBP**	**SES**	**WGA ADDS**	**WGA Remote**
No. Systems Built	5	11	5	1	1
On-Sun Op (hrs)	6360	40,000	25,050	4000	400
Rated Output (kW)	22	10	25	9.5	8[1]
Peak Output (kW)	22.9	8.5	25.3	11.0	8
Peak Efficiency Net	20%	19%[2]	29.4%	24.5%	22.5%
Ann Efficiency Net	14.5%	15.7%	24.6%	18.9%	N/A[3]
Ann Energy (kWhrs)	36,609	20,252	48,129	17,353	N/A

[1]The Mod 2 ADDS drives a conventional submersible water pump. The test pump is undersized for the output of the system. Therefore, mirror covers are used to limit output to the pump capacity.

[2]The SBP system peak efficiency is calculated at its design point of 800 W/m^2. All other system efficiencies are calculated at their design points of 1000 W/m^2.

[3]The Mod 2 system has not operated for 1000 hr.

tem 3 was fielded in July 1999 at the STAR site and moved to the University of Nevada Las Vegas (UNLV) test site in August 2001 in preparation for a 1-MW Dish-Stirling project in Nevada. System 4 was fielded in September 1999 at the Salt River Project-Pima-Maricopa Indian Community Landfill site and was configured to run on solar energy during the day and landfill gas when solar is not available. The major components of the system are described in the following section. Details of the system design and performance are listed in Table 2.

System Components. There are four major system components: the dish, the thermal receiver, the Stirling engine, and the system controls.

The dish concentrator (Fig. 2) consists of 16 round, stretched-membrane mirror facets, each 3.2 m dia, mounted on a truss structure that attaches to an azimuth/elevation drive on top of a pedestal. The facets are attached in a staggered manner, with some facets on the front and some on the back of the structure, to increase the porosity of the dish and reduce wind loads. The engine support arm articulates at the hub to allow the system to move to a face-down position for stow, keeping the engine near ground level for ease of access for maintenance.

The receiver consists of a cavity containing a direct-insolation heater head in the shape of a truncated cone. The heater head is divided into four spiral-shaped quadrants, each feeding one cylinder of the engine and composed of a bank of small, parallel tubes. Burners for hybrid operation are located immediately behind the tube banks; a shutter/plug door closes over the cavity aperture to reduce thermal losses and allow recuperation of the exhaust gases when operating in the hybrid mode.

The engine is the STM 4-120, four-cylinder, kinematic Stirling engine shown in Fig. 3. Each cylinder is attached to one heater-head quadrant that contains a double-acting piston. The four cylinders are arranged in a square pattern with the pistons moving axially. The connecting rods actuate against a swashplate, which both converts the axial motion of the pistons into rotary motion, and by varying the angle of the swashplate, effects engine stroke control output power from the engine. The engine runs nominally at 2,200 rpm and drives a standard induction motor/generator

Fig. 2 SAIC system at the Salt River Project near Phoenix, Arizona

through a gear reduction drive at 1800 rpm. Heat rejection from the engine is provided by a water/glycol cooling system that uses standard radiators and a cooling fan. The engine has a separate controller that communicates with the concentrator controller.

The system is controlled by a micro-processor-based control system. Operator commands are entered through a central control computer that can be located locally or remotely from the system. When enabled by the operator, the system automatically tracks the sun, switches between solar and fuel inputs, stows itself at night and during high winds, and reacts appropriately to fault conditions as required. The control system also includes data logging and heater-head temperature balance for concentrator tracking adjustment.

Performance. The system waterfall chart, which shows the performance of each system component as power flows through the system, is shown in Fig. 4. The first vertical bar in Fig. 4 shows the total amount of solar energy falling on the dish. Each successive bar shows the losses associated with the following sequential transfers of solar energy and heat into electrical power: the reflectivity of the glass, intercept of the reflected solar beam, absorption of solar beam in the receiver, conversion of the heat in the Stirling engine, efficiency of the electrical generator, and last system parasitic power requirements to operate controls, pumps, fans, etc. SAIC and SES currently have two systems operating at UNLV that are demonstrating about the same power output as a function of insolation.

The solar-to-net-electric energy conversion efficiency of the system has been measured at 20% and the peak power output 22.9 kW [17,18]. The estimated system annual performance, which is based on the system performance curve of Fig. 5, TMY2 direct-normal solar radiation data for Albuquerque, New Mexico, is 36,609 kWhrs with an availability of 90% and an annual efficiency of 14.5%. This estimate, which is also made for the other systems reported in this paper, represents an upper bound on the annual performance of the system since it does not include down time due to problems with the system or transients associated with startup and variable weather conditions.

Over the course of the program, SunDish systems logged over 5,800 hr of solar operation, delivering 63,574 kWh of electrical energy to the grid. The systems also accumulated over 600 hr of hybrid operation on natural gas, delivering 6,622 kWh. The system performance curve, shown in Fig. 5, is a plot of the net, measured power output as a function of the direct-normal insolation (DNI) level. The scatter of the data in this figure and others like it presented later in this paper is caused by solar and thermal transients experienced during start up and normal operation, dirty mirrors, etc. The SunDish system is rated at 22 kW at 1000-W/m^2 insolation. A number of system changes aimed at improving performance have been identified, but not yet developed or implemented. These include increasing the area of the dish by about 25%, increasing the temperature of operation of the receiver, and increasing the optical performance of the concentrator by changing the facet design and optical contour.

Systems operation has demonstrated periods of relatively high availability, on the order of 88%. However, annual availabilities are far short of the long-term goals of 95–98%. Current mean time between failure for the SunDish system is about 40 hr. System incidents that require operator intervention include major events associated with the dish and engine, but also include faults due to sensors, controls, computer programming, communication, and wiring. Problems with sensors, such as thermocouples and connectors, caused over 80% of the system faults recorded for these systems. This instrumentation is for detailed monitoring of the system and will not be installed on a commercial system. Major system faults in the engine are due to hydrogen leakage through joints and seals, internal engine seal leakage, swashplate actuator stalls, and heater head braze joint hydrogen leaks. The most significant problems with the dish are due to optical alignment instability, facet focus control, drive wear and tracking, and limit switch and control problems. Improving the dish focal image to smooth and balance the flux on the heater heads is currently being pursued and should dramatically reduce stresses on the engine resulting in improved system availability.

Corporate Business Development Plan. SAIC and STM Power, Inc., and utility team members Arizona Public Service and Salt River Project intend to follow two key strategies to enter the power sales market. First, to support a U.S. National Energy Plan that encourages the use of solar energy and, second, to deploy the systems needed to achieve and verify the system reliability and to address customer-side of the meter power markets.

SAIC and STM Power believe that there is a clear value proposition for Dish-Stirling systems, once systems costs have been lowered to $2000 US/kW. However, they also see market-driven sales at costs as high as $4000 US/kW. The remote market is currently available to photovoltaic systems, which have very high reliability. Markets like these will not be available to Dish-Stirling systems until high levels of reliability are achieved.

In the U.S., niche markets for Dish-Stirling power generation depend on federal or state government subsidies, required to close

Fig. 3 STM Power engine during on-sun operation

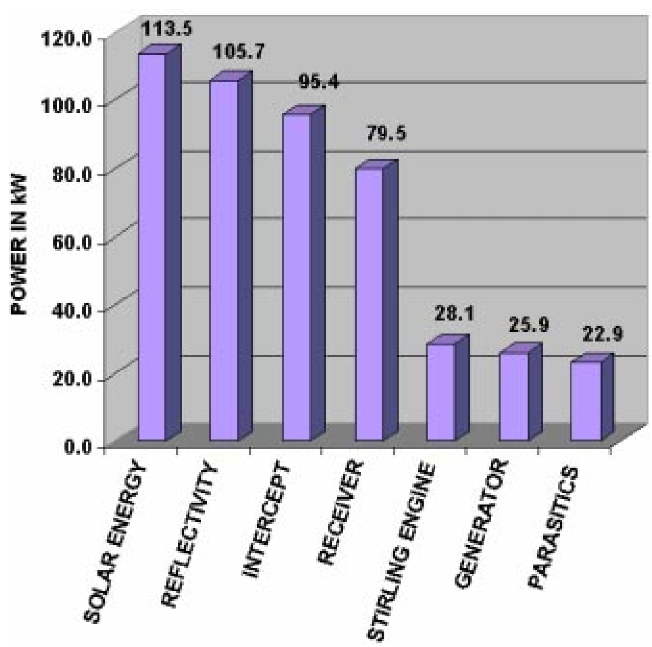

Fig. 4 SAIC system waterfall chart

the gap between the current cost of power from these systems (~30¢ US/kWhr) and the price that the market is willing to pay (6¢ US/kWhr), a difference of 24¢ US/kWhr. State or national Portfolio standards, pollution abatement credits, renewable energy investment tax credits, and/or renewable energy production credits are all needed to help close this gap. The two biggest barriers to the deployment of Dish-Stirling systems are the cost of money and the ability to sell the power through a long-term contract. No-interest or low-interest federally guaranteed loans are an essential part of the strategy to reduce the cost of energy from these systems and take them into the commercial marketplace.

Schlaich-Bergermann und Partner EuroDish.

Background. The EuroDish project is a joint-venture project between the European Community, German/Spanish Industries (SBP, MERO, Klein+Stekl, Inabensa), and research institutions Deutsches Zentrum für Luft- und Raumfahrt (DLR, Germany) and Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT, Spain) [19]. The project, which is headed by Schlaich Bergermann und Partner (SBP), is directed at developing a small series of production prototype systems. EuroDish is the successor to two previous generations of Dish-Stirling systems, the Distal I and II systems [20,21]. The new design replaces the stretched-membrane concentrator used in Distal I and II with a glass-fiber composite shell onto which glass mirrors are bonded with an adhesive. The engine used in the EuroDish is the next-generation SOLO Kleinmotoren 161. Two new 10 kW EuroDish units, shown in Fig. 6, were installed at the Plataforma Solar de Almeria (PSA), Spain, early in 2001 for test and demonstration purposes. Details on the system designs and performance are listed in Table 2.

System Components. The concentrator consists of a thin shell, glass-fiber-reinforced resin sandwich with the mirrors applied to its surface that is supported by a space frame ring truss. Similar to the stretched-membrane designs, the 8.5-m diameter concentrator obtains high stiffness and low deadweight by profiting from the advantageous load bearing behavior of a shell structure. To simplify shipping the concentrator, the shell is divided into 12 identical segments that fit into a standard container for assembly at the site. Based on a detailed structural analysis of the shell and ring truss for both dead weight and wind loads, the resulting sandwich cross section comprises 20 mm of foam and two 1-mm reinforced plastic layers stiffened with a radial rib along the center line. The system is designed to maintain full performance up to wind speeds of 10 m/s with a minor reduction in output power for wind speeds up to 15 m/s. The concentrator is suspended on a space frame turntable rolling on six wheels, similar to previous generation designs. The drive arcs are equipped with simple pre-stressed roller chains. The drive units were redesigned to use standard steel rollers, spur gears and low cost servomotors.

The receiver is at the back of the water cooled cavity and is directly attached to the cylinder heads of the Stirling engine. Its 78 tubes are made from high-temperature steel, 3-mm outer diameter, and their ends are vacuum brazed to manifolds attached to the engine heater head. The receiver tubes absorb the concentrated solar radiation, heating the helium working gas to approximately 650°C. The full load on the receiver is reached at insolation levels of approximately 800 W/m^2. At higher insolation levels, a speed-controlled cooling fan maintains the upper temperature limit at the absorber to avoid overheating the receiver and overpowering engine. Even though this results in increased heat losses from the system at high solar radiation conditions, this is a strategy to increase the annual full-load hours on the system.

The Stirling engine used in this system is the SOLO 161, based on the V-160 engine originally developed by USAB, Sweden, and further developed by SOLO Kleinmotoren GmbH, Sindelfingen. The engine, shown in Fig. 7, is a 90-deg V-type power unit with a swept volume of 160 cm^3 in which helium is the working fluid. The maximum engine working pressure is 150 bars, and the operating gas temperature is 650°C. The engine is mechanically coupled to an induction generator that provides an electrical output of 10 kW at 1500 rpm. The advantages of this engine are its advanced technology and simple, robust construction. The SOLO 161 Stirling engine performance was proved in the DISTAL II units and in the ADDS system at Sandia; and it has demonstrated mature, reliable performance. Consequently, in the EuroDish, only elementary improvements and/or redesign were conducted. These include: joining of the tubes to the manifolds and manifold parts together by vacuum brazing; a new receiver cavity design of a water-cooled aluminum cylinder to address failures due to vibration; and a simplified cooling circuit that uses a single radiator instead of four as in the previous engine design.

The EuroDish control concept allows for fully automatic system operation. Its kernel is a control PC running under Windows NT, located in the operations room or locally in a cabinet at the dish, which communicates with up to 16 Dish-Stirling systems through a rugged industrial field bus. The sun position is calculated by the PC control software, obtaining exact time from a GPS receiver or an internet time server. Positioning commands are then sent to the drive control in the local cabinet at each dish. To reduce the number of discrete components in the control cabinet, a so-called motion controller was developed. The motion controller is a microprocessor board located in the cabinet at each dish whose main function is to carry out the positioning commands from the control PC. It is equipped with a field-bus interface to the control PC, to the servo motor controllers for dish the azimuth and elevation drives, and to a manual terminal. Additionally, several other functions were implemented in the upgraded EuroDish controller, including a hardware watchdog and safety de-track functions, manual drive operation, and weather data acquisition.

A new feature, implemented in the EuroDish control system, is the capability for remote access through a web server that will be integrated directly into the control PC in the future. Through the

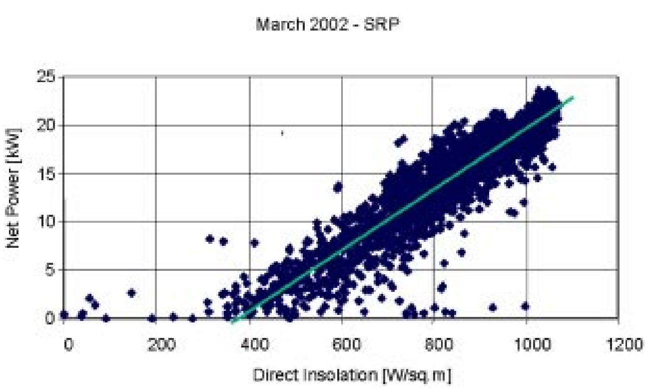

Fig. 5 SAIC system net power output versus direct normal insolation

Fig. 6 Two 10-kW SBP Eurodish prototypes at Plataforma Solar de Almería, Spain

worldwide web, it is now possible to access system status information and online data as well as stored operational data and state and error logs. This enables continuous, operational supervision and preventive maintenance. As a side effect, runtime statistics and selected online data can also be made available to the public online.

Performance. The EuroDish prototypes at PSA were built in 2001 and are still being optimized for performance. The peak solar-to-net-electric energy conversion efficiency of the system is expected to be 21–22%, based on the experiences of former projects with the same engine. The first measurements of peak system efficiency resulted in 20%. The estimated annual performance of a EuroDish system operating in Albuquerque, New Mexico, is the production of 20,252 kWhr of electric energy with an availability of 90% and an annual efficiency of 15.7%.

Additional measurements of one EuroDish system showed improved concentrator performance, that is increased power input to the receiver [19]. The waterfall diagram of Fig. 8 includes this improvement in the receiver efficiency. Because this system is smaller than the SAIC/STM Power and SES systems, its efficiency is slightly lower. The DNI versus net power output of the EuroDish system during a typical operating day is shown in Fig. 9. The plot in Fig. 9 is nonlinear because the system was designed for optimal performance at a DNI level of 800 W/m^2. When the insolation exceeds this level, a fan in the receiver cavity is activated to reject additional heat and maintain the receiver at a fixed temperature. This strategy results in a slight increase in losses at higher insolation levels, but also produces higher annual output from the system. While this may seem counterintuitive, it occurs because the number of operating hours at 800 W/m^2 insolation and below (i.e., at higher efficiency because of the design point) is much greater than the number of hours above 800 W/m^2. In theory, the annual performance from a system could be optimized for a single location, at least in the statistical sense. Pragmatically, this is more a function of how much DNI will be available at the expected locations for which the systems are being designed.

Since the Eurodish prototypes have not been operated for a long time, no reliable number for system availability can be calculated. The systems were operated close to 1000 hr without severe outages, most caused by errors in the control code, electronics or sensor failures. During the last 150 hr, the system operated without intervention except for two restarts after grid power failure and a discharge valve replacement.

SBP and the associated EuroDish industry have performed cost estimates for a yearly production rate of 500 units per year (5 MW/yr) and 5000 units per year, which corresponds to 50 MW/yr. The actual cost of the 10-kW unit without transportation and installation cost and excluding foundation is approximately $10,000 US/kW. The cost projections at production rates of 500 and 5000 units per year are $2,500 US/kW and $1,500 US/kW, respectively.

Corporate Business Development Plan. The two most important issues for commercializing Dish-Stirling systems are cost reduction and system reliability. In addition to ongoing efforts to reduce overall system cost by combining system components, the SBP Team is focused on developing reliable pre-assembled systems, preparing the first pre-production tools, and continuously operating systems under different meteorological and site conditions. Lessons learned and continuous evaluation of system down times will form a sound and reliable data base which is needed to improve system reliability and enable entry into markets.

The European Dish-Stirling Consortium intends to erect as many units as possible at specially selected places in the southern Europe, for example at universities, interested electric utilities, renewable institutes, and local electric authorities within the next two years. With this first step, market showcases and reference systems will help to develop the on-sun operating database needed to provide for further market introductions. In a next step, clustered 0.3–1 MW demonstration plants (30–100 units at one location) are anticipated. This step will help to extend operational experiences and to start the first small series production. These activities will be encouraged by special premiums for solar-electric power, some currently in place and others anticipated in southern Europe.

Stirling Energy Systems' Dish-Stirling System

Background. SES acquired the intellectual and technology rights to the McDonnell Douglas [11] concentrator and the license to manufacture the USAB (now Kockums) 4-95 Stirling engine-based PCU in 1996. At that time, SES initiated a commercialization program to build on the existing solar dish design by improving its manufacturability while continuing to operate the systems and improve the technology. In March 1998, the Dish Engine Critical Components (DECC) Project started with the objective of developing a commercial dish Stirling system. The DECC is a DOE-industry cost-shared project to commercialize the Dish-Stirling system for emerging markets. During Phase I of the project, completed in October 1999, its focus was on operating and evaluating the performance of the Stirling engine, the *critical* system component. The main activities were to demonstrate per-

Fig. 7 The 10-kW SOLO 161 engine and receiver

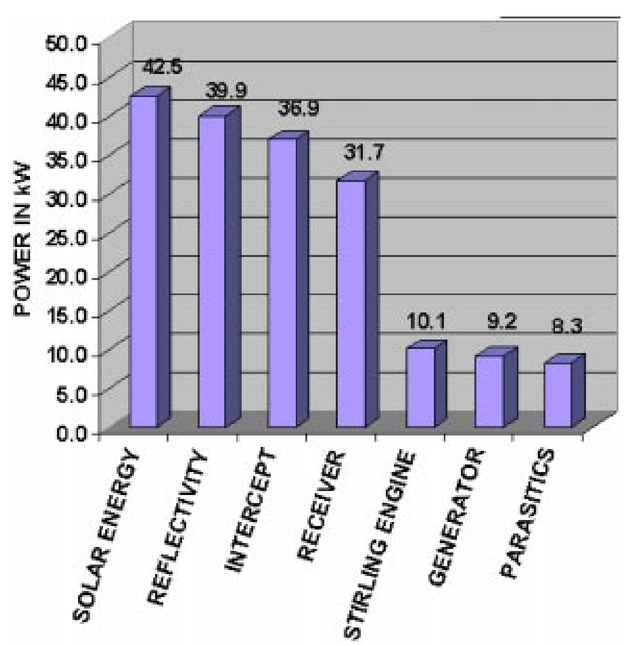

Fig. 8 SBP system waterfall chart

formance and reliability of the engine with primary focus on the internal *hot* parts. DECC Phase II, which started in October 2000 and continues through 2002, is directed at building and testing two complete next-generation systems. As for the two systems previously discussed, the design and performance parameters for the SES system are listed in Table 2.

System Components. Figure 10 is a photograph of two SES systems in operation at the test site at Boeing in Huntington Beach, CA. The SES Dish-Stirling system generates approximately 25 kW of electrical power at a solar insolation of $1000\ W/m^2$. The Kockums 4-95 engine is shown in Fig. 11. The subsystems of the Kockums 4-95 Stirling Power Conversion Unit are: the receiver that transfers the concentrated solar energy to the engine working fluid; the Stirling engine that converts heat into rotational motion of the engine; the electrical generator; a cooling system that rejects waste heat to the ambient air; and the control system that controls and monitors system operation. The basic characteristics of the SES concentrator are listed in Table 2. The main features of the design are a patented balanced design in which the weight of the mirrors offsets the weight of the PCU at the focal point; a slot in the reflective surface that allows the PCU to be lowered to ground level for easy maintenance; and design modularity which allows it to be manufactured in major subassemblies and quickly installed in the field.

Currently, there are four 4-95 Power Conversion Units (PCUs), one in bench testing at Kockums in Malmo, Sweden, and three used on a rotating basis for on-sun operation on two concentrators. Two complete systems are on-sun at the SES/Boeing Solar Test Site in Huntington Beach, CA, one is operating at a test site in Nevada, and components for five more systems are in storage. The first Dish-Stirling module began power generation operation for the DECC Project on June 28, 1998, three different 4-95 Stirling engines have been used with Concentrator No. 1. System Module No. 2 began producing power on February 20, 2000, and testing will continue through DECC Phase II, December 2002.

Performance. The SES Dish-Stirling Systems continue to accumulate both bench and on-sun operating time throughout the DECC Phase II program. Table 2 lists the on-sun operating time for all systems since the start of the DECC program in 1998. An additional 95,101 hr of bench testing of the Kockums 4-95 engine has also been accumulated over this time [22,23]. A peak, on-sun performance of 24.9 kW was achieved on September 6, 2000 with a corresponding 28.8% net system efficiency at direct-normal insolation of $986\ W/m^2$. This performance is consistent with the net peak electrical power efficiency of 29–30% (at $1000\ W/m^2$ solar insolation) [10] achieved during the on-sun testing period of 1984-88 at Barstow, California. The estimated annual production for a system operating in Albuquerque, New Mexico, is 48,129 kWhrs of electrical energy at an availability of 90% and an annual efficiency of 24.6%.

The systems are continuously monitored and repaired whenever a problem occurs. Consequently, they have demonstrated excellent availability, greater than 98%, during the most recent 1000 hr of operation. The system waterfall chart from solar energy to net power out is shown in Fig. 12. The numbers shown in the figure are from power measurement data records, system measurements performed at Huntington Beach, California, and from manufacturer's performance specifications for components.

The direct-normal insolation is plotted versus the net power output from the systems for the time period between March and April 2000 in Fig. 13. The results show that at $1000\ W/m^2$ the Power output is 24.3 kW. The outlying data in Fig. 13 result from dirty mirrors on the concentrating and low pcu performance, which result in reduced system performance and a dirty normal-incidence pyranometer, which results in a lower than actual DNI measurement.

System Cost. Current production costs for the SES Dish-Stirling system are at prototype-scale, a few, hand-built units. Therefore, installed costs are high at about $10,000 US/kW or $250,000 US per dish system. These costs are distributed with 40% in the concentrator and controls, 33% in the PCU, and the remaining 27% of the costs in the balance of plant and installation of the system. The SES system is made up of a number of basic components, such as mirrors (glass), mirror backings (stamped steel), structural steel supports (primarily extruded steel tubing), electronic controls (small computer chips), and an engine system with many components that are similar to automotive engines (pistons, crankshafts, engine block, radiator system, fan, water and oil pumps, etc.). Consequently, SES believes that there is substantial potential to reduce the cost of their Dish-Stirling system.

Corporate Business Development Plan. SES is transitioning from a development and test phase to a pre-commercialization phase of operation for its Dish-Stirling technology. Early market efforts have concentrated on developing solar farms (10–100 MW) in the Southwestern U.S. desert areas (particularly in Arizona, Nevada, and southeastern California), and in selected solar-rich international markets. SES is teaming with major companies in Spain, Italy, and South Africa to find ways to enter these markets. SES is also in discussions with major utilities serving the Southwest U.S. to obtain power purchase agreements for peaking power to supplement the power production from conventional power plants. The company's solar products will also help the utilities of Arizona and Nevada to meet renewable energy portfolio standard requirements in effect in these states.

SES projects the majority of its sales will be of equipment to

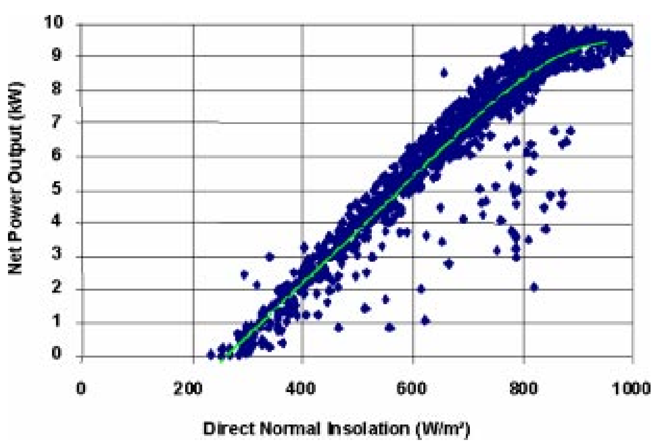

Fig. 9 SBP system net power output versus direct normal insolation

Fig. 10 SES systems on test at Huntington Beach, California

utility companies or independent power producers. They are working with customers to develop projects and to provide on-going support services to the solar power plants. In foreign countries, SES is considering the licensing of Dish-Stirling marketing rights.

WGAssociates' Advanced Dish Development System

Background. The Advanced Dish Development System (ADDS) project is a direct result of the technology development activities in the Cummins Dish-Stirling Joint Venture Program and the successful experience with the SOLO 161 Stirling engine on a Cummins CPG-460 Concentrator at Ft. Huachuca, Arizona [24]. The project started in October 1998 as a test bed for advanced components and systems-level testing to address the issues of the remote power market. Development activities have focused on extending the application of Dish-Stirling systems to water pumping, reliability improvement, and incorporating advanced components such as structural facets, heat pipe receivers, and advanced controls and communications. Testing includes long-term unattended, automated operation of stand-alone 9.5-kW Dish-Stirling solar power generation systems in both on- and off-grid modes at the National Solar Thermal Test Facility (NSTTF) in Albuquerque. In 1999, the first-generation, grid-connected (Mod 1) system was fielded at the NSTTF and unattended operation initiated. In 2000, an upgraded, second-generation (Mod 2) system design, which includes stand-alone water-pumping capability, was developed. Figure 14 is a photograph of the Mod 1 and Mod 2 systems on test at the test Facility.

System Components. The ADDS design features the WGAssociates (WGA) WGA-500 solar concentrator and controls and the SOLO 161 Stirling power conversion unit (PCU). To address remote power markets, the systems were designed to operate autonomously, for low capital and installation costs, and field-level maintainability. The details for the system specifications and performance of the two ADDS systems are listed in Table 2. Even though they are similar, both sets of parameters are included here because the Mod 2 system is a stand-alone water pumping unit that has some unique features. The waterfall efficiency chart for the Mod 1 is shown in Fig. 15.

The concentrator uses an elevation-over-azimuth tracking space frame dish structure fitted with paraboloidal contoured, trapezoidal shaped, glass-metal mirror facets. The tracking structure is constructed primarily of structurally efficient, thin-wall tubing. The azimuth drive is the field proven, Winsmith planocentric reducer. The Mod 1 elevation drive employs a 10-ton commercial ball screw. To facilitate maintenance of the PCU, it is configured to bring the SOLO 161 PCU below the horizon for access from ladders or from the back of a pick-up truck. The elevation ball screw is powered by a 1750-rpm, $\frac{1}{2}$-hp (373-W) gear-motor through a secondary worm gear reducer, resulting in an average elevation slew speed of about 40 deg/min. Because the system must operate off grid, the Mod 2 Dish-Stirling system is designed with DC drive motors.

The mirror facets are glass/metal structural facets [25]. They utilize a sandwich construction consisting of thin-glass mirrors bonded to a sheet-metal membrane. An aluminum honeycomb is bonded with epoxy between the back of the sheet-metal membrane and a second sheet-metal membrane. The Mod 1 system uses two concentric rows of mirrors, each row consisting of 16 panels. The Mod 2 concentrator utilizes a single row of 24 facets. Facet mounting to the structure is accomplished by the use of three-point mounting studs that facilitate alignment.

The Collector Control System (CCS) used on both ADD systems is an adaptation of one developed by Cummins Power Generation for their two Dish-Stirling systems. This basic control system has over 40,000 hr on-sun tracking and has shown itself to be flexible, robust, and reliable. The CCS provides both control and monitoring of the concentrator and the PCU and provides for autonomous system operation. Sun tracking uses a hybrid approach consisting of both open- and closed-loop tracking. Closed-loop tracking employs four differential-thermocouple sensors equally spaced around the receiver aperture. After a day of closed-loop tracking, algorithms in the tracking program automatically derive seven concentrator misalignment parameters. Once the misalignment parameters are *learned* and applied to the open-loop tracking algorithm, open-loop tracking is close enough to *capture* the focused image.

The control system is configured so that, if the computer *locks up* or otherwise does not respond, the concentrator is driven to stow in elevation to the vertical limit. On the Mod 1 system, the fail-safe system includes a 12-VDC battery and inverter in the event of loss of grid power. The operator has three ways to interface with the CCS: for routine day-to-day operation, a push button control panel is used; when additional system diagnostics are needed, a hand-held terminal can be plugged into the control panel; and, for detailed diagnostics, a computer interface is available. This interface also provides for monitoring and the remote control of the system though an internet connection.

The ADDS system uses a SOLO 161 Power Conversion Unit, which is the same engine used by Schlaich for their Distal and

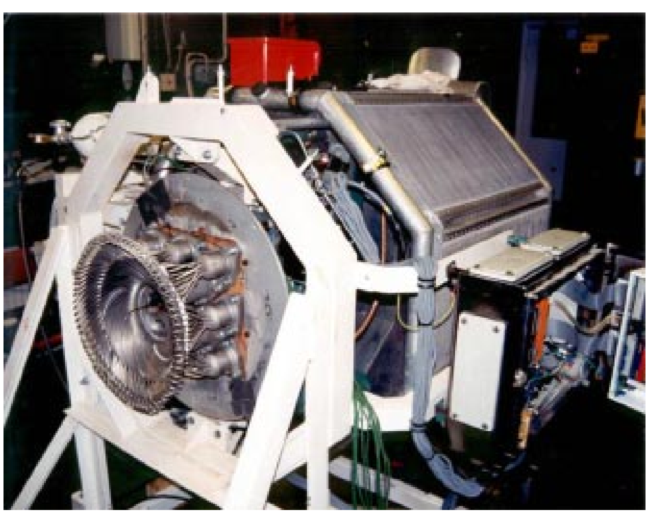

Fig. 11 Kockums 4-95 kinematic Stirling engine

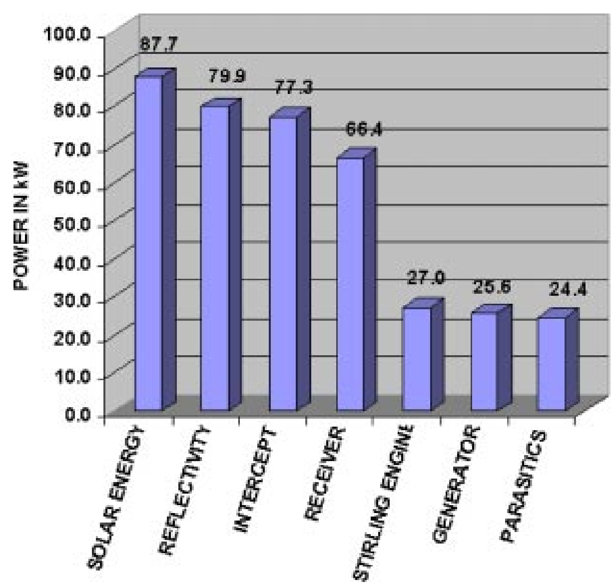

Fig. 12 SES system waterfall chart

Eurodish systems, shown in Fig. 7. The SOLO 161 engine is being developed by SOLO Kleinmotoren primarily for cogeneration applications. The SOLO 161 utilizes a direct-illumination solar receiver and pressure control of the working fluid to vary power output. Small working fluid leaks are automatically made up through an external bottle located on the concentrator tracking structure. The Mod 1 PCU uses a 3-phase induction motor/generator to supply 3-phase, 480-V power to the utility grid. This approach provides power for starting the engine and automatically synchronizes voltage and frequency with the utility grid. In the Mod 2 stand-alone system, a synchronous generator is used. In this approach, the generator output varies both in voltage and frequency and directly drives an induction motor and water pump. Because water pumping is a common remote-power need, the Mod 2 design drives a conventional 3-phase 480-V, 7.5 or 10-hp (5.6 or 7.5-kW) submersible water pump. A standard 12-VDC automotive starter is used to start the Mod 2 version of the PCU.

Performance. Testing of the ADDS systems has evolved from concentrator testing early in the project to ongoing system operational, reliability, and performance testing. The Mod 1 system operates automatically and unattended, including weekends and holidays. After the system detects that DNI is within specifications, it tracks to acquire the sun, starts the PCU, and supplies power to the grid. If the anemometer detects high winds, the system automatically drives to stow where it remains until wind speed returns to a safe level for a specified period of time. When clouds are detected (low DNI), the system drives off sun and continues to offset track. When DNI returns to specified levels the system reacquires the sun and starts the PCU. If the sun does not return within a specified time or if the sun elevation falls below a defined angle, typically 2 deg, the concentrator stows. When a fault is detected, the system automatically sends the system to stow and notifies the operator through a pager. In many cases, the operator is able to resolve the problem and resume operation remotely.

Because the SOLO 161 is intended for indoor co-generation applications, helium was initially used as the working fluid. To increase performance, the gas system was converted to accept hydrogen as the working fluid, increasing the system power output from 9 kW to 9.5 kW at 1000 W/m^2, the system rating, even though the concentrator area was reduced by 11% (by covering mirror area) to avoid overpowering the engine. Although system output could have been increased to over 10 kW using the original mirror area, the current specification results in lower engine pressure and longer expected life on the critical Pumping Leningrader (PL) seals. Figure 16 is a scatter plot showing net system power as a function of direct normal solar insolation taken at 1-min intervals on February 6, 2002. The Mod 1 system has demonstrated a peak efficiency of 24.5%. The estimated annual performance for a system operating in Albuquerque is energy production of 17,353 kWhrs at an availability of 90% and an annual efficiency of 18.9%. The Mod 2 ADDS system drives a conventional submers-

Fig. 14 WGA ADD systems, Mod 1 and Mod 2, on test at Sandia's National Solar Thermal Test Facility

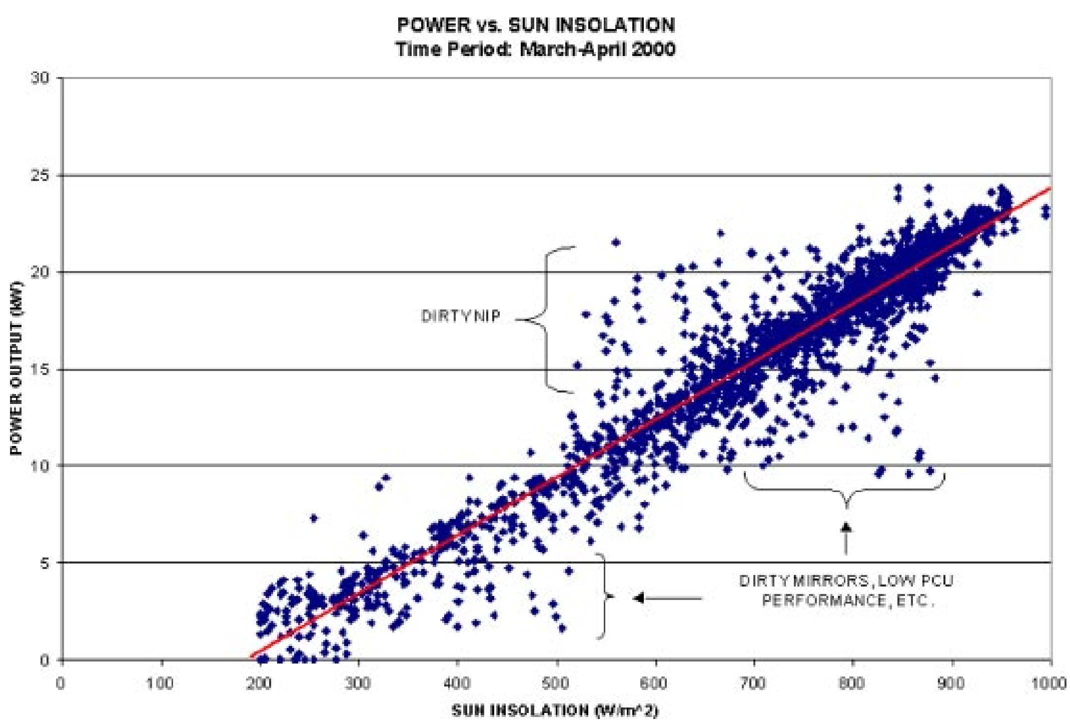

Fig. 13 SES system net power output versus direct normal insolation

ible water pump. The test pump, which is currently being utilized, is undersized for the output of the system, resulting in the peak net output for Mod 2 being less than rated.

Availability and reliability of the ADDS has steadily improved since automated system operation was initiated in November 1999. During the period between January 6, 2000 and October 24, 2000, the Mod 1 system accumulated 1711 on-sun, power-producing hours at times when the insolation was within the system operational specifications, a total of 2369 hr, yielding a gross availability of 72.2%. This availability does not account for periods when the wind exceeded operational limits, and down time for tours, training, and development. [26] In 2001, the data acquisition system was enhanced to accurately record system availability by allowing operators to take ''time out'' to install and evaluate new features or to take the system off line for tours or other non-operational interruptions. The system also now accounts for low-insolation and high-wind conditions. Since August 1, 2001, availability, which is defined as the time the system produces net positive power divided by the time insolation and wind are within operational specifications, has been about 90%. This availability definition accounts for lost time while the system is slewing to go on sun and while warming up. On days in which the system operates perfectly, availabilities range from the upper 90s% on clear-sky days to less than 50% on mostly cloudy days. Frost and snow significantly impact availability on some days. An availability definition based on lost time from maintenance and faults has been about 94% during the same time period. System mean time between failure (MTBF) has improved along with availability. Data currently indicates a system MTBF of about 250 hr for the Mod 1 ADDS. Most of the down-time incidents are related to controls and are minor in severity.

The WGA ADD system produces up to 11 kW at optimum DNI conditions. It has been field tested for three years and proved to meet present day reliability, availability, and efficiency targets. The system design employs commercially available components, including the PCU. This unit can be deployed in large-scale, on-grid applications. Moreover, it is particularly well suited to cost effective, modular installations in remote areas as an unattended, off-grid power source, or for distributed generation applications. In either case, additional units may be incrementally installed to meet increased power needs.

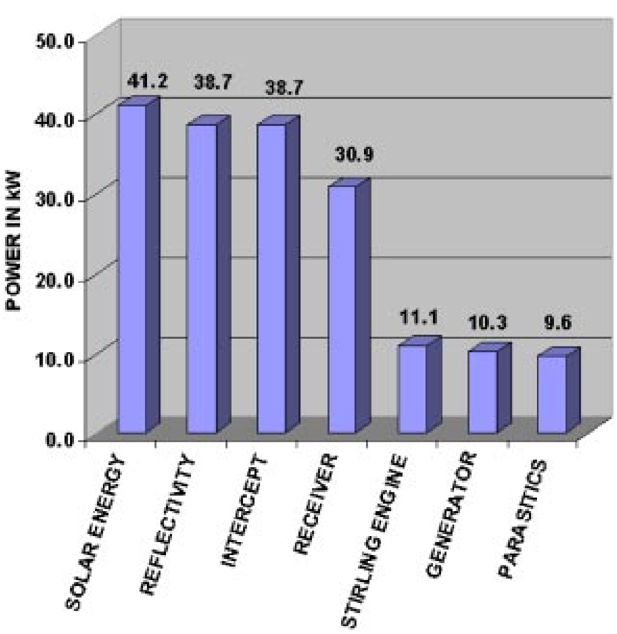

Fig. 15 Waterfall chart for the Mod 1 ADD system. Power and efficiency for the SOLO 161 engine and solar receiver are estimates.

A Mod 3 design, which will incorporate improvements resulting from the Mod 2 operation, is being developed. The Mod 3 design will represent the next phase of production readiness, reflecting a significant reduction in the manufacturing costs.

Corporate Business Development Plan. WGA continues to work with Sandia on the refinement of the Mod 1 and Mod 2 system designs and is developing a Mod 3 design on its own. WGA is also working with independent power producers towards the development of a project for a multiple-unit build. A large number of operational systems are needed to improve and demonstrate system reliability to the point required by the market.

IV Advanced Dish Receivers

The receiver is a *key* component in a Dish-Stirling system because it must convert the concentrated solar energy to heat and transfer it to the engine working fluid at high-flux conditions of from 75 to 100 W/cm^2 and temperatures of 700–800°C. In this section of the paper, we review some of the advanced receiver concepts that are currently being developed including heat-pipe receivers, hybrid receivers, and a volumetric receiver that could be used for a future Dish-Brayton system.

Heat-Pipe Receivers. Heat-pipe receivers use sodium or a mixture of sodium and potassium to transfer heat from the surface of the receiver to the engine heater head [15,16]. Heat pipes utilize a capillary wick to distribute the liquid metal over the back surface of the absorber. The liquid metal evaporates, vapor is transported to the engine heater head where it condenses, and the liquid metal refluxes to the absorber. In these receivers, the liquid metal condenses at a constant temperature thereby providing uniform heating to the Stirling engine, unlike DIR receivers that can experience large temperature differences between quadrants or along tubes of the receiver. Since the receiver materials typically limit the peak receiver temperature and thus the performance, in a heat pipe receiver the peak temperature is the average temperature, which raises the achievable working gas temperature considerably. The increased working gas temperature, improved receiver efficiency, improved temperature balance among the four cylinders of the engine, and overall simplicity resulted in a 20% increase in system efficiency [27].

The sodium heat pipe receiver for a 25-kW system stretches the traditional sizes and shapes of heat pipes. Most developmental research at Sandia has concentrated on wick improvements to increase the operating margin of the heat pipe. The most promising wick design has been a stainless steel felt, with over 95% porosity provided by 4-μm fibers. This felt provides a large pumping capability with low flow losses. The fine fibers present new manufacturing challenges, requiring extremely clean sodium environments in order to prevent corrosion. Cleaning techniques and processes that virtually eliminate corrosion issues seen in early felt-wick heat pipes, while not significantly impacting the cost, have been developed at Sandia. Bench-test heat pipes have demonstrated over 5000 hr of operation without degradation, whereas prior tests failed at less than 2000 hr. Some smaller capsule heat pipes have been tested for over 30,000 hr without degradation [28,29,30].

Sandia has also developed wick modeling techniques and tools [31] that are critical to the successful design of the heat pipe receivers. Distributed pore size wicks, like the felt metal, rely on vapor generation in the wick, rather than at the heated surface. This provides sufficient heat transfer through the wick while also providing liquid transport along the wick. This approach, which was pioneered by Thermacore Inc., is contrary to conventional heat-pipe technology approaches. Sandia has demonstrated the applicability of these modeling approaches on powdered-metal sintered wicks, operating one heat pipe receiver to 116-kW thermal throughput and closely matching the predicted results of the models.

The felt wick heat pipe needs additional development in several areas [32]. The fine fibers of the wick tend to crush over time under the weight of the sodium column. This effect and/or other non-uniformities in the wick structure are thought to have caused the occurrence of hot spots in a few cases. In addition, the integration of the heat pipe chamber with the engine heater heads is a second area that needs to be addressed. While efforts have begun in these two areas, further development is limited by the availability of resources.

Sandia has tested two engines with heat pipe receivers, and a number of additional receivers have been tested on-sun with gas-gap calorimeters for proof-of-concept. In 1996, an STM Power 4-cylinder engine was tested with a felt-wick heat pipe receiver [27]. This was followed by more extensive testing of the engine with a Thermacore, powder-metal-wick heat pipe receiver. This engine demonstrated more than a 20% improvement in efficiency and throughput compared with a DIR receiver on a highly accurate dish. The results would be more dramatic on a less accurate dish, because the temperature distribution on the receiver follows the flux distribution capabilities of the dish. In 2000, Sandia integrated the latest felt-wick receiver with the SOLO Kleinmotoren engine on the ADDS at Sandia. The design took advantage of flexibility in the SOLO cooler, allowing for thermal expansion of the receiver shell. Unfortunately, the receiver failed in initial testing. The failure was traced to an improper clearance in a braze joint where the heater head tubing passed through the heat pipe wall. This resulted in a breach of the heat-pipe containment. Additional work on this receiver has not been possible due to limited resources.

Hybrid Heat-Pipe Receivers. Hybridization is one way to improve the value of electricity from Dish-Stirling systems by making it available on demand. Combining a heat-pipe receiver with a hybrid receiver has the potential to improve the receiver performance, reduce the cost of the receiver, and provide dispatchable electric power.

Two prototype hybrid, heat-pipe receivers have been developed and tested for the SOLO V160/161 by the DLR in Germany [33]. The most recent design has an outer diameter of 36 cm, a cylindrical inner-wall diameter of 21 cm, and is 24 cm deep. It was designed to transfer 45 kW of thermal power to the engine at a maximum temperature of 850°C. The heat pipe structure comprises spot-welded mesh screens with arterial webs to enhance sodium flow. For hybrid or fossil-only operation, a lean, pre-vaporize combustor, which uses combustion gas re-circulation, was developed to lower the combustion temperature. The receiver was tested for almost 400 hr in the laboratory and field, resulting in Dish-Stirling system efficiencies of 16% solar and 15 % in hybrid operation. As part of the same project, a new type of capillary wick structure for the heat pipe was manufactured using radio-frequency, plasma spraying. During preliminary testing, it demonstrated promising performance but has not been fully tested.

Sandia is also developing a 75-kWt hybrid heat-pipe receiver for Dish-Stirling applications. This receiver is a 6-X scaleup of an earlier bench-scale concept that was successfully tested [34]. The design is a compact package comprising a fully-integrated solar absorber, sodium heat pipe, metal-matrix combustor, and folded-membrane recuperator. During the design of this package, special attention was also paid to developing a design that is manufacturable and low cost. Towards this end, Sandia worked closely with commercial fabricators, whose estimates indicate that the hybrid incremental cost will be competitive with the cost of power from its diesel competition. So far, the receiver has been tested in gas-only mode at throughput power levels from 18 to 75 kWt, at output temperatures up to 750°C, and orientations corresponding to sun elevations of 12, 22, 45, and 80 deg. The tests established several landmarks at 75 kWt, including: 1) preheat of fuel/air mixtures above 600°C without preignition, 2) internal wall temperatures over 800°C with minimal warping, particularly at critical internal seals, and 3) 68% thermal efficiency including parasitics. An efficiency of 75% should be achievable with the addition of an external insulation package. The tests also verified that smooth ignition is easily attainable and that buoyancy effects are not a problem. During testing, some non-fatal problems occurred including brief periods of leakage at an internal seal and warping of the burner matrix. Late in the scheduled tests, a hot spot, believed to be the result of a wick flaw, developed on the gas-fired surface. This behavior has been seen in other heat pipe receivers and is the subject of an ongoing investigation, which is on hold due to budget limitations. A comprehensive report on the hybrid receiver is currently in preparation.

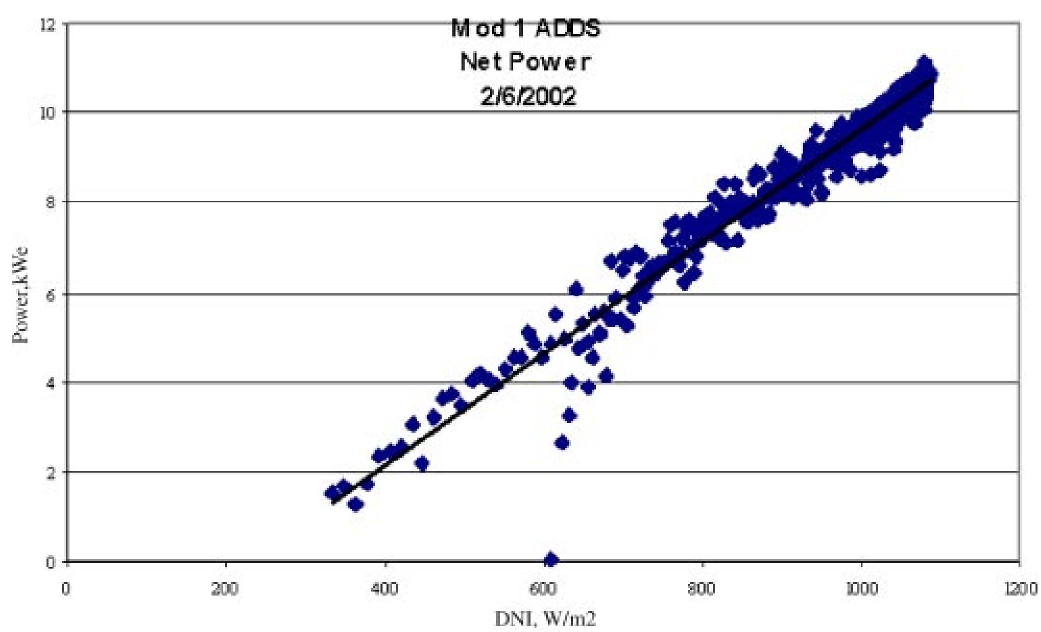

Fig. 16 Mod 1 ADD system net power output versus direct normal insolation

BioDish Hybrid Receiver. The BioDish hybrid receiver is a ceramic receiver being developed to absorb solar radiation on one side and to burn a biogas on the backside of the receiver. The project, which involves a number of participants, is co-funded by the European Community. An advanced, fiber-reinforced, SiC-ceramic material, which is already used in non-solar applications, is being developed to withstand an inner pressure of 150 bars of helium in the small channels. The largest design challenge is the manufacture of the complex receiver geometry. The project participants are also performing an economic analysis for a Bio-Solar power plant. The typical plant size would be a farm of 50–100 Dish-Stirling systems with a biomass gasification providing biogas to augment solar operation and to operate the plant at night.

A schematic of the BioDish receiver design is shown in Fig. 17. The absorbing part of the receiver is designed as a ceramic half bowl with internal channels. The concentrated solar radiation illuminates and is absorbed on the inner surface of the bowl. Through the rotationally symmetric design, the flux distribution and the heat transfer to the working gas of the Stirling engine are optimized. The heater heads, which are also made of ceramic, connect the receiver to the engine and allow for higher temperatures and higher cycle efficiencies than current metallic heads. The biogas combustion system consists of a combustor, located on the center axis and surrounded by a cylindrical air pre-heater and a ceramic shell for ducting the combustion gases. Combustion occurs between the receiver and the shell while combustion gases flow through the pre-heater heating incoming combustion air. To meet the requirements of hybrid operation, the power output of the combustor has to be quickly adjustable. This is accomplished by controlling the combustion air flow. To limit emissions from the combustion system, the maximum temperature of combustion is limited to 1400°C.

The design is compact and easy to install in an existing Dish-Stirling system. Preliminary cost estimates for the hybrid receiver are about $15,000 US at modest production levels of 100/yr. The additional cost of adding a biomass gasifier is estimated to be about $3,000 US.

Volumetric Receiver. Because they have the potential to be low cost, reliable, and readily hybridized, micro turbines are being considered as possible converters for some advanced dish-engine systems. The expected conversion efficiency of small, recuperated gas turbines is somewhat lower than of comparable Stirling engines by about 10 percentage points, ranging from 27 to 33%. Solarization of a gas turbine is achieved by installing the solar receiver between the recuperator and the combustor of the gas turbine. Air is heated in the receiver before it is introduced into the gas turbine, thereby replacing all or part of the fuel with solar energy.

One option for the solar receiver is the pressurized volumetric receiver shown schematically in Fig. 18. The concentrated solar radiation enters the receiver through a domed quartz window, which closes the opening of the pressure vessel. Inside the vessel, the volumetric absorber, made with highly porous ceramic foams or similar materials, is heated by the incident radiation. The air passes through the porous absorber where it is heated by forced convection before going to the gas turbine. The hot air from the receiver is ducted to the gas turbine combustor where, if necessary, it is further heated by combustion of fossil fuel. DLR has been developing this receiver technology for several years and has successfully demonstrated operation of several units under conditions similar to those required for a recuperated gas turbine cycle [35]. Tests of this receiver have been conducted up to absorbed power levels of 95 kW, air inlet and outlet temperatures of 580°C and 940°C, and air pressure of 3 bar. The pressure drop through the receiver is less than 20 mbar, which is important for application to gas turbines. A similar receiver for power tower applications has been operated at a power level of 400 kW, air outlet temperatures of 800°C, and pressures of 15 bar.

V Cost of Energy from Dish-Stirling Systems

To be successful, Dish-Stirling systems must meet the needs of the markets; that is, they must be capable of producing electricity at costs that are acceptable to a range of power markets. To do this, the combined costs resulting from the capital costs of the systems; the cost of money, taxes, insurance, inflation; and the cost of operating and maintaining the systems all have to be factored into the cost of electricity from Dish Stirling. This type of cost analysis is a standard financial calculation that is well-documented in the literature [36]. It results in a quantity called the levelized energy cost (LEC), which is the annualized cost of energy from a power plant taking into consideration all of the previously mentioned variables divided by the total, annual kilowatt hours produced by the plant.

Before proceeding to the LEC cost analysis, it is important to emphasize several points. The predicted variable is the *cost* of electricity per kWhr not its *price*. Its price includes adders for distribution costs, other services provided by the local utility, and profit. These are not included in the analysis. Second, solar Dish-Stirling systems, as other renewable energy power systems, are nonpolluting. They emit no hydrocarbons, particulates, CO, CO_2, or other green house gases. Some Independent Power Producers provide a premium for power produced from *green* (or nonpolluting) sources. Some U.S. states and foreign governments have renewable portfolio standards (RPS) or system benefits charges (SBC) to encourage the use of renewable energy for power generation. RPSs mandate that companies providing power in the state provide a portion of that power from renewable sources;

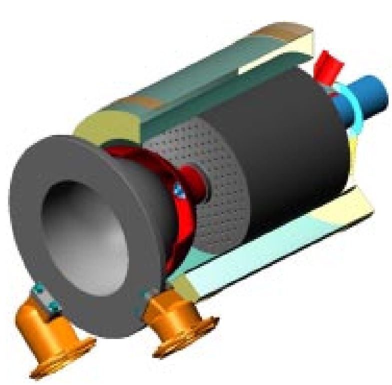

Fig. 17 BioDish hybrid receiver

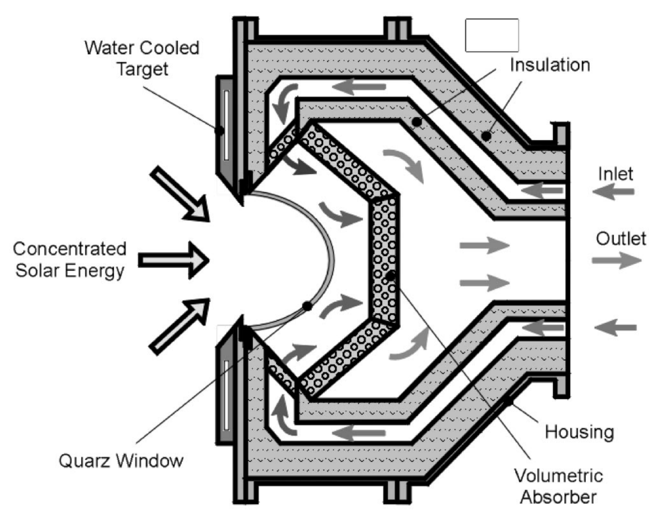

Fig. 18 DLR pressurized volumetric air receiver

Table 3 Parameters for the LEC analysis

Parameter	Case 1	Case 2	Case 3	Case 4
System Rating (kW)	25			
Location	Albuquerque, NM (TMY2 Data Model)			
Combined Tax Rate (%)	40%			
Debt to Cap Ratio (%)	50	50	50	50
Blended Cost of Capital (%)	20	15	10	6
Term of the Loan (yrs)	10	15	20	25
Fixed Charge Rate (%)	24.9	18.1	12.8	8.8
System Capital Cost ($US/kW)	10,000	5,000	2500	1500
Annual Availability (%)	88	92	97	98
Annual Performance (kWhrs)	46,277	50,504	52,831	60,735

while SBCs collect a surtax from the consumer and put it into a pool for developing solar energy and/or other energy resources. The U.S. Federal government currently gives a production tax credit of 1.7¢ US/kWhr for power produced from wind and closed-loop biomass power. This provision is being considered for expansion this year to include power produced from "swine and bovine waste nutrients, geothermal power, solar power, and open-loop biomass" [37]. Solar energy includes Dish-Stirling, power towers and troughs, and photovoltaic power generation. By the time this paper is in print, the decision on the extension of the production tax credit should be resolved. Last, Dish-Stirling systems are capable of operating on the customer- or demand-side of the power meter. In this sense, they can operate as distributed generation offering all of the advantages of any other distributed generator, i.e., line conditioning, limited freedom from the grid, and sale of power back to the grid.

None of the methods for providing additional *value* to power produced from Dish-Stirling systems are included in this analysis. Many believe that it is the approach for assigning additional value to green power sources, in the form of tax credits or through the legislation of pollution penalties and issuance of pollution-offset certificates for green power, that will enable electricity from Dish-Stirling systems and other renewable power sources to bridge the cost gap and enter the competitive marketplace, much like wind power has been able to do over the last three years. Unfortunately, in the current regulatory landscape in the U.S. and many countries, the process of *valuing of green power* is caught up in and secondary to the continuously changing debate over restructuring of the electric utility sector. In the U.S., it is likely to be 3–5 years before this debate plays out. Once restructuring legislation is in place, as much as a decade may be required to resolve court challenges and establish sustainable sets of conditions that the financial community will accept for providing financing for renewable technologies.

Achieving a competitive LEC depends on low O&M and capital costs. Reliability of operation is important for Dish-Stirling systems because poor reliability results in increased O&M costs. A reasonable long-term target for O&M costs for a Dish-Stirling system is in the range of 1–1.5¢ US/kWhr. Precisely what constitutes a competitive LEC from Dish-Stirling systems is an entirely different matter and depends, to a large extent, on the market. It is entirely too easy to say that these systems must compete in base-load markets with coal or with peaking, gas-turbine power plants at LECs of 3–5¢ US/kWhr. This statement ignores the *value* of clean, distributed power described above. Also, as a distributed generation system, Dish Stirling can also compete in demand-side applications with the "price" of power not the cost. It is not unreasonable to expect Dish Stirling power generation to become a significant player in a number of markets if the LEC from the technology is reduced to 8–10¢ US/kWhr.

The LEC analysis presented below demonstrates the sensitivity of the LEC to capital and O&M costs and, to a lesser extent, to the *risk* of investing in a new technology, represented by the rate at which money can be borrowed. This analysis is a generic one and does not represent a specific Dish-Stirling system. The variables for the four *cases* evaluated are presented in Table 3. Figure 19 is a plot of the LEC as a function of system operating and maintenance costs for the four cases.

Case 1. This case represents the current state of the art of Dish-Stirling systems. The systems are expensive prototypes that are hand built and demonstrate modest reliability and system availability. If they will invest in the technology at all, the venture capital community requires a large return on their investment in a relatively short period of time. At this point in the development cycle, the venture capital is more likely to look for a quick return on their investment, realized within 3–5 yr by the sale of the company or their share therein. The cost of energy is more than $1 US/kWhr, so sales of systems are low and supported by those interested in *getting in on the ground floor* or for whom the cost of energy is not the motivating factor for purchase.

Case 2. Case 2 is a modest improvement on Case 1. The system cost is half of what it was for Case 1 and the performance reflects a modest improvement. Reductions of half over prototype costs could be supported by relatively low levels of production. The perceived investment risk remains high, however; the motivation for investment is probably the same as for Case 1. Even though reliability and availability are not yet at the required levels, at LECs below 50¢ US/kWhr the remote power community and some export markets may be interested in the potential of Dish Stirling power generation.

Case 3. In the scenario represented by Case 3, there is significant mass production of Dish-Stirling systems and the reliability and performance have been demonstrated sufficiently to establish for the investment community that the technology is not high risk. This could be similar to the current status of trough-electric technology where more than 350 MW have been in continuous opera-

Fig. 19 Levelized energy cost versus O&M costs

tion in the California desert for a decade or more [3]. The LEC for reasonable O&M costs ranges from 15 to 20¢ US/kWhr. In this cost range and given a stable, restructured, utility environment, Dish Stirling should start to be introduced into some green power opportunities in the U.S. and Europe and may find application in some remote markets, if they can meet reliability requirements.

Case 4. Case 4 represents what the cost of energy and O&M might look like for a mature Dish-Stirling technology. The investment community treats the risk of investment at the same level as for any mature rankine, Brayton, or combined-cycle system. At modest O&M costs, on the order of 2¢ US/kWhr or less, the LEC will be less than 8¢ US/kWhr. This case is not intended to represent the ultimate potential of Dish-Stirling technology but, at a cost $1500 US/kW, it represents an aggressive target. Further reductions in the cost of energy and improvements in O&M will require major technology changes.

As mentioned earlier, this analysis has not included the *value* of distributed generation or of reducing greenhouse gas emissions, associated with Dish-Stirling technology. It has also not included any of the cost offsets provided by existing or pending legislation on premiums, portfolio standards, or for green energy, available in parts of the U.S. and Europe. Even without these additional cost incentives, green power and remote power markets should be available to systems if costs, representative of Case 3, can be achieved. The potential markets and a market-entry path for Dish-Stirling technology are discussed in the next section of this paper.

VI Markets for Dish-Stirling Systems

A potential path for Dish-Stirling technology, as well as other renewable energy technologies, into the commercial marketplace is shown in Fig. 20. Initial sales are for so-called *opportunity* markets to parties for whom the cost of energy is not the issue. As the costs are reduced and the system reliability increases, the systems will be sold into higher-value green power and distributed generation markets. One of the advantages of Dish-Stirling systems in these markets is their modularity, which allows for the incremental addition of capacity as required. Modularity also allows for the potential consumer to *experiment* with the technology without having to invest in a large-scale power plant. As the reliability increases further to meet even more stringent requirements, Dish Stirling systems will be sold for remote power applications. Last, if costs decline sufficiently, they may also be sold for bulk power generation. These markets are briefly described below.

Opportunity Power Markets. At an initial cost of $8,000–$10,000 US/kW and a cost of energy more than $1 US/kWhr, not many systems will be sold and the buyers are those motivated by having the newest form of power generation equipment or by the future potential of Dish Stirling technology. These markets represent the chance to demonstrate Dish-Stirling technology and educate policy makers and power producers while, at the same time, adding to the operational database and improving the system performance. This is also the time to start introducing the technology to financial institutions.

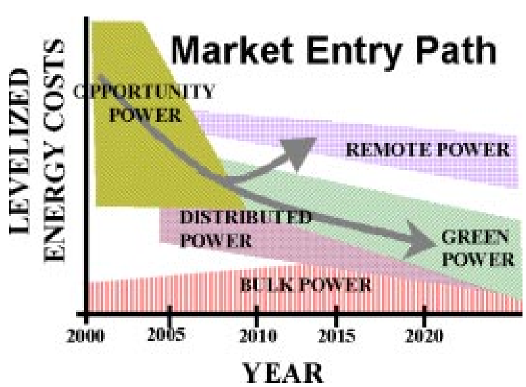

Fig. 20 Market Entry Path for Dish-Stirling systems

Green Power Markets. Green power is electricity generated from solar, wind, and other renewable energy sources, including Dish-Stirling systems. The primary reason for the emergence of green power markets is to replace part of the conventional, fossil-fuel-fired generation and the associated production of greenhouse gases. The general approach is to offer a green power product to the customer at a premium price that, when distributed over the customer base, will cover the incremental cost of generation and a modest profit. Generally, the green product is *blended* with conventional fossil electricity or represents a fixed purchase of kilowatt hours of green electricity per month.

More than 100 MW of new renewable energy resources have been brought on line due to green power market development. Estimates of market growth in the U.S. through 2010 range from 1931 to 6971 MW under low- and high-growth scenarios [38], respectively. The four barriers that determine whether the green power markets grow quickly or slowly are the progress or degree of *pull back* of utility restructuring plans; the establishment of favorable *rules* for restructured markets; the level of consumer acceptance of green power markets; and the continued decline in premiums for green power purchases. Even a relatively modest level of Dish Stirling penetration into growing green power markets could result in the deployment of hundreds of MW of Dish-Stirling systems.

Distributed Generation. Distributed generation is electrical power generation that is located near to the load and it may be located on either side of the meter. On the supply side of the meter, the cost of the power must compete with the cost of base load power plus any additional benefits. These benefits could include improvement in power quality, higher efficiency of transmission due to reduced transmissions distances, avoided fuel costs, and offsetting the need to build new base-load plants and transmission [39]. These are additional to the clean energy benefits of renewable energy technologies such as Dish Stirling and may add further value to these systems. One study [39] shows that distributed benefits enable entry of Dish-Stirling systems into the market when costs reach the level represented by Case 3 of the previous section and that the market size increases to 1.5 GW/yr in the Southwest U.S. as costs drop to a LEC of 5.3¢ US/kWhr. This is a low LEC for electricity from Dish-Stirling systems and will be achieved only at very high production levels for very mature system configurations.

On the demand side of the meter, distributed generation competes with the retail price, not the cost, of electricity, which averaged 8.8¢ US/kWhr in the U.S. in 2001, ranging from a low of 5.7¢ US/kWhr in Washington State to a high of 14.6¢ US/kWhr in New York [40]. The increased value of distributed generation may result in it being attractive to the consumer. However, it also requires that someone, probably an independent power producer, purchase or lease equipment, and provide for the operating and maintenance costs. It requires open access to the grid and rules that allow excess power when it is generated to be sold back to the utility, called net metering. These added complications may make demand-side generation unattractive to all but green-power providers and the most aggressive or larger users.

Remote Markets. Remote power is installed at locations far from the grid. This could be for limited applications in developed countries or for village power in developing countries where national electrical power grids are not developed. The requirements for remote power vary with the application, but include some combination of reliability and ease of maintenance and repair. Consequently, even though these potential markets represent a high value, they will be open to Dish-Stirling systems only when the system reliability exceeds a minimum threshold, probably on the order of one-year mean time between failure. Several propri-

Table 4 Cost Projections for Dish-Stirling Systems

Build Rate and O&M	Costs ($US/kW)
5 MW/yr	3000–5000
50 MW/yr	2000–3000
O & M Cost @50 MW/yr	0.01–0.02/kWhr

etary studies of remote and village power markets suggest that the market size is in excess of tens of gigawatts with the potential to be much larger if the reliability of the systems is high and cost is low. Applications for these systems include power for villages, water pumping and, in some desert areas, desalination of brackish water. This market segment may represent the highest value and, ultimately, may be the largest segment available to Dish-Stirling systems.

Bulk Power Markets. To compete in bulk power markets, which are the lowest-cost, highest-volume energy markets, the LEC from Dish-Stirling systems will have to compete with gas turbine power generation and/or combined-cycle plants where the current costs are typically quoted as 3–4.5¢ US/kWhr. Bulk power will become a market for Dish-Stirling as production costs drop even further and when base load energy costs increase due to carbon taxes and the cost of implementing emission controls.

Near-Term Opportunities. There are two near-term opportunities for deployment of Dish-Stirling systems one in the U.S. and one in Spain. The U.S. deployment is being sponsored by the U.S. Department of Energy's Concentrating Solar Power Program. It has an anticipated release date of May–June 2002 and will be for 1 MW of Dish-Stirling systems in Southern Nevada [5]. There is not much information available on this project at this time. The project is expected to require three years to complete and cost between $12–14 million US. The plant is to be operated like a conventional power plant with the operating and maintenance costs paid by the power purchase agreement.

In 1998, the Spanish Ministry of Industry and Energy developed legislation to promote energy production from renewables, waste, and cogeneration. Since then there have been discussions regarding the size of the subsidy and the eligible technologies. A royal law finalizing the legislation is expected to be enacted during the summer of 2002. The pending legislation is for a subsidy of 0.12 EURO/kWhr resulting in an electricity price of 0.156 EURO/kWhr (11 and 14¢ US/kWhr, respectively) for solar-only electricity generating systems at power levels of 5 kW up to a maximum of 50 MW. The solar power producer will deliver electricity to the local utility and be reimbursed according to the actual price of electricity plus the subsidy. The amount of the subsidy will be reevaluated every four years. Several companies and consortia are ready to start erecting solar power plants, once the final amount of subsidy is determined.

For reliable Dish-Stirling systems that have *reasonable* production costs, the Spanish subsidy should be very attractive. Even though Spain has a well developed electricity grid, there are some niche opportunities for power production on the Balearic and Canary Islands where small systems could help to increase the capacity of the grids, offsetting the need to build new fossil-fired power plants.

While the current cost of Dish-Stirling systems is about $10,000 US/kW installed, this reflects the one-of-a-kind, hand-built nature of the current design. Even at relatively modest rates of production these costs will easily be 1/3 current costs. Table 4 shows the cost projections of the four manufacturers whose systems are featured in this paper. Even at the relatively low production rate of 50 MW/yr (2,000 25-kW systems or 5,000 10-kW systems) and at an O&M cost of 1–2¢/kWhr, the cost of electricity from Dish-Stirling systems will be 15–20¢/kWhr enabling entry into some village and remote-power markets. As system costs fall and reliability improves, it is reasonable to expect LECs less than 10¢ US/kWhr, which will expand the markets to distributed generation and demand-side applications. The consideration of SBCs, RPS, and other tax incentives serves to reduce the effective LEC even further thereby making power generation from Dish-Stirling even more attractive. As performance increases and costs fall, the cost of power from Dish-Stirling could eventually compete with conventional bulk power generation.

VII Summary and Conclusions

Dish-Stirling systems have successfully demonstrated that they can produce electrical power for extended periods of time. The major technical issue is establishing high levels of system reliability, thereby reducing the operating and maintenance costs. The second barrier to market entry is the initial cost of the systems that, to a large extent, depends on increasing the production levels of components and systems. These two issues are being addressed.

The following summarize the current status of Dish-Stirling system and market development:

1. High-value markets for Dish-Stirling will start to develop as reliability increases and the LEC of energy from the systems falls below 20¢ US/KWhr. As the cost of energy from Dish-Stirling continues to decrease, new markets emerge with even a modest share of these markets representing huge opportunities for sales.
2. Dish-Stirling systems are flexible power generators—they offer high levels of performance, are modular, operate in solar-only and hybrid modes, and have demonstrated grid-connected and stand-alone operation.
3. Four Dish-Stirling system designs, comprising four different solar concentrators and three Stirling engine/generators, are successfully demonstrating technical feasibility of solar power generation using this technology today.
4. One system, the ADDS Mod 2, is demonstrating off-grid operation for water pumping.
5. Like other renewable energy technologies, Dish-Stirling systems require stable, sustainable energy markets that "value" clean energy through green power programs, renewable portfolio standards, etc. in order to find deployment opportunities. The development of these markets has been impeded by the suspension of restructured, market-based programs in some states.

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