Stirling Energy Systems, Inc.

Solar Power Now
The SES Stirling Solar Dish Technology
ABB Sharyland Dedication Seminar
October 11, 2007

Creating a brighter future for humanity through SOLAR ENERGY
CSP or Concentrated Solar Power is gearing up and coming

Deployment will be large-scale, central-station applications (250 to 1000 MW projects)

355 MW built in California in the late 80’s and early 90’s

Recently a 65 MW project completed in Nevada

Rooftop solar plays an important role, but is not the pathway to large-scale solar power generation

Over 35 applications including large PV submitted to BLM for federal desert land in Southern California

Stirling has two projects with Power Purchase Agreements for 900 MW with SDG&E and 850 MW with SCE

Large Central Station CSP deployment is key to meaningful penetration of renewable solar production in the U.S.
Solar Power Now – Available Options

- PV – Both Low Cost Panels and CSP, tracking and fixed
- Solar Parabolic Trough Technology
- Solar Power Tower or Central Receiver
- Stirling Solar Dish
Technological Comparison

Stirling Solar Dish Efficiency vs. Other Solar

<table>
<thead>
<tr>
<th>Efficiency Type</th>
<th>Energy (kWh/m²)</th>
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<tr>
<td>Solar Dish Stirling</td>
<td>629</td>
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<tr>
<td>Central Receiver</td>
<td>327</td>
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<tr>
<td>Parabolic Trough</td>
<td>260</td>
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<tr>
<td>Tracking Photovoltaic</td>
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Source: Southern California Edison and Sandia National Laboratories

Efficiency is key to cost-competitiveness
The SES Stirling Solar Dish Technology
Details of the SES Solar Dish Assembly

- Power Conversion Unit (PCU)
- PCU Boom
- Azimuth Drive
- Elevation Drive
- Mirror Facet
- Box Trusses
- Main Beam
- Hydrogen Storage
- Dish Controller (inside pedestal)
- Pedestal
- Pedestal (inside pedestal)
What is the Solar Powered Generating System?

- 25kW stand-alone solar-electric generating system
- Dish concentrator tracks and focuses the Sun’s energy onto a Solar Receiver in the PCU heating hydrogen gas which in turn powers a Stirling engine
- Operation of the Stirling engine converts thermal energy to shaft power and drives an electric generator producing electricity
- The Stirling engine is a closed system that produces no combustion products and consumes no water and uses only solar energy to produce electricity

Holds the World’s record as the most efficient technology for converting solar energy to grid quality electricity at 29.4%
SES Solar Dish Stirling Operation

- Dish Concentrator Focuses Sun’s Energy on Receiver
- Stirling Engine Converts Thermal Energy to Electrical Energy

Click image to advance animation
The SES Solar Dish Assembly On-Sun
Time-Lapse of Actual Solar Dish Tracking
Early Design Operating Solar Dishes
SES Solar Technology Installed at the SES Model Power Plant in New Mexico
The SES Power Generating System On-Sun at the Model Power Plant in New Mexico
The SES Power Generating System On-Sun at the Model Power Plant in New Mexico
The SES Power Generating System On-Sun at the Model Power Plant in New Mexico
The SES Power Generating System at the Model Power Plant in New Mexico

(0-Degree & Facing North)
Note that the Night Stow and Maintenance Position also faces north in a similar position with the PCU angled downward near the ground (see slide 93)

Wind Stow
(90-Degrees Facing Skyward)
Peak Power When It’s Needed Most

- Predictable “time-of-day” output
- SES Power Generating System provides reliable power when it is needed most
- Deliver periods shown are San Diego Gas & Electric summer weekday periods

Plant Summer Output without Cloud Cover – SES Solar Dish Technology

![Graph showing output as a percentage of full capacity over time of day. The graph is divided into Super Off-Peak, Off-Peak, On-Peak, and Semi-Peak periods. The output varies throughout the day, with a peak in the mid-afternoon.]

SES Solar Dish Stirling – Typical Power Curve

Sandia Model Power Plant Dish 1 Net Power 5/24/06

Time of Day

Solar Insolation (w/m²)

Net Power (kW)
SES Solar Dish technology provides power during sunlight hours year-around.
Modular & Scalable!

- Thousands of the SunCatcher Solar powered generating units can be constructed to comprise a single large-scale electric generating facility.

- Installed dishes can be energized to produce power as they are completed during plant construction.

- Maintenance can be done quickly on individual units with quick change out of power conversion units resulting in high overall availability.
Power Conversion Unit & Stirling Engine System
SunCatcher Power Conversion Unit ("PCU")

✓ The PCU houses the Solar Receiver, Stirling Engine, Generator, Gas Radiator Cooling System and Auxiliaries

✓ The conversion process begins with the Solar Receiver absorbing the focused solar energy in a system of receiver tubes containing hydrogen gas

✓ The hydrogen gas within the solar receiver tubes absorbs the heat from the incoming solar energy raising the pressure in the receiver to approximately 200-bars or 2,900 pounds per square inch

✓ The high pressure hydrogen gas in turn drives the pistons of a high-efficiency, 380 cubic centimeter, 4-cylinder reciprocating Stirling Cycle Engine producing 35 Hp at 1800-rpm

✓ The rotating shaft power produced by the Stirling engine in turn powers an electrical generator producing 25kW at 575 Volt AC / 60Hz of grid-quality electricity

✓ The Stirling Engine is a closed-cycle, sealed system and the hydrogen gas is cooled, compressed and recycled back to the Solar Receiver

✓ The Stirling engine requires no combustion, produces no emissions and consumes no water
The SunCatcher PCU will use the Kockums’ Stirling Engine Design

- SES will use the Kockums’ Stirling Engine design for Solar Two which is the same design used by Kockums in its submarine propulsion system.

- Kockums, a Swedish shipbuilder, is the world’s leader in non-nuclear submarine technology and has over three decades of involvement in the research and development of high performance kinematics Stirling engines. Kockums has developed this engine technology for use as its submarine propulsion system. The Stirling Engine provides an alternative to surfacing and charging batteries with diesel power thereby adding submerged endurance and stealth to its submarines. Kockums has built over eight commercially successful submarines with the Stirling Engine propulsion system.

- The Kockums’ Stirling engine design being used by SES is a proven, highly reliable, efficient, high tech engine with many hours of operating history and testing.
SES Stirling Engine Test Unit

Stirling Engine External Heater
Head Heat Exchanger
Cutaway View of Stirling Engine and Key Components
Power Conversion Unit with Generator
PCU Design Model

- Lift point
- Service Canopy
- Slew Shield
- Aperture
- Swing-out control and power boxes
- Radiators (3)
Exploded View of Power Conversion Unit Components
Expanded View of Power Conversion Unit Components

Stirling Engine Systems
Expanded Views
Stirling Engine with Solar Receiver
Assembled Power Conversion Unit

- Generator
- Stirling Engine
- Solar Receiver Heat Exchanger
PCU Radiator Gas Cooling System

Two Speed High Volume Fan

Commercial Grade Radiator (total of 3 with one on each side and one on bottom)
The hydrogen gas is heated in the Solar Receiver at constant volume to a higher pressure (points 2 to 3).

During the rotating cycle of the Stirling engine, the heated hydrogen is admitted into a cylinder and powers the cylinder piston assembly toward the crankshaft in the power stroke losing pressure (points 3 to 4).

The hydrogen gas is next cooled to a lower pressure at constant volume in the cold end of the engine by the radiator cooling system (points 4 to 1).

At the same time as the power stroke, gas in an adjacent cylinder that has been cooled is compressed and transferred back to the Solar Receiver (points 1 to 2).

The hydrogen gas is next heated in the Solar Receiver repeating the cycle.

The difference between work supplied (expansion) and work performed (compression) provides for a net output that is converted to mechanical motion driving an electrical generator.
Stirling Engine Block With Cylinder Head Removed
Stirling Engine Cylinder Head and One Quadrant of Solar Receiver
Stirling Engine Piston and Internals
Stirling Engine – Side View
Stirling Engine – Bottom View
Stirling Engine – Side View
Stirling Engine – Top View
Gas Management System

Gas Management System Schematic

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<tr>
<td>1</td>
<td>Pressure Transducer (Pmax)</td>
<td>23</td>
<td>Compressor Out Check Valve</td>
<td>A (+15 Mpa, Stirling Engine)</td>
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<tr>
<td>4</td>
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<td>24</td>
<td>Compressor In Check Valve</td>
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<td>5</td>
<td>Pressure Transducer (Ptank)</td>
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<td>External Refill Check Valve</td>
<td>C (Check Valve Block (2 per engine))</td>
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<td>10</td>
<td>Supply Valve</td>
<td>30</td>
<td>Supply Filter</td>
<td>D (Compressor Inle Block)</td>
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<td>11</td>
<td>Dump Valve</td>
<td>31</td>
<td>Dump Filter</td>
<td>E (Distribution Block)</td>
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<td>12</td>
<td>Engine Short Circuit Valve</td>
<td>32</td>
<td>Seal Housing Drainage Filter</td>
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<tr>
<td>13</td>
<td>Compressor Short Circuit Valve</td>
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<td>Compressor Filter</td>
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<td>14</td>
<td>Tank Valve</td>
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<td>15</td>
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<td>Cycle Safety Valve</td>
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<td>20</td>
<td>Min Pressure Check Valve (Supply)</td>
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<td>Compressor/Supply Tank Safety Valve</td>
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<td>21</td>
<td>Max Pressure Check Valve (Dump)</td>
<td>51</td>
<td>Manual Engine Dump Valve</td>
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<tr>
<td>32</td>
<td>Seal Housing Drainage Check Valve</td>
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<td>Note: Dotted lines represent manifold blocks</td>
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</table>

**VALUES**

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Note: Engine Short Circuit Valve (12): No Voltage = OPEN
All other valves: No Voltage = CLOSE
SES Model Power Plant Operating at Sandia

- Located at the NSTTF
- Proving Ground & Showcase
- On-Going System Testing
  - Performance
  - Reliability
  - Systems Integration
- Augmented with Sandia Scientists & Engineers

MPP – A Slice Out of Large-Scale Solar Plant
SES Solar Technology Installed at Sandia
SES Model Power Plant Video
Stirling Engine
SES Solar Dish in Stow for Maintenance
Stirling Engine
SES Key Advantages
SES Solar Technology - Key Advantages

- Cost Competitive in utility-scale Central Station Deployment
- Fuel is Free and Hedges Price Volatility of Fossil Fuel Sources
- Very High Solar-to-Electric Efficiency
  - Over twice that of other Conventional Solar (other technologies require roughly twice the equipment and thus higher cost). Stirling holds the world record for conversion efficiency at 29.4%.
- Provides Peak Power When Needed Most
- Zero Pollution
  - No Combustion Products or Air Emissions
  - No Water Discharge
  - No Hazardous Heat Transfer Fluids
- No Natural Gas Infrastructure Needed or additional Power Generation Facilities
- High Contour Terrain Tolerance = Minimal Land Grading and Flexible Siting
- Very Low Water Use Compared To Other Thermal CSP (< 1%)
- Water is only required for Mirror Washing and No Water is consumed in the Power Cycle
- Uses the Kockums’ Stirling Engine design which is a Highly Reliable, Low Maintenance and Thermodynamically Efficient
- Modular System with High Availability
- Electrical Collection System utilizes Wind Farm Technology and Equipment
SES Technological Advantages

Stirling Solar Dish Efficiency vs. Other Solar

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Source: Southern California Edison and Sandia National Laboratories

Efficiency is key to SES cost-competitiveness
Proven, World-Leading Solar Technology

- Developed by leading solar industry pioneers: Kockums, McDonnell Douglas, Southern California Edison, the Department of Energy, and Sandia National Laboratories
- Proven track record of 20+ years of R&D and testing at a total cost of over $400 million
- World’s most efficient solar generation technology: converting sunlight into grid-quality electricity

Operating History

- **Power Conversion Unit:**
  - 158,000 hrs On-Sun & Test Cell

- **Dish Concentrator:**
  - 100,000 hrs On-Sun

- **Complete System:**
  - 33,000 hrs On-Sun

Equivalent Daily Solar Operation:

- **Power Conversion Unit:** 48 years
- **Dish Concentrator:** 30 years
- **Complete System:** 10 years
Power Conversion Unit (PCU)
Heater Head

- Heater Tubes: 72 Tubes
- Cylinder Housing
- Regenerator Housing
PCU Design Model

- Lift point
- Service Canopy
- Slew Shield
- Aperture
- Swing-out control and power boxes
- Radiators (3)
PCU Design Model

Flip back cover

Swing-out control and power boxes lock in “access” position

Engine
PCU Design Model

Hydrogen Bottle

Generator

(radiators removed for clarity)
Controls Overview

✓ Dish Controls
  • Sun tracking
  • Azimuth and elevation drives
  • 24VDC drive motors
  • Battery system

✓ PCU Controls
  • System starting
  • Engine controls
  • Grid intertie
  • Alarms and Trips

✓ SCADA System
  • Supervisory Control and Data Acquisition
  • Fault logging, P/M indicators
  • Overall system performance
  • Individual dish performance
SCADA Screen Sample – 25kW Dish Stirling Operation Summary
Site Configuration & Solar Field Deployment
Solar Field Consists of 18MW & 24MW Blocks Made up of Three or Four 6MW Groups Each Consisting of 1.5MW Groups (Collection Voltage after 1.5MW Group is 34.5kV)
1.5MW Solar Group Construction and Areas of Disturbance

Paved Arterial Road

LEGEND
- UNPAVED ACCESS ROUTE
- PAVED ROADSWAYS
- SUNCATCHER UNIT
- GROUND GRID CABLE WITH 4" BUFFER
- 200V COLLECTOR CABLE WITH 4" BUFFER
- 34.5kV CABLE WITH 12" BUFFER

NOTES
1. THIS IS A REPRESENTATION OF A 1.5MW SOLAR GROUP. THE 1.5MW SOLAR GROUP WILL BE ARRANGED TO FIT THE CONTOURS OF THE SITE.

2. ONE 1.5MW SOLAR GROUP IS COMPRised OF SIXTY (60) SUNCATCHER UNITS CONNECTED INTO FIVE (5) TWELVE-UNIT GROUPS CONNECTED TO A 600V, 400A COLLECTION PANELBOARD.
Aerial Rendering of a Typical Portion of the Solar Field (SunCatchers Facing Southwest On-Sun)
Proposed Sprung Structures
For Assembly

Engineered Structures:
- Re-locatable
- Designed to meet all seismic, wind and weather conditions
- Reduced construction cost and timelines
Concrete Caisson SunCatcher Foundation (Conventional)
Metal Fin-Pipe SunCatcher Foundation (Under Evaluation)

✓ One of Several Options being studies that do not require Concrete
✓ Engineered to all Seismic, Wind and Soils Conditions
✓ Speed of installation, estimated at less than 30 minutes per foundation
✓ Able to accept SunCatcher load immediately after installation, no concrete curing time required
Computational Fluid Dynamic Modeling of Multi-Dish Array for Wind Effects Analysis

Top View of the 5-by-5 Field

- Wind direction 0
- Wind direction 45
- Wind direction 90
- 56 ft
- 112 ft
Notice that only the first dish is affected by the full wind load and the remaining dishes only encounter the wake flow of the first dish.
Note that the velocity profiles for dishes 3-8 are very similar, i.e. the boundary effect is limited to the first two rows.
Mirror Loading, 0 Degree Wind Direction

Dish Load

Increase in load due to unobstructed wake
**Structural Design Tools**

- **Systems Design Tool**
  - CFD Wind load model
  - FEA structural model
  - CIRCE2 optical model
  - MathCad user interface

- **Provides Structural Designer with True Metric**
  - Deflection impact on flux distribution

- **Empirical Validation of Tools**
  - Fluxmapper
  - Deflection measurements
Systems Design Tools

✓ Field Layout Optimization

✓ Features
  • Row stagger
  • TOD and TOY electricity value
  • Edge effects

✓ Shading Model
  • True dish shape
  • Incorporates real shading performance degradation
  • Input TMY2 or 15-minute Solar 2 data

✓ Results
  • Shade shape validated with hardware

![Energy and Revenue vs. Month]
✓ Optimize aim point using molecular dynamics-like code
✓ Increase output with existing aperture design
  – 1 to 1.5 percentage points performance improvement
✓ Uniformity
  – Reduced quadrant difference from near 100°C to 20°C
  – Increases operating “headroom”
✓ Aperture effects
  – Aperture 7.5” diameter, compared to MDAC at 9.5”
  – Expect 0.5kW additional output
Development Facilities

✓ Model Power Plant – Sandia Site

✓ Engine Test Facility
  • Assembly and documentation development
  • Lamp bank testing (short term)
  • Gas fired testing (long term cyclic)

✓ Electronics Lab: SES Controls Simulator
  • Critical to next-generation software development

✓ Sandia National Laboratories
  • Materials
  • Manufacturing
  • Failure analysis
  • Lightning protection
  • Facilities
FRACAS Implementation Underway

Failure Reporting Analysis and Corrective Action System

XFRACAS Also Includes..

✓ Tracking of part repair/replacement and serialized system configuration management.
✓ Integration with reliability analysis engines including part life calculations, system reliability and reliability growth analyses
✓ Interactive graphical interface.
✓ Web-based- easy access, collaboration and deployment to multiple sites.
✓ Reliability data/history repository
✓ Framework for FMEA and failure analysis.
✓ Flexible and scalable enterprise system.
Commercialization – Testing Overview

• Tests are conducted at various product levels:
  • Component
  • Subsystem
  • System
  • Power Plant

• Types of Testing
  • Proof-of-concept
  • Development/Commercialization
  • Integration
  • Requirements Validation
  • Endurance

• Test Locations
  • Suppliers
  • Sandia National Labs
    • Fossil-fuel fired engine test cell
    • Model Power Plant Dish Stirling units
    • Bench test facilities
  • Stirling Engine Test Cells
## Test Planning – Example

<table>
<thead>
<tr>
<th>Component</th>
<th>Phase 3 Product Definition</th>
<th>Phase 4 Tech Data Package</th>
<th>Phase 5 Test and Readiness</th>
<th>Phase 6 Low Rate Initial Production</th>
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Operations and Maintenance (O&M)

✔ Solar Dish Stirling system and overall power plant are designed to minimize O&M costs
  • Modular design for **Ease of Maintenance**
  • 25kW units in 1.0 – 1.5 MW groups provides **High Availability**
  • Quick R&R with “rotatable” spares **Minimizes “Down-time”**
  • Self-contained vehicles enable **Efficient Maintenance Actions**
  • Power Conversion Unit (PCU) design allows **Low Cost Overhauls**

✔ Overhaul philosophy uses two maintenance levels…
  • Line (field)
  • Depot (on-site repair facility)

✔ Automated monitoring and decision-making systems via SCADA (Supervisory Control and Data Acquisition) provide O&M efficiencies
**Pathway to Commercialization**

**Starting Point**
- 20 Year History
- Development units
  - HB, NV, SA, SNL
- Model Power Plant
  - 6 Systems
  - SES Supply Chain

**Commercialization Program**
- Product Commercialization
- Supply Chain Development
- Expand Company Infrastructure
- Model Power Plant
- 1 MW Pilot Project
- SCE and SDG&E Projects

**Goals**
- US & International Markets
- US Based Supply Chain with Global Reach
- Ultra-Low Cost Systems
- High Volume Manufacturing
- 5,000 MW by 2018

*The Commercialization Program is the pathway to fulfilling production contracts*
High Volume, Low Cost Manufacturing Model

- SES is leveraging potential strategic partners and key suppliers to transform hand-built units into a high performance, low-cost product
- Significant cost reductions are possible based on a learning curve approach widely used in industry

Cost Reduction Drivers:
- Economies of Scale
- Automation
- Simplify product / reduce number of parts
- Off-the-Shelf Components
- Simplify assembly
Keys to Cost Reductions

• **Design Optimization**
• **Maximum Automation** - Invest in Proper Equipment
• Use of **Off-the-Shelf Commercial Hardware** Whenever Possible
• Dedicated **High Volume Manufacturing**
• **Large Central Station Generation Application**
A New Generation of Solar Power

✓ The SES Solar Technology is the world’s most efficient solar technology (conversion of sunshine to grid-quality electricity)

✓ Proven and backed by 20+ years of testing of the Solar Dish Stirling Engine

✓ Launching commercialization phase for high volume production

✓ Leveraging strategic partners and suppliers for low cost manufacturing

✓ Pursuing future siting opportunities for continued growth
Solar Energy is an Abundant, Clean, and Free Resource

**FACT:** 1,750 MW of SES Solar Systems can displace 1.8 million tons of coal consumption per year – reducing CO₂ emissions by 4 million tons.

**FACT:** 13 square miles of SES Solar Systems can produce power equivalent to the Hoover Dam - in an area less than 5% of the size of Lake Mead.
Tour of the SES Model Power Plant at Sandia By President Bush
The Dawn of Efficient Large-Scale Solar Power
“The SES Stirling Technology”
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