Stirling Engines for Low-Temperature Solar-Thermal-Electric Power Generation

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This dissertation discusses the design and development of a distributed solar-thermal-electric power generation system that combines solar-thermal technology with a moderate-temperature Stirling engine to generate electricity. The conceived system incorporates low-cost materials and utilizes simple manufacturing processes. This technology is expected to achieve manufacturing cost of less than $1/W. Since solar-thermal technology is mature, the analysis, design, and experimental assessment of moderate-temperature Stirling engines is the main focus of this thesis.

The design, fabrication, and test of a single-phase free-piston Stirling engine prototype is discussed. This low-power prototype is designed and fabricated as a test rig to provide a clear understanding of the Stirling cycle operation, to identify the key components and the major causes of irreversibility, and to verify corresponding theoretical models. As a component, the design of a very low-loss resonant displacer piston subsystem is discussed. The displacer piston is part of a magnetic circuit that provides both a required stiffness and actuation forces. The stiffness is provided by a magnetic spring, which incorporates an array of permanent magnets and has a very linear stiffness characteristic that facilitates the frequency tuning. In this prototype, the power piston is not mechanically linked to the displacer piston and forms a mass-spring resonating subsystem with the engine chamber gas spring and has resonant frequency matched to that of the displacer. The fabricated engine prototype is successfully tested and the experimental results are presented and discussed. Extensive experimentation on individual component subsystems confirms the theoretical models and design considerations, providing a sound basis for higher power Stirling engine designs for residential or commercial deployments.

Multi-phase Stirling engine systems are also considered and analyzed. The modal analysis of these machines proves their self-starting potential. The start-up temperature, i.e., the heater temperature at which the system starts its operation, is derived based on the same modal analysis. Following the mathematical modeling, the design, fabrication, and test of a symmetric three-phase free-piston Stirling engine system are discussed. The system is designed to operate with moderate-temperature heat input that is consistent with solar-thermal collectors. Diaphragm pistons and nylon flexures are considered for this prototype to eliminate surface friction and provide appropriate seals. The experimental results are presented and compared with design calculations. Experimental assessments confirm the models for flow friction and gas spring hysteresis dissipation. It is revealed that gas spring hysteresis loss is an important dissipation phenomenon in low-power low-pressure Stirling engines, and should be carefully addressed during the design as it may hinder the engine operation. Further analysis shows that the gas hysteresis dissipation can be reduced drastically by increasing the number of phases in a system with a little compromise on the operating frequency and, hence, the output power. It is further shown that for an even number of phases, half of the pistons could be eliminated by utilizing a reverser. By introducing a reverser to the fabricated system, the system proves its self-starting capability in engine mode and validates the derived expressions for computing the start-up temperature.

USA TODAY

January 21, 2008 Monday
FINAL EDITION

Taking on the $olar challenge; **Stirling** Energy works to cut power's notorious cost

BYLINE: Julie Schmit

SECTION: MONEY; Pg. 1B

LENGTH: 1506 words

ALBUQUERQUE -- When the sun breaks through the clouds here, **solar** dish No. 0 springs to action.

Like a giant sunflower, the mirrored face of the 40-foot dish will follow the sun continuously from east to west throughout the day, generating electricity for 10 to 15 homes.

The dish is a prototype for 70,000 that a small Phoenix company hopes to plant on two 7,000-acre **solar** farms in the California desert over the next seven years.

If fully built out, the two **solar** plants will be two of the biggest in the world. Together, they'd almost double the amount of **solar** energy produced nationwide, power 1 million Southern California homes and cleanly generate nearly as much electricity as two smog-producing coal plants.

"This is something that hasn't been done before," says Bruce Osborn, CEO of **Stirling** Energy Systems, the company doing the project. "We're not aware of any showstoppers. ... No fatal flaws."

A 30-employee company that has sometimes struggled to make payroll, **Stirling's** success or failure will have global implications. States and nations want renewable sources of energy to reduce dependence on fossil fuels and to pollute less. **Solar,** the most expensive renewable energy, accounts for less than 1% of U.S. electricity generation.

But given high oil prices and increased concerns over global warming, anything **solar** is hot. **Stirling's** project also aims to commercialize a decades-old technology that is the most efficient at converting sun power to electricity but which has struggled with costs and reliability.

"They clearly have the technology. It's a matter of whether they can get the cost out," says Michael Niggli, chief operating officer of San Diego Gas & Electric, one of the customers **Stirling** hopes to supply.

Stirling's plans are ambitious. Skeptics, which include a co-founder who left in 2000, say the technology may be too costly to produce power at competitive rates.

Stirling's plans call for construction to begin in 2009 for two $1 billion farms on federal land in California's Mojave Desert northeast of Los Angeles and in the Imperial Valley east of San Diego. State and federal regulators still have to approve the plans.

In 2005, Southern California Edison and San Diego Gas & Electric, two of California's biggest utilities, signed contracts enabling them to buy all of **Stirling's solar** power for 20 years. The utilities have pledged to buy 800 megawatts annually with the possible addition of 950 more.

Contract prices weren't disclosed, but **Stirling** officials have said they'd compete with what utilities pay for peak power. That's more than coal, which supplies half the USA's electricity, but less than most **solar** prices.

Stirling's technology is a type of **solar** thermal power, which uses mirrors to concentrate the sun's heat to drive a generator to produce power. The type of **solar** most people know is photovoltaic, in which rooftop panels use semiconductor materials that convert sunlight into electricity.

Solar thermal is well-suited to large-scale production on desert farms where the sun shines almost every day. Consulting firm Cambridge Energy Research Associates says it's likely to be the next high-growth renewable power in the USA. Nearly 5,000 megawatts may go online by 2020, Cambridge says, more than 10 times the amount produced today.

The most prevalent **solar** thermal technology is a "trough" system, in which hundreds of mirrored sun catchers feed one or a few **engines.**

Stirling Energy Systems' technology is different in that each mirrored dish is accompanied by its own **engine. The Stirling engine** was named after the Rev. Robert **Stirling,** a Scottish clergyman, who patented it in 1816 while seeking an alternative to steam **engines** with explosive boilers.

Technology dates to 1980s

Stirling Energy's dish system was initially developed by McDonnell Douglas in the mid-1980s before being sold to Southern California Edison. Edison sold the technology to **Stirling** Energy Systems, which was founded in 1996 to buy it, for less than $300,000, says **Stirling** co-founder David Slawson, 60.

The owner of a massage-therapy college in Oregon, Slawson says he was attracted to the cause of clean energy after waking up one morning, throwing open his window and coughing on fumes. Another **Stirling** co-founder was Harry Braun, author of The Phoenix Project: Shifting from Oil to Hydrogen, a book advocating that the USA shift away from fossil fuels.

Slawson, a political science major with no engineering background, spent much time recruiting investors. Sometimes, he says, cash was so tight he felt like "a robin needing to feed chicks" on paydays.

In 2003, **Stirling** attracted its biggest investor, Robert Nissenbaum, an organic foods pioneer and founding partner of Imagine Foods. "When I got involved, the company had a long way to go," says Nissenbaum, **Stirling** vice chairman, noting that lack of funds had delayed engineering progress. "Since then, we've slowly but surely gotten all the wheels in motion," he says. "We're cautiously optimistic." **Stirling's** chairman is Robert Clark, a former president of AT&T.

Osborn, 52, first worked on **Stirling solar** dish and **engine** technology as a 22-year-old engineer at Ford. He joined **Stirling** Energy Systems in 1999 but left in 2002. Market prospects for **solar** were dim then, he says, and the company wasn't raising enough funds to move forward. He returned in 2004, took the reins from Slawson the next year and watched interest in **solar** rise.

Osborn won't reveal much about **Stirling's** finances except to say that it's raised "tens of millions" over the years and that 2007 was its best fundraising year. He says the company has been "quietly perfecting" its technology with government engineers at Sandia National Laboratories in New Mexico, where dish No.0 and five others have been running for two years.

Sandia and SES engineers have improved the dishes' design, squeezing out 40% of the steel and making them stronger. They've learned optimal spacing to minimize land use but maximize sun collection. The mirrors have survived lightning strikes and bullets.

Osborn agrees cost is **Stirling's** biggest technical challenge. Each hand-built test dish cost $225,000. That needs to drop to less than $50,000, Osborn says.

As an executive at Western Digital, Osborn oversaw products that went from prototype to high-volume manufacturing in a month. **Stirling** plans a "conservative" approach to dish construction, he says. It'll build two more at Sandia this year, two more next year, then 40 in the Mojave. Then, he plans to ramp up to 80 a month, then 80 a day.

Osborn says the modular nature of the system is part of its beauty. Largely built at the factory, each system could be erected in the field by a few workers within hours, he says. Improvements will be put into newer dishes as **Stirling** learns from older ones.

"It's not like you build the shuttle, launch it and it works or it doesn't," Osborn says. "Nothing will stop us cold in our tracks."

Outlook questioned

Whether **Stirling** can produce power at profitable rates remains to be seen. Its two utility customers expect their first power in 2010. Braun left **Stirling** to focus on wind technologies after losing faith that **Stirling** could compete. "It'll be way too costly," he says, given maintenance costs and the cheaper cost of generating power from wind.

Barry Butler, a materials science expert who several years ago worked for a **Stirling** competitor on a similar dish technology, said in written testimony to California energy regulators last year that technology like **Stirling's,** while promising, wouldn't likely be ready for mass rollout until 2020. He says maintenance will drive up **Stirling's** costs while rival **solar** technologies get better and cheaper.

Getting all of **Stirling's** power to consumers may also be difficult. For **Stirling** to get the 900 megawatts to San Diego Gas & Electric, the utility needs a new 150-mile transmission line. Like most power lines, it'll likely prove controversial. Southern California Edison needs to upgrade lines to add **Stirling's** power and what will be produced from new wind farms.

The utilities have agreed to pay **Stirling** so much, leaving it to **Stirling** to produce at a profit. Still, they benefit if **Stirling** succeeds. California requires retail sellers of electricity to secure 20% of their energy in 2010 from renewable sources to avoid possible penalties. The utilities also need power most on hot, sunny afternoons when **Stirling's** dishes will be at their peak.

"The sun is the 'great untapped resource,' says Southern California Edison's Stuart Hemphill, director of renewable and alternative power.

Osborn's heard the naysayers for years. He disputes Butler and Braun, noting that the company has made "substantial progress" since Braun left and since Butler worked on the competing system in 2002.

Of all the renewables, he says, **solar** will be the biggest.

"I guarantee there will be issues and challenges. But that's just part of business," he says.

At least with **solar,** "You don't have to worry about the fuel supply. It's free from the sky."

Company

Minor Terms

- SAN DIEGO GAS & ELECTRIC CO
- SOUTHERN CALIFORNIA EDISON CO

Industry

- SOLAR ENERGY
- ELECTRIC POWER PLANTS
- ENERGY & ENVIRONMENT
- FOSSIL FUEL POWER PLANTS
- RENEWABLE ENERGY
- ELECTRIC POWER INDUSTRY
- NATURAL GAS & ELECTRIC UTILITIES
- SOLAR POWER PLANTS

Minor Terms

- COAL FIRED PLANTS
- COAL INDUSTRY
- ELECTRICITY TRANSMISSION & DISTRIBUTION
- OIL & GAS PRICES
- GLOBAL WARMING

Subject

Minor Terms

- AIR POLLUTION
- GLOBAL WARMING
- SMOG
- APPROVALS

Geography

- CALIFORNIA, USA
- UNITED STATES
- SAN DIEGO, CA, USA

Minor Terms

- LOS ANGELES, CA, USA

People

Minor Terms

- WILLIAM A OSBORN

SUBJECT: SOLAR ENERGY (92%); FOSSIL FUEL POWER PLANTS (90%); ENERGY & ENVIRONMENT (90%); RENEWABLE ENERGY (90%); ELECTRIC POWER PLANTS (90%); **SOLAR** POWER PLANTS (89%); ELECTRIC POWER INDUSTRY (89%); NATURAL GAS & ELECTRIC UTILITIES (89%); ELECTRICITY TRANSMISSION & DISTRIBUTION (77%); COAL INDUSTRY (77%); COAL FIRED PLANTS (77%); OIL & GAS PRICES (74%); AIR POLLUTION (74%); GLOBAL WARMING (71%); SMOG (69%); APPROVALS (60%) ENVIRONMENT; SERIES; **SOLAR** ENERGY

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TICKER: SCE (AMEX) (51%); SDO (AMEX) (53%)

INDUSTRY: NAICS221111 HYDROELECTRIC POWER GENERATION (58%); SIC4911 ELECTRIC SERVICES (58%)

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economy
- Distributed generation
- Biomass

affordable system."

Serial #3 was erected in May 2005 as part of a prototype six-dish model power plant at the Solar Thermal Test Facility that produces up to 150 kilowatts (kW) of grid-ready electrical power during the day. Each dish unit consists of 82 mirrors formed in a dish shape to focus the light to an intense beam.

The solar dish generates electricity by focusing the sun's rays onto a receiver, which transmits the heat energy to a Stirling engine. The engine is a sealed system filled with hydrogen. As the gas heats and cools, its pressure rises and falls. The change in pressure drives the pistons inside the engine, producing mechanical power, which in turn drives a generator and makes electricity.

Lead Sandia project engineer Chuck Andraka says that several technical advancements to the systems made jointly by SES and Sandia led to the record-breaking solar-to-grid conversion efficiency. SES owns the dishes and all the hardware. Sandia provides technical and analytical support to SES in a relationship that dates back more than 10 years.

Andraka says the first and probably most important advancement was improved optics. The Stirling dishes are made with a low iron glass with a silver backing that make them highly reflective —focusing as much as 94 percent of the incident sunlight to the engine package, where prior efforts reflected about 91 percent. The mirror facets, patented by Sandia and Paneltec Corp. of Lafayette, Colo., are highly accurate and have minimal imperfections in shape.

Both improvements allow for the loss-control aperture to be reduced to seven inches in diameter — meaning light is highly concentrated as it enters the receiver.

Other advancements to the solar dish-engine system that helped Sandia and SES beat the energy conversion record were a new, more effective radiator that also costs less to build

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FOR IMMEDIATE RELEASE
November 9, 2004

Sandia, Stirling to build solar dish engine power plant

Goal is to deploy solar dish farms with 20,000 units producing energy

ALBUQUERQUE, N.M. — The National Nuclear Security Administration's Sandia National Laboratories is joining forces with Stirling Energy Systems, Inc. (SES) of Phoenix to build and test six new solar dish-engine systems for electricity generation that will provide enough grid-ready solar electricity to power more than 40 homes.

SANDIA RESEARCHER Chuck Andraka, left, talks with Bob Liden, Stirling Energy's executive vice president and general manager. (Photo by Randy Montoya) **Download 300dpi JPEG image, 'solartalk.jpg', 912K** (Media are welcome to download/publish this image with related news stories.)

Five new systems will be installed between now and January at Sandia's National Solar Thermal Test Facility. They will join a prototype dish-Stirling system that was erected earlier this year, making a six-dish mini power plant producing up to 150kW of grid-ready electrical power during the day.

"This will be the largest array of solar dish-Stirling systems in the world," says Chuck Andraka, the Sandia project leader. "Ultimately SES envisions 20,000 systems to be placed in one or more solar dish farms and providing electricity to southwest U.S. utility companies."

Sandia and SES staff will work together over the next couple of months to assemble the five new state-of-the-art systems.

SANDIA RESEARCHER Chuck Andraka makes adjustments to a Stirling Energy Systems, Inc. solar dish-engine system

Each dish unit, which consists of 82 smaller mirrors formed in the shape of a dish, will be similar to the system installed earlier this year with some modifications tc improve the design. The frame is steel made by Schuff Steel, also of Phoenix, while the mirrors, provided by Paneltec of Lafayette, Colo., are laminated onto a honeycomb aluminum structure invented and patented in the late 1990s by Sandia researcher Rich Diver (6218). The engine will be assembled at Sandia's test facility using parts that were contracted out by SES.

installed at Sandia's National Solar Test Facility earlier this year. Five more will be erected by January as test units.
(Photo by Randy Montoya)
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Once the units are installed, Sandia and SES researchers will experiment with the systems to determine how best they can be integrated in a field, as well as improving reliability and performance.

"It's one thing to have one system that we can operate, but it's a whole other thing to have six that must work in unison," Andraka says.

Each unit operates automatically. Without operator intervention or even on-site presence, it starts up each morning at dawn and operates throughout the day, tracking the sun and responding to clouds and wind as needed. Finally it shuts itself down at sunset. The system can be monitored and controlled over the Internet. Researchers want to make the six systems work together with the same level of automation. The controls and software that perform this integration will be scalable to much larger facilities.

The solar dish generates electricity by focusing the sun's rays onto a receiver, which transmits the heat energy to an engine. The engine is a sealed system filled with hydrogen, and as the gas heats and cools, its pressure rises and falls. The change in pressure drives the pistons inside the engine, producing mechanical power. The mechanical power in turn drives a generator and makes electricity.

The cost for each prototype unit is about $150,000. Once in production SES estimates that the cost could be reduced to less than $50,000 each, which would make the cost of electricity competitive with conventional fuel technologies.

AN ARTIST'S rendering of a field of dish-Stirling engine systems.
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Bob Liden, SES executive vice president and general manager, says solar electric generation dish arrays are an option for power in parts of the country that are sunny like New Mexico, Arizona, California, and Nevada. They could be linked together to provide utility-scale power. A solar dish farm covering 11 square miles hypothetically could produce as much electricity per year as Hoover Dam, and a farm 100 miles by 100 miles in the southwestern U.S. could provide as much electricity as is needed to power the entire country.

"Another application could be to operate as stand-alone units in remote areas off the grid, such as the Navajo reservation, and supply power to one or several homes," Liden says. Stand-alone units have already been demonstrated as an effective means of pumping water in rural areas.

He notes the dish-Stirling system works at higher efficiencies than any other current solar technologies, with a net solar-to-electric conversion efficiency reaching 30 percent. Each unit can produce up to 25 kilowatts of daytime power.

"This is the perfect type of electricity generation for the Southwest," Liden says. "It's a renewable resource, it's pollution free, and the maintenance of a solar farm is minimal."

One of the system's advantages is that it is "somewhat modular," and the size of the facility can be ramped up over a period of time, Andraka says. That is compared to a traditional power plant or other large-scale solar technologies that have to be completely built before they are operational.

The cooperation between SES and Sandia is seen as critical to the success of this technology. This on-site teaming is a new way of doing business in the energy field and is being watched with interest at DOE headquarters, Andraka says. "There is no more effective way of providing technology transfer," he says.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin company, for the U.S. Department of Energy's National Nuclear Security Administration. Sandia has major R&D responsibilities in national security, energy and environmental technologies, and economic competitiveness.

Sandia Media Contact: Chris Burroughs, coburro@sandia.gov, (505) 844-0948

Sandia Technical Contact: Chuck Andraka, ceandra@sandia.gov, (505) 844-8573

Stirling Energy Systems Contact: Robert Liden, rliden@stirlingenergy.com, (602) 957-1818

Major New Solar Energy Project Anno By Southern California Edison and Stir Energy Systems, Inc.

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August 9, 2005

Corporate Comm
(626) 302-2255

ROSEMEAD, Calif., Aug. 9, 2005—Edison International (NYSE:EIX) subsidiary Southern California Edison (SCE), the nation's leading purchaser of renewable energy, and Stirling Energy Systems today announced an agreement that could result in construction of a massive, 4,500-acre solar generating station in Southern California. When completed, the proposed power station would be the world's largest solar facility, capable of producing more electricity than all other U.S. solar projects combined.

The 20-year power purchase agreement signed today, which is subject to California Public Utilities Commission approval, calls for development of a 500-megawatt (MW) solar project 70 miles northeast of Los Angeles using innovative Stirling dish technology. The agreement includes an option to expand the project to 850 MW. Initially, Stirling would build a one-MW test facility using 40 of the company's 37-foot-diameter dish assemblies. Subsequently, a 20,000-dish array would be constructed near Victorville, Calif., during a four-year period.

"At a time of rising fossil-fuel costs and increased concern about greenhouse-gas emissions, the Stirling project would provide enough clean power to serve 278,000 homes for an entire year," said SCE Chairman John Bryson. "Edison is committed to facilitating development of new, environmentally sensitive, renewable energy technologies to meet the growing demand for electricity here and throughout the U.S."

Although Stirling dish technology has been successfully tested for 20 years, the SCE-Stirling project represents its first major application in the commercial electricity generation field. Experimental models of the Stirling dish technology have undergone more than 26,000 hours of successful solar operation. A six-dish model Stirling power project is currently operating at the Sandia National Laboratories in Albuquerque, New Mexico.

"We are especially pleased about the financial benefits of this agreement for our customers and the state," said Alan Fohrer, SCE chief executive officer. "The contract requires no state subsidy and provides favorable pricing for ratepayers because tests have shown the Stirling dish technology can produce electricity at significantly lower costs than other solar technologies."

How It Works

The Stirling dish technology converts thermal energy to electricity by using a mirror array to focus the sun's rays on the receiver end of a

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Stirling engine. The internal side of the receiver then heats hydrogen gas which expands. The pressure created by the expanding gas drives a piston, crank shaft, and drive shaft assembly much like those found in internal combustion engines but without igniting the gas. The drive shaft turns a small electricity generator. The entire energy conversion process takes place within a canister the size of an oil barrel. The process requires no water and the engine is emission-free.

Comparison to Other Solar Technologies

Tests conducted by SCE and the Sandia National Laboratories have shown that the Stirling dish technology is almost twice as efficient as other solar technologies. These include parabolic troughs which use the sun's heat to create steam that drives turbines similar to those found in conventional power plants, and photovoltaic cells which convert sunlight directly into electricity by means of semiconducting materials like those found in computer chips.

Related Facts

- SCE procured more than 13,000 gigawatt-hours* of renewable energy in 2004, more than any U.S. utility and enough to power almost two million homes for an entire year.
- In 2004, more than 18% of the power SCE delivered to the 13 million Californians it serves came from renewable energy sources.
- SCE's current renewable portfolio can deliver 2,588 MW of electricity, including
  - 1,021 MW from wind
  - 892 MW from geothermal
  - 354 MW from solar
  - 226 MW from biomass
  - 95 MW from small hydro.
- Within the next several weeks, SCE will launch its ninth request for offers by independent power producers in the past three years and the third exclusively for proposals by renewable energy providers. These open, competitive solicitations have resulted in 12 new renewable contracts with a maximum potential capacity of 1,630 MW.

*A gigawatt equals one billion watts.

Visuals available at www.edisonnews.com
Under "Press Kits", "Edison, America's Leading Purchaser of Renewable Energy"

- Two 300 dpi photos of Stirling dish
- Two artists renderings, one of the inside of a Stirling engine, the other of a large installation of Stirling dishes
- An animated clip of how the Stirling engine generates electricity
- Time-lapse photography of a Stirling dish tracking the sun from dawn to dusk

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An Edison International (NYSE:EIX) company, Southern California Edison is one of the nation's largest electric utilities, serving a population of more than 13 million via 4.6 million customer accounts in a 50,000-square-mile service area within central, coastal and Southern California.

Stirling Engines

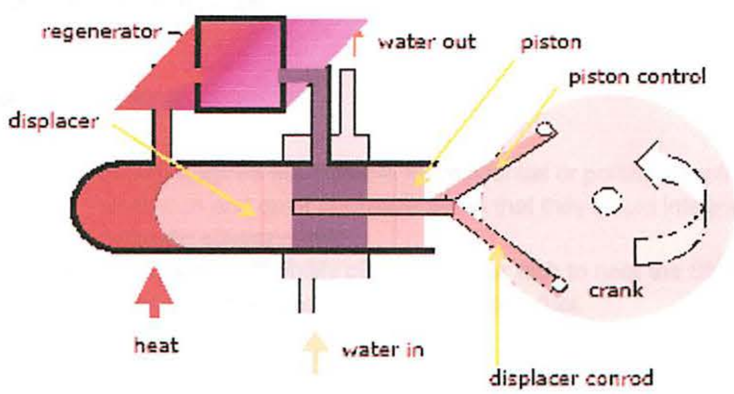
Size Range

1 KW to 25 KW

Technology

The Stirling engine is an external combustion engine allowing, in theory, for a range of fuel sources such as combustible gas or solar energy. The heat supplied to the engine causes the working fluid to expand, moving the piston. A displacer then transfers the fluid into the cold zone of the engine where it is recompressed by the working piston. The fluid returns to the hot region of the engine and the cycle continues (see figure below). The purpose of the regenerator is to capture heat from the working fluid as it moves from the hot to cold part of the engine with the heat being given back to the fluid on its return journey - this reduces the amount of fuel needed to reheat the working fluid. The noise created by a Stirling engine is considerably less than other technologies due to the low number of moving parts and the absence of internal combustion.

Sterling Engine Schematic



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Performance and Efficiency

- High theoretical efficiencies
- Current operational efficiencies 12% to 20%, due to material and design limitations.

Low-Cost Solar-Thermal-Electric Power Generation

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SUMMARY

In this research, we plan to investigate the feasibility of a distributed generation technology based on low-concentration-ratio non-imaging optical concentrators, used in conjunction with moderate efficiency integrated thermal-to-electric energy converters. The latter device is intended to be based on a Stirling engine design incorporating integrated electric generation capability.

We note that flat panel photovoltaic generation technology is available at roughly a cost of $3.7/Watt (thin-film technology in large quantities,) and that it is believed in the energy community that a similar technology offered at roughly $1/Watt would lead to widespread deployment at residential and commercial sites. Thus, a project goal is to consider cost and focus on complete system designs that meet or exceed the cost goal of less than $1/Watt. We believe the cost of the technology based on output power per dollar is the most important parameter, as opposed to efficiency. In contrast, photovoltaic devices based on silicon technology have needed to achieve high efficiency because of the inherent cost of the silicon wafer area.

A low-power single-phase free-piston Stirling engine prototype is designed and fabricated as a test rig to provide a clear understanding of the Stirling cycle operation, to identify the key components and the major causes of irreversibility, and to verify corresponding theoretical models. The prototype incorporates a very low-loss resonant displacer piston subsystem. The displacer piston is part of a

"**Low-Cost Distributed Solar-Electric Technology**," *University of California Energy Institute (UCEI,)* 2002-2003.

Dissertations

Artin Der Minassians, "**Stirling Engines for Low-Temperature Solar-Thermal-Electric Power Generation**," *Ph.D. Dissertation*, Fall 2007. [pdf]

Conference Papers

A. Der Minassians and S. R. Sanders, "**A Magnetically-Actuated Resonant-Displacer Free-Piston Stirling Machine**," *5th International Energy Conversion Engineering Conference and Exhibit (IECEC)*, 25–27 Jun 2007. [pdf]

A. Der Minassians and S. R. Sanders, "**Multiphase Free-Piston Stirling Engine for Solar-Thermal-Electric Power Generation Applications**," *5th International Energy Conversion Engineering Conference and Exhibit (IECEC)*, 25–27 Jun 2007. [pdf]

A. Der Minassians, K. H. Aschenbach, and S. R. Sanders, "**Low-Cost Solar-Thermal-Electric Distributed Generation**," Invited paper for *The International Symposium on Optical Science and Technology, SPIE's 48th Annual Meeting*, San Diego, CA, 3–8 Aug 2003. [pdf]

PRESENTATIONS

"**Stirling Engines for Low-Temperature Solar-Thermal-Electric Power Generation**," Dissertation Talk, 19 November 2007. [ppt]

"**A Magnetically-Actuated Resonant-Displacer Free-Piston Stirling Machine**," 5th International Energy Conversion Engineering Conference and Exhibit (IECEC), 25 June 2007. [ppt]

"**Multiphase Free-Piston Stirling Engine for Solar-Thermal-Electric Power Generation Applications**," 5th International Energy Conversion Engineering Conference and Exhibit (IECEC), 25 June 2007. [ppt]

"**Low-Cost Solar-Thermal-Electric Power Generation**," Boise State

University, 14 November, 2005.

"**Low-Cost Solar-Thermal-Electric Power Generation**," Solar Research Seminar, UC Berkeley, 30 March, 2005.

"**Low-Cost Solar-Thermal-Electric Power Generation**," Ph.D. Qualifying Exam Presentation, EECS Department, UC Berkeley, January 2005.

"**Low-Cost Distributed Solar-Thermal-Electric Power Generation**," The International Symposium on Optical Science and Technology, SPIE's 48th Annual Meeting, San Diego, CA, 3 – 8 Aug 2003. [ppt]

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Stirling Engines

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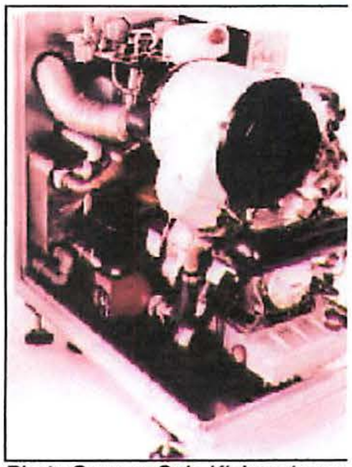
Stirling engine developments have been directed at a wide range of applications, including:

- Small scale - residential or portable power generation.
- Solar dish applications - a renewable application where heat reflected from concentrating solar collectors is used to drive the Stirling engine. Several government-funded programs are aimed at enhancing this application.
- Vehicles - Auto manufacturers along with the U.S. government are investigating utilizing Stirling engines in vehicles.
- Refrigeration - Stirling engines are being developed to provide cooling for applications such as microprocessors and superconductors.
- Aircraft - Stirling engines could provide a quieter-operating engine for small aircraft.
- Space - Power generation units aboard space ships and vehicles.



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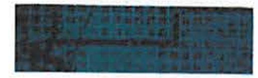

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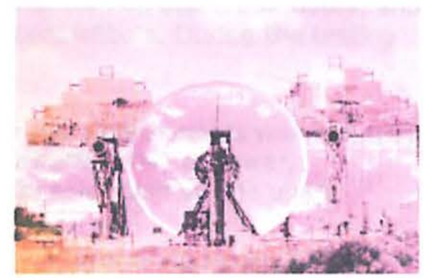
Sandia, Stirling Energy Systems set new world record for solar-to-grid conversion efficiency

31.25 percent efficiency rate topples 1984 record

ALBUQUERQUE, N.M. —On a perfect New Mexico winter day — with the sky almost 10 percent brighter than usual — Sandia National Laboratories and Stirling Energy Systems (SES) set a new solar-to-grid system conversion efficiency record by achieving a 31.25 percent net efficiency rate. The old 1984 record of 29.4 percent was toppled Jan. 31 on SES's "Serial #3" solar dish Stirling system at Sandia's National Solar Thermal Test Facility.



Sandia and Stirling Energy Systems set new world record for solar-to-grid conversion efficiency. The record establishes a new solar-to-grid conversion efficiency of 31.25 percent. The old record, which has stood...
Click here for more information.

The conversion efficiency is calculated by measuring the net energy delivered to the grid and dividing it by the solar energy hitting the dish mirrors. Auxiliary loads, such as water pumps, computers and tracking motors, are accounted for in the net power measurement.

"Gaining two whole points of conversion efficiency in this type of system is phenomenal," says Bruce Osborn, SES president and CEO. "This is a significant advancement that takes our dish engine systems well beyond the capacities of any other solar dish collectors and one step closer to commercializing an affordable system."

Serial #3 was erected in May 2005 as part of a prototype six-dish model power plant at the Solar Thermal Test Facility that produces up to 150 kilowatts (kW) of grid-ready electrical power during the day. Each dish unit consists of 82 mirrors formed in a dish shape to focus the light to an intense beam.

The solar dish generates electricity by focusing the sun's rays onto a receiver, which transmits the heat energy to a Stirling engine. The engine is a sealed system filled with hydrogen. As the gas heats and cools, its pressure rises and falls. The change in pressure drives the pistons inside the engine, producing mechanical power, which in turn drives a generator and makes electricity.

Lead Sandia project engineer Chuck Andraka says that several technical advancements to the systems made jointly by SES and Sandia led to the record-breaking solar-to-grid conversion efficiency. SES owns the dishes and all the hardware. Sandia provides technical and analytical support to SES in a relationship that dates back more than 10 years.

Sandia is a National Nuclear Security Administration laboratory.

Andraka says the first and probably most important advancement was improved optics. The Stirling dishes are made with a low iron glass with a silver backing that make them highly reflective —focusing as much as 94 percent of the incident sunlight to the engine package, where prior efforts reflected about 91 percent. The mirror facets, patented by Sandia and Paneltec Corp. of Lafayette, Colo., are highly

Invited Paper

Low-cost distributed solar-thermal-electric power generation

Stirling Engine

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ABSTRACT

Due to their high relative cost, solar electric energy systems have yet to be exploited on a widespread basis. It is believed in the energy community that a technology similar to photovoltaic (PV), but offered at about \$1/W would lead to widespread deployment at residential and commercial sites. This paper addresses the investigation and feasibility study of a low-cost solar thermal electricity generation technology, suitable for distributed deployment. Specifically, we discuss a system based on nonimaging solar concentrators, integrated with free-piston Stirling engine devices incorporating integrated electric generation. We target concentrator-collector operation at moderate temperatures, in the range of 125°C to 150°C. This temperature is consistent with use of optical concentrators with concentration ratios on the order of 1-2. These low ratio concentrators admit wide angles of radiation acceptance and are thus compatible with no diurnal tracking, and no or only a few seasonal adjustments. Thus, costs and reliability hazards associated with tracking hardware systems are avoided. Further, we note that in the intended application, there is no shortage of incident solar energy, but rather it is the capital cost of the solar-electric system that is most precious. Thus, we outline a strategy for exploiting solar resources in a cost constrained manner. The paper outlines design issues, and a specific design for an appropriately dimensioned free-piston Stirling engine. Only standard low-cost materials and manufacturing methods are required to realize such a machine.

Keywords: Solar Thermal Collectors, Solar Thermal Electricity, Stirling Engine

1. INTRODUCTION

In this paper, we discuss the technical and economic feasibility of a low-cost distributed solar-thermal-electric power generation technology based on the use of a solar thermal collector (STC) in conjunction with a free-piston Stirling engine. The solar thermal collector is to be comprised of low-concentration nonimaging concentrators and absorbers with spectrally selective coatings. The Stirling engine converts moderate temperature heat to electricity by way of integrated electric generation. In spite of its relatively low conversion efficiency, the proposed system can be a cost-effective alternative to solar photovoltaic (PV) modules, as discussed in the sequel.

The system is conceived to operate with collector temperatures in the range of 125°C to 150°C, which is consistent with the use of stationary solar thermal collectors employing low-concentration nonimaging reflectors.[1] Thus, the system avoids the costs and maintenance issues associated with tracking collectors based on high concentration ratio concentrators. However, the use of low temperature heat limits the theoretical maximum thermodynamic efficiency achievable by the heat engine. Although this limits the overall system efficiency, this disadvantage can be compensated for by lower costs in materials and in maintenance.

An operating temperature of 150°C permits a maximum thermodynamic (Carnot) efficiency of 29%, assuming the sink temperature is 25°C. We might reasonably expect the Stirling engine and generator to achieve a thermal-electric efficiency of about 19%, roughly 66% of the Carnot efficiency (see section 3), while the collector operates at a thermal efficiency of about 40%. Thus, the estimated overall efficiency of the system would be about 8%.

We take the view that cost effectiveness of solar electric technologies should be judged by output power per dollar rather than by efficiency or other technical merits. This view reflects the observation that there are

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vast untapped siting opportunities in both urban and rural regions of the world. Research into photovoltaics has been focused on improving efficiency because there has been no significant decrease in the inherent cost of silicon wafer area. However, the proposed solar-thermal-electric system is designed for fabrication out of low-cost materials. A collector is built of glass, aluminum, copper, and insulation, while engines and generators are primarily steel, aluminum, copper, and plastics. In high-volume manufacturing, the cost of the proposed system will be determined by the weight of its bulk materials. This study of solar-thermal-electric systems involves searching for a more cost-effective balance between system efficiency and materials cost.

2. POTENTIAL OF STATIONARY SOLAR THERMAL COLLECTORS AND STIRLING ENGINES FOR LOW-COST SOLAR ELECTRICITY

Table 1 compares efficiency and cost for flat panel photovoltaic technology, tracking parabolic trough collector (PTC) technology, and for the discussed low temperature stationary solar thermal conversion technology. Although a case can easily be made to support the cost effectiveness of a tracking-based system, we note such a technology usually needs to be compared with larger scale utility installations. PV modules do not require diurnal tracking and have a peak efficiency of about 15%.[2] Current prices on PV technology suggest they are cost effective on smaller scales at sites where grid electricity is not available.

2.1. System Cost Analysis

The system cost per watt (CPW) of peak electricity output is an important figure of merit for judging cost effectiveness of investment in an electrical generation system. Since investors prefer a short period after which the revenue from energy sold offsets the initial investment, the output power of the system should be maximized for a fixed capital cost. The cost per unit peak output power of the proposed system, CPW_{sys}, is given by

$$CPW_{sys} = CPW_{eng} + \frac{CPA_{STC}}{G_{peak} \cdot \eta_{sys}^{opt}}, \tag{1}$$

where CPW_{eng} is the engine cost per watt, CPA_{STC} is the collector cost per area (CPA), G_{peak} is the peak solar insolation, and η_{sys}^{opt} is the optimal efficiency of the entire solar-thermal-electric system.

PV modules currently retail for as low as $5 per watt of peak output electrical power.[2] Despite extensive research efforts devoted to increasing their efficiency and lowering their cost, PV modules are unlikely to achieve significant cost reduction due to the cost of silicon. In contrast, solar thermal collectors are primarily comprised of metal formed into simple shapes and coated with appropriate films to reduce optical and thermal losses. One can expect that the cost of collectors and Stirling engine machines will be limited only by material cost in large volume manufacturing. In mature, cost-optimized large-volume industries such as those manufacturing electric motors, automotive parts and other industrial products, the cost of products is proportional to the weight of materials used. Since collectors will dominate the mass of the system, they will dominate the cost of the system in large-scale manufacturing. Assuming that CPW_{eng} is negligible, G_{peak} = 800 W/m^2, and η_{sys}^{opt} = 10%, the collectors for our system must retail for less than \$400/m^2 to match the price of PV technology. A market survey (see Table 4) of stationary collectors for solar heat reveals that several models retail in quantities of 500 m^2 for less than \$200/m^2, independent of performance.[3] Furthermore, the materials cost breakdown shown in Table 2 indicates that a representative collector for hot water can easily undercut this cost requirement considering

Table 1. Comparison of solar electric technologies. PTC price is estimate for 500 m^2 of collector only.

System Type	Efficiency [%]	Temperature [°C]	Retail Price [$/W]
Stationary PV[2]	15	N/A	5
Tracking PTC[3]	20	330	1
Stationary STC	8	150	Unknown

Table 2. Materials cost breakdown of Thermo Dynamics G Series STC.[5]

Collector Material	Mass [kg/m²]	Specific Cost [$/kg]	Cost [$/m²]
Low-Iron Cover Glazing	7.8	1.87	14.60
Sheet Aluminum	2.75	6.00	16.50
Sheet Copper	1.26	6.35	8.00
Fiberglass Insulation	1.2	0.83	1.00
Total	13	N/A	40.10

economies of scale. Note that specific cost of metals is taken from Ref. 4. Based on the materials cost breakdown in Table 2 and a complete system efficiency of 6.9%, the estimated collector material cost is roughly $0.71/W.

The cost of the Stirling engine can be estimated by calculating the mass of materials used in a prototype design (see section 3). We assume the aluminum parts will be cast in mass production, and that the cost of copper heat exchangers used in the design approaches the cost of the wire used to fabricate them. Table 3 shows the cost of materials used in the prototype Stirling engine design. Given the engine design output power of 200 W, the estimated engine cost is $0.31/W considering economies of scale. Note that cost of metals is taken from Ref. 4. Simple design changes can reduce the amount of structural aluminum used and a new aluminum heat exchanger design can reduce the amount of copper used. We predict that the metals content of the engine can be reduced to almost half, which will further reduce the contribution of the engine to the overall system cost. Further, power density can be increased, as discussed in section 3, resulting in additional cost reduction. Thus, an argument can be made for a complete system cost (collector and engine) in the range of $1/W.

2.2. System Efficiency

The efficiency of a solar thermal collector, η_{STC}, as measured experimentally and approximated with a linear temperature dependence near the desired temperature of operation, is given by

$$\eta_{STC} = \eta_0 - \frac{U}{G}(T_m - T_{amb}), \tag{2}$$

where η_0 is the maximum collector efficiency, U is the thermal loss coefficient, G is the power density of incident sunlight, T_m is the mean temperature of the collector in the Kelvin scale (K), and T_{amb} is the ambient temperature in K. Assuming there is no drop in temperature from the collector to engine, the efficiency of the heat engine, η_{eng}, is given by

$$\eta_{eng} = \epsilon_{Carnot}(1 - \frac{T_{amb}}{T_m}), \tag{3}$$

where ϵ_{Carnot} is the fraction of the theoretical Carnot efficiency that the engine achieves. The system conversion efficiency, η_{sys}, is then given by

$$\eta_{sys} = \eta_{STC} \cdot \eta_{eng}. \tag{4}$$

Table 3. Materials cost breakdown of prototype three-phase Stirling engine.

Engine Material	Mass [kg]	Specific Cost [$/kg]	Cost [$]
Cast Aluminum	4.8	5.50	26.40
Copper Wire	3.5	10.00	35.00
Total	6.9	N/A	61.40

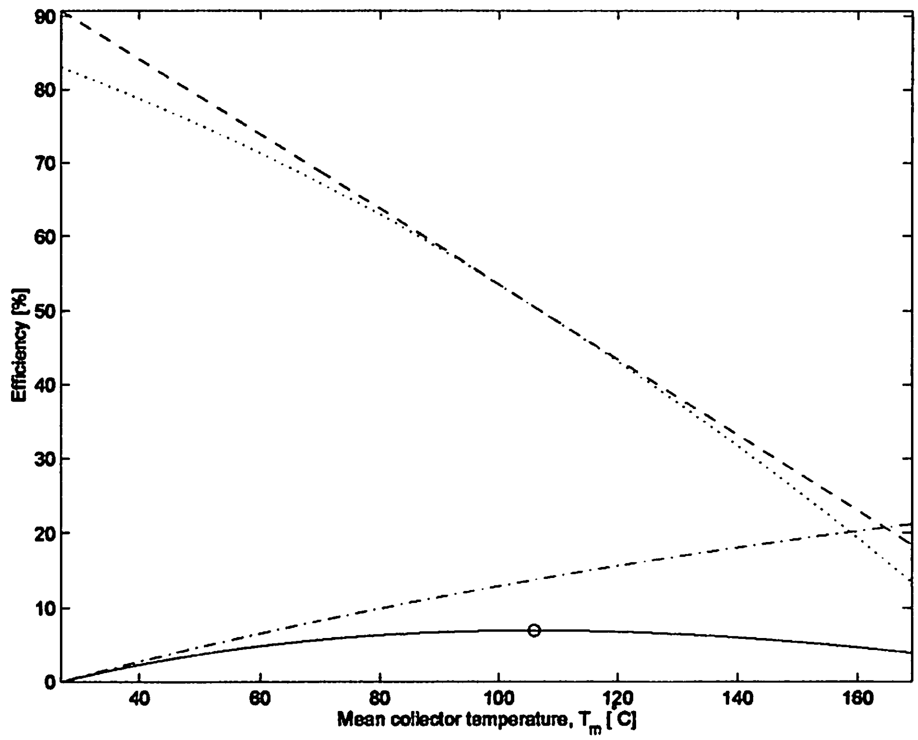

Figure 1. Efficiency as a function of temperature for a representative system. The parameters used are $\eta_0 = 91\%$, $U = 4.080$ W/m^{2}K, $T_{amb} = 27°$C, and $\epsilon_{Carnot} = 66\%$. The measured collector efficiency is in dotted line, the linearized collector efficiency is in dashed line, the engine efficiency is in dash-dotted line, and the system efficiency is in solid line. The circle indicates the point of optimal system efficiency.

The efficiencies of the collector, engine, and system are plotted as a function of temperature in Fig. 1. At optimal system efficiency, the mean absorber temperature, T_m^{opt}, is given by

$$T_m^{opt} = T_{amb}\sqrt{1 + \frac{\eta_0 \cdot G}{U \cdot T_{amb}}} \ . \tag{5}$$

The corresponding optimal system efficiency, η_{sys}^{opt}, is given by

$$\eta_{sys}^{opt} = \epsilon_{Carnot}\left(\eta_0 - \frac{U}{G}\left(T_m^{opt} - T_{amb}\right)\right)\left(1 - \frac{T_{amb}}{T_m^{opt}}\right) . \tag{6}$$

To minimize cost per watt of output electricity, it is desirable to operate a system of given cost at the temperature corresponding to peak system efficiency. This temperature is a function of collector properties as well as ambient temperature and intensity of sunlight. The heat engine can be designed to regulate its loading to maintain optimum collector temperature and system efficiency. It is shown in Fig. 1 that the system efficiency is rather flat over a range of temperatures near the extremum. As ϵ_{Carnot} of a practical heat engine is expected to be closer to unity with higher temperatures, the temperature of optimum system efficiency will be somewhat higher than shown.

2.3. Market Available Collectors

Solar thermal collectors generally consist of a transparent cover and selective absorber surface, under which there is tubing to guide heat transfer liquid and insulation to reduce thermal losses. The solar hot water industry has

Table 4. Comparison of market available STCs. The last four columns, from left to right, are computed using Eqs. (5), (2), (6), and (1), respectively. Assumptions: $\epsilon_{Carnot} = 66\%$, $T_{amb} = 27°C$, CPW_{sys} computed assuming engine cost is zero. All costs are approximated by discounted retail price of 500 m^2 collector area.

Collector Model	η_0 [%]	U [W/m²K]	CPA_{STC} [\$/m²]	T_m^{opt} [°C]	η_{STC}^{opt} [%]	η_{sys}^{opt} [%]	CPW_{sys} [\$/W]
Flat Plate Collectors							
Thermo Dynamics G Series	74	5.247	194	79	40	3.9	6.27
Arcon HT	79	3.796	142	101	44	5.8	3.07
HFE Solar Eurostart Sc	86	5.180	174	87	47	5.2	4.20
Sonnenkraft GK6	88	5.487	145	85	48	5.1	3.52
Solarnetix FC-25	85	4.840	150	91	47	5.4	3.48
CPC-based Collectors							
AOSOL CPC 1.5X	75	4.280	158	90	41	4.7	4.16
SOLEL CPC 2000 1.2X	91	4.080	193	106	51	6.9	3.49

improved upon flat plate collectors by reducing optical and thermal losses by using high transmission covers and selective absorber materials. More recent designs have employed nonimaging compound parabolic concentrator (CPC) reflectors to improve collector performance. For a small sacrifice in maximum collector efficiency due to imperfect reflector surfaces, CPCs effect a reduction in thermal losses in proportion to the concentration ratio. At the higher temperatures produced by concentration, the thermal ineffectiveness of the engine's heat exchangers have less negative effect on the engine efficiency. Furthermore, since the reflector can be much thinner and lighter than the absorber plate it obviates, the collector cost per unit area can be substantially reduced. We envision a system using collectors based on low-cost truncated 2D CPCs with concentration ratio of about 1.5. The large acceptance angle associated with such a CPC will allow for sufficient hours of operation over all seasons without any tilt adjustments. A representative CPC-based collector would be the SOLEL CPC 2000 trough array, for which the concentration ratio is 1.2, η_0=91% and U= 4.080 W/m²K.[6] An ideal heat engine powered by this collector would run at T_m^{opt} = 106°C and η_{sys}^{opt} = 10.5%, whereas a more practical engine would result in perhaps η_{sys}^{opt}=6.9%. Table 4 compares the technical and economic performance of several commercially produced flat plate and CPC-based solar thermal collectors.[3] Although many of these collectors are already shown to be cost-effective at retail prices, the production cost of such collectors is expected to be much lower.

3. STIRLING ENGINE

The Stirling Engine has been in existence for many years, spread over two centuries. The research and development on Stirling cycle machines has been documented in open literature such as Refs. 7, 8, 9 and 10. The Stirling engine converts heat to mechanical power in a manner similar to other mechanical engines, that is, by compressing a working gas when it is cold, heating the compressed working gas, and then expanding it with a power piston to produce work. The Stirling engine works on a closed cycle with a gaseous working fluid that may have a nominal working pressure many times that of atmospheric pressure.[7]

In this paper we focus on free-piston Stirling engines rather than machines incorporating conventional crank mechanisms. Removal of the mechanical crank mechanism reduces frictional losses, complexity, and associated maintenance requirements. Our interest is more narrowly focused on free-piston machines that directly drive electrical generation devices. With this arrangement, we note the following advantageous features. There is no need for any mechanical coupling from the motional elements to the outside of the pressurized container. Thus, there is no emphasis on difficult sealing requirements that have plagued conventional crank mechanism Stirling designs. And, consequently, we anticipate essentially zero leakage of working fluid, allowing long-term maintenance free operation with the fluid pressurized to the level required by the application. A further advantageous

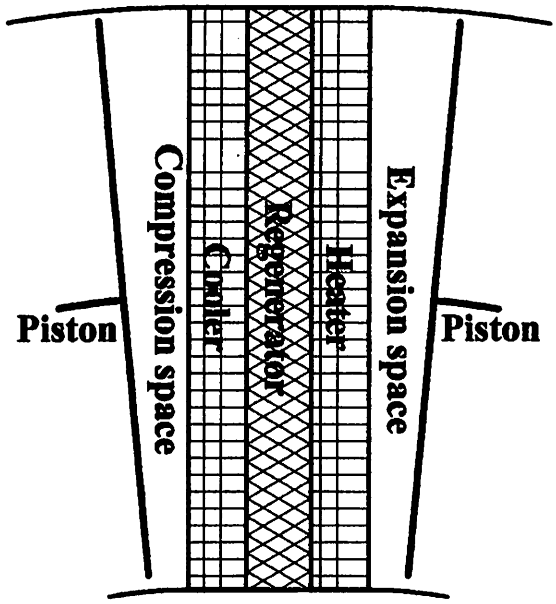

Figure 2. Schematic configuration of an Alpha type Stirling engine.

feature of the machine is that the power piston is actually realized with a flexible diaphragm, rather than with a sliding piston. This feature effectively eliminates leakage around the piston, and most significantly eliminates any need for lubrication, which is again consistent with the need for long-term maintenance free operation.

To the best of our knowledge, all existing free-piston designs are single-acting machines that have an inherent complexity and loss mechanism in the need to drive a displacer piston. Also, all existing double-acting multiple-piston machines incorporate pistons that are mechanically linked with a swashplate or other such mechanical linkage. As such, these machines are capable of delivering relatively high power density, but do not necessarily result in the low-cost low-loss system that we aim to realize.

The use of a multiple-phase, double-acting, free-piston machine has not been reported in the literature. A likely reason for this is the potential difficulty in coordinating the phasing among the pistons. Therefore, we discuss the design and analysis strategies of a multiple-phase Stirling engine system in this section.

3.1. Three-Phase Stirling Engine System Design

Stirling engines are categorized as Alpha, Beta and Gamma type engines.[7] The two latter configurations incorporate a displacer between expansion and compression spaces. Furthermore, in these two configurations, working fluid has to flow through curved passages joining appropriate working spaces. Hence, in order to minimize the fluid flow losses along these curved passages and to eliminate the thermal leakage and mechanical friction losses associated with the displacer, the Alpha configuration, where heat exchangers (heater, cooler and regenerator) are aligned cylinders with the same radii, is considered for the present Stirling engine design, Fig. 2. In this configuration, the pistons have a skewed-phase sinusoidal motion where the efficiency and output power of the engine is a function of the phase delay between compression and expansion spaces.

Since we intend to extend the design to a multiple-phase configuration, we need to select a number of phases that are linked together to form the system. In other words, we need to specify the best phase delay between expansion and compression spaces. Thus, we select the case (among feasible phase delays) that has the highest efficiency. We considered identical operating conditions and performed second-degree (Adiabatic[7]) analysis on a prototype design for phase delay candidates of 60, 90 and 120 degrees which, respectively, are associated with six, four and three phase systems. The results of the mentioned simulations have been compared in Fig. 3 and readily suggest the three-phase engine system as the preferred design.

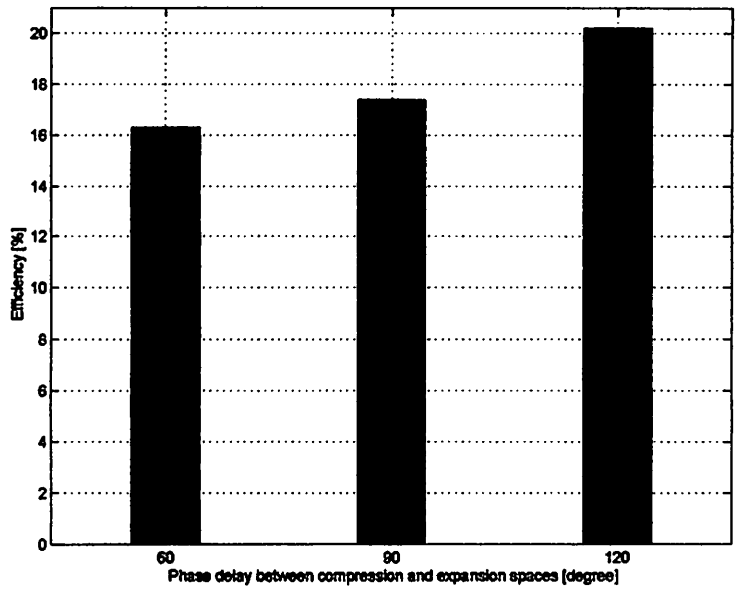

Figure 3. Calculated efficiency versus phase delay between compression and expansion spaces of a single engine for three, four, and six phase Stirling engine systems.

Engine dimensions were chosen based on very simple Beale analysis.[7] We initially intend to use ambient pressure air, which obviates the need for difficult working fluid retaining seals. Operation in the range of 50 Hz is also considered due to the feasibility of achieving a gas-spring-mass resonance in this range, the documented successful Stirling machine work in this frequency range, and the convenience of implementing a simple voice-coil type generator that operates at this frequency. In fact, fluid flow correlation data suggests lower frequencies can lead to higher thermodynamic efficiencies, but at the expense of reduced power output and a more costly generator element.

Dynamic behavior of the three-phase configuration also must be studied to ensure the potential of having expected operating characteristics: symmetrical three-phase steady state operation and self-starting capability. To do so, the first-degree (Isothermal[7]) model of a Stirling engine was reformulated for a three-phase design. Fig. 4(a) shows an eigenvalue plot in the complex plane, with eigenvalues numerically calculated for the linearized three-phase system. The complex pair in the right half plane corresponds to forward three-phase operation in generation mode. Since this mode is unstable, it will spontaneously grow until a loading mechanism (the generator and rectifier system) absorbs mechanical power at the same rate that mechanical power is produced. This is the intended mode of operation. Also of interest is the complex pair of eigenvalues in the left half plane. This pair corresponds to backward three-phase operation where mechanical power needs to be supplied at this resonant frequency to support the motion. This mode corresponds to operation as a Stirling heat pump. The third pair of eigenvalues located directly on the complex axis, correspond to a "zero-sequence" or simple oscillation mode where none of the working gas volumes undergoes any expansion or compression. Rather, each of the gas volumes is simply shuttled back and forth (in phase) through its respective regenerator. Although this latter mode is of no interest from a thermodynamic point of view, it is useful in allowing an independent assessment of fluid flow losses. Fig. 4(b) shows how each piston assembly develops its motion at start-up, whereas Fig. 4(c) displays the motions of the three independent piston assemblies on the same graph during the start-up transient. Convergence to a balanced three-phase steady state operation is illustrated in Fig. 4(d).

3.2. Losses in Stirling Engine

There are a number of loss contributors in a Stirling engine system, including ineffectiveness in the heat exchangers (i.e. the heater, cooler, and regenerator), fluid flow losses in these elements, mechanical friction losses, and

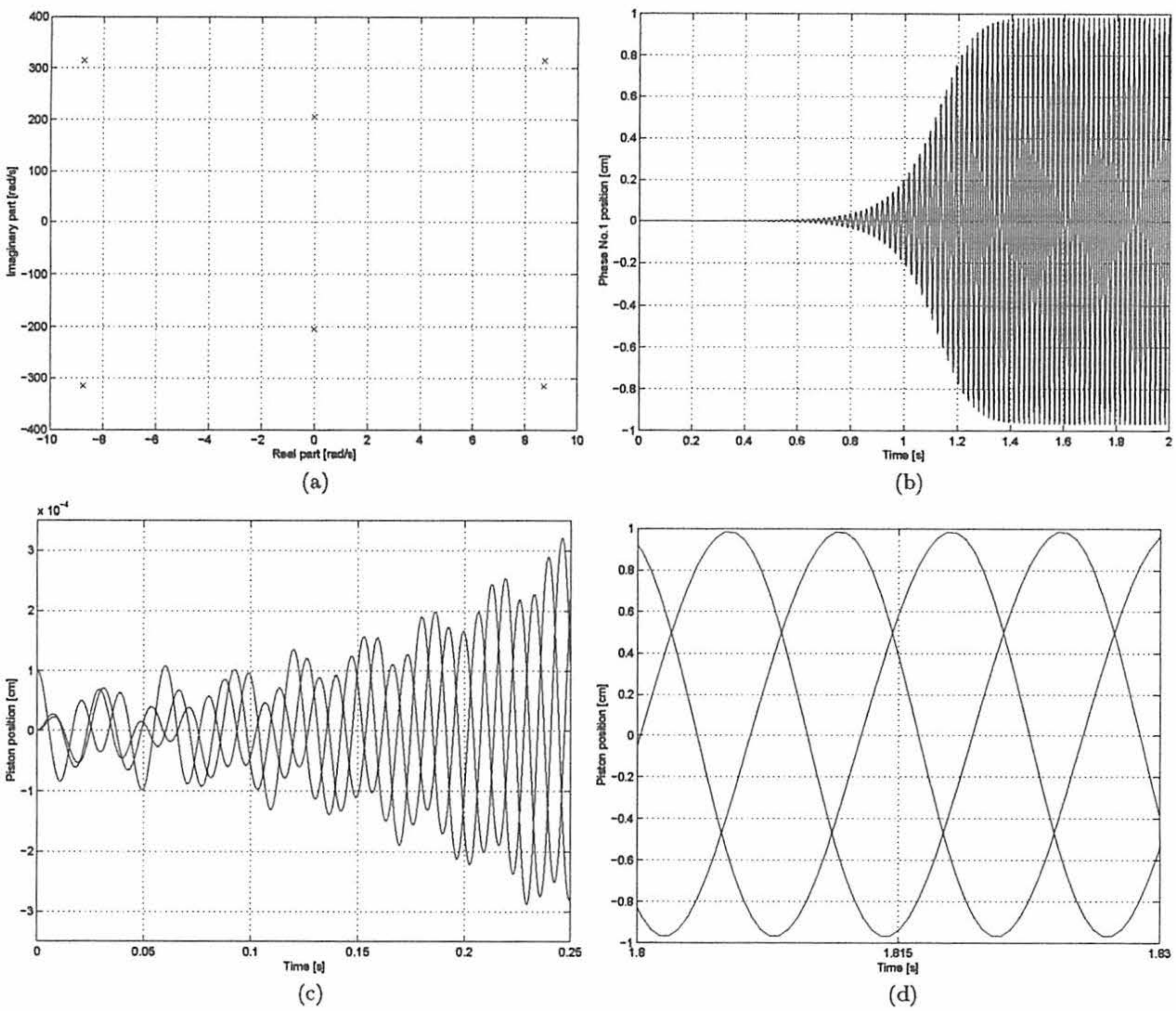

Figure 4. Dynamic simulation of three-phase system. **(a)** Eigenvalue analysis result of the three-phase Stirling engine system. **(b)** Phase No. 1 position. **(c)** System develops its motion starting from a slight perturbation, indicating potential for self-start. **(d)** After startup in (c), system reaches its three-phase steady state operating condition.

static heat loss. Heater and cooler ineffectiveness can be thought of as temperature drops associated with the heater and cooler, respectively, that directly affect system efficiency by degrading the available Carnot efficiency. Regenerator ineffectiveness can be analyzed as a thermal heat loss since it manifests itself in placing extra thermal load on the heater and cooler. On the other hand, fluid flow losses are supplied as a fraction of the available mechanical output power.

Mechanical friction is virtually eliminated by replacing moving pistons by diaphragms. Thus, losses associated with surface-to-surface friction and lifetime limitations associated with mechanical wear are avoided. As a further consequence, it will enable the engine system to self-start upon application of heat.[11] Sudden expansion and contraction is another source of loss that results from unequal heater, cooler, or regenerator diameters.[12] In order to prevent this type of loss, equal-diameter heat exchangers are considered in this design.

Due to the temperature differential from heater to cooler, some heat is lost from the heater by thermal leakage through the regenerator. By increasing the thermal resistance of the regenerator housing, one can minimize this

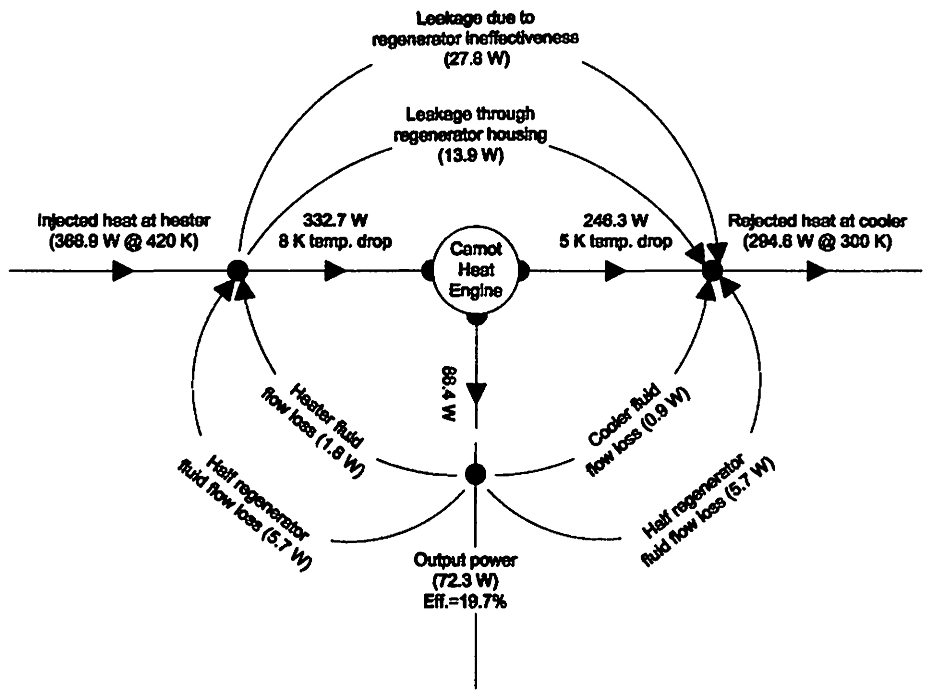

Figure 5. Power balance diagram of the designed Stirling engine.

loss. This can be achieved by choosing a good thermal insulating material for the regenerator housing and by decreasing the housing cross-section to a minimal mechanical dimension. We note that low cost organic materials are appropriate for this low temperature application.

A good heat exchanger should provide enough surface area to transfer the required heat to the working fluid with the least possible temperature drop and, at the same time, introduce the least possible flow friction (or pressure drop) loss. Since these are two competing requirements, a good design of heat exchanger maintains a reasonable balance between temperature and pressure drops. Based on our design criteria, wire screens appear to be the best option for the heat exchangers of the Stirling engine. In this section, we characterize the flow friction and convective heat transfer of such heat exchangers. It is worth noting that the regenerator is a column of woven wire screens with circular cross section, whereas the heater and cooler are columns of stacked wire screens (not woven) with square cross section.

Unfortunately, there is no strong theory behind the flow friction and heat transfer characteristics of wire screen exchangers. Rather, all available data are empirical correlations obtained from experiments on various fluids at various operating conditions. Some of these correlations have been compared in Ref. 13 and updated in Ref. 14. All compared correlations are for steady flow conditions, except the one by Tanaka.[15] In addition to the summary and comparison, output power and efficiency analysis of the GPU-3 Stirling engine has been calculated[13] and compared with the experimental data.[7] The analysis on the GPU-3 engine that is based on the Tanaka correlation is conservative with respect to actual experimental data.[13] That is, the predicted efficiency based on the Tanaka correlation is actually exceeded by the experimental measurement. Furthermore, since the working fluid conditions reported on by Tanaka (e.g. temperature, pressure, fluid type, Reynolds number) fit in the range of conditions for the Stirling engine design discussed here, we have relied on the Tanaka correlations in our design computations.

A spreadsheet calculator has been assembled to help quickly adjust the design parameters of the Stirling engine. Based on a Schmidt analysis,[7] it calculates the injected and rejected heats as well as output mechanical power of an Alpha Stirling engine with specified dimensions, working fluid and phase difference between expansion and compression spaces. It also computes all the above mentioned power losses and temperature drops and adjusts the final results accordingly. Based on the spreadsheet analysis, we expect the three-phase Stirling engine system to produce about 217 W at 19.7% efficiency (that is about 70% of corresponding 28.6% Carnot efficiency). These are the efficiency data referred to previously. Figure 5 shows the power balance diagram of a single Stirling engine in the designed three-phase system. Further, the spreadsheet calculator predicts that output power and efficiency can be increased to 257 W and 19.3% (67% of corresponding Carnot efficiency) by using helium as working fluid. Or, power output can be increased to 2.75 kW at an efficiency of 18.7% by increasing the working fluid (air) pressure to 10 bars.

CONCLUSION

We have outlined a promising case for the use of distributed solar-thermal-electric generation, based on low temperature differential Stirling engine technology in conjunction with state-of-the-art solar thermal collectors. Although the predicted efficiencies are modest, the estimated cost in $/W for large scale manufacturing of these systems is quite attractive in relation to conventional photovoltaic technology. In an on-going program at UC Berkeley, experimentation with representative prototype systems is in progress.

ACKNOWLEDGMENTS

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REFERENCES

1. W. T. Welford and R. Winston, *High Collection Nonimaging Optics*, Academic Press, San Diego, 1989.
2. *Solar Electric Products Catalog: Solar Electric Modules, 10th Edition*, Kyocera Solar, Japan, 2003.
3. H. Schweiger, *The Potential of Solar Heat for Industrial Processes (POSHIP), Final Report, Project No. NNE5-1999-0308*, European Commission - Directorate General for Energy and Transport, European Union, 2001.
4. W. Callister, *Materials Science and Engineering: An Introduction*, Wiley, New York, 2003.
5. *G Series Solar Collectors Technical Specifications*, Thermo Dynamics, Canada, 1999.
6. *SOLEL-CPC 2000, Colector Solar Termico de Concentracion*, Siemens Controlmatic, Barcelona, 2000.
7. I. Urieli and D. M. Berchowitz, *Stirling Cycle Engine Analysis*, Adam Hilger, Bristol, 1984.
8. G. T. Reader and C. Hooper, *Stirling Engines*, E. and F.N. Spon, London; New York, 1983.
9. Walker and J. R. Senft, *Free Piston Stirling Engines*, Springer-Verlag, Berlin; New York, 1985.
10. T. Finkelstein and A. J. Organ, *Air Engines: The History, Science, and Reality of the Perfect Engine*, ASME Press, New York, 2001.
11. R. M. Erbeznik and M. A. White, "Test results and commercialization plans for long life stirling generators," *Proceedings of the 31st Intersociety Energy Conversion Engineering Conference* **2**, pp. 1265–1270, 1996.
12. I. Yamashita and K. Hamaguchi, "Effects of enterance and exit areas on the pressure drop and velocity distribution in regenerator matrix," *JSME International Journal* **series II, vol. 42, no. 3**, pp. 498–505, 1999.
13. B. Thomas, "Evaluation of 6 different correlations for the flow friction factor of stirling engine regenerators," *Proceedings of the 34th Intesociety Energy Conversion Engineering Conference* **no. 01-2456**, 1999.
14. B. Thomas and D. Pittman, "Update on the evaluation of different correlations for the flow friction factor and heat transfer of stirling engine regenerators," *Proceedings of the 35th Intesociety Energy Conversion Engineering Conference* **1**, pp. 76–84, 2000.
15. M. Tanaka, I. Yamashita, and F. Chisaka, "Flow and heat transfer characteristics of the stirling engine regenerator in an oscillating flow," *JSME International Journal* **series II, vol. 33, no. 2**, pp. 283–289, 1990.

Energy Cost Reduction Program

Sterling

Energy Cost Reduction with Optimized Resource Usage
A major university issued a Request for Proposal (RFP) in 2003 to help the Facilities staff manage their energy costs.Sterling Energy submitted a proposal and won the contract to develop a tool in the form of a Microsoft Excel spreadsheet to give the staff the hands-on ability to manage energy costs.The campus energy requirements consist of electricity, heating, and chilling needs. Electricity is provided by two on-site cogeneration units and two Power Purchase agreements (PPAs) with the local utility. Natural gas is provided under two separate contracts with the regional gas utility. The natural gas is used in the cogenerators as well as in stand-alone boilers. Lastly, chilling needs are fulfilled by three banks of electric chillers located on campus.In order to reduce energy costs, the university staff needed a flexible tool to determine the optimum resource mix to serve any given campus load (a combination of electricity, heating, and chilling).Sterling Energy thus created a tool that would provide the optimum mix of cogeneration vs. PPA electricity, boiler heating vs. GT steam, and multi-bank chiller operations. The model output consists of equipment operating levels and power and gas purchase amounts to minimize the hourly variable energy cost.The inputs for this energy “dispatch” model are the following:

- Technical data: This data includes the relevant performance specifications of the cogeneration units, boilers, and chillers
- Contract data: PPA electricity pricing as well as natural gas tariffs are the primary inputs. However, all other variable operating costs are included here.
- Availibility and load data: This includes instantaneous resource availability (from 0 to 100% for each component) as well as the energy needs on the campus.The model was designed for hands-on use by the staff who need not be thoroughly versed in either spreadsheet use or all aspects of energy management. This is achieved by:
- Employment of a graphical user interface such that energy usage, flows, and costs are related to the campus geographical sources and uses of electricity, heat, and chilling.
- Model layout in a “compartmentalized” fashion such that each of the required input disciplines is concentrated in print-scaled areas for quick editing/updating.The model determines the optimum mix of resources by first determining the total variable operating cost under each of dozens of scenarios (representing all operating resource mix possibilities). Then these scenarios are ranked by operating cost, and the lowest-cost scenario is returned in the form of an operating profile.Furthermore, the operating profiles may be scrolled through from best to worst to illustrate the cost benefits of one resource mix as compared to other possibilities.The spreadsheet is relatively compact (on the order of 500 kb) and operates without the use of macros or databases so that it may also serve as a foundation for the development of future applications:
- A “real-time” controls system such that current energy use can be monitored and fed directly into the spreadsheet code to constantly update optimum operations
- A long-term energy cost management model which will forecast energy cost on an hourly/monthly/annual basis. This will allow for budgeting as well as benchmarking or economic analysis of capital spending projects.

Location: Major University
Project Description: Energy Resource Management
Delivered Product:Client-based program to manage and analyze campus energy costs

Welcome to the California Energy Commission

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DER Equipment

Stirling Engines

Capital costs of Stirling engines are relatively high ($2,000-$50,000/kW), and are generally not cost competiti other DER technologies. Stirling engines are manufactured in very low quantities which results in the high cap cost. At the high end of the cost range are Stirling engines for very specialized (e.g., space) applications. Developers are working to lower first costs through a combination of design refinements and material substitu

Reducing the cost of Stirling engine technologies has been a focus of ongoing research due to a number of material-related issues specific to the design architecture. Among these are:

- High temperature heater head assemblies require large surface areas, and must be made from exotic materials that are particularly difficult to machine, braze and weld.
- The cooler section also requires large surface areas to allow for sufficient heat transfer with minimal v volumes.
- The regenerator assembly has a need for very fine mesh heat-transfer matrices that can operate near heater head temperatures, and therefore requires high-temperature materials.
- Shaft-seal assemblies separating the high-pressure hydrogen working space from the lubricated drive are expensive to machine due to the seal complexity and very tight tolerances.

Page Updated: January 18, 2002

Stirling Energy Systems
etc.

Dear Sirs:

Do you have plans to offer your "SES Sun Catcher" solar dish and Stirling energy systems at "retail" quantities of 10 – 100 in the next couple of years? You are clearly directing most of your efforts to your large scale "solar farm" projects on gigawatt scales. However your system is particularly attractive for "scaling down", unlike your competitors AUSRA etc. which require steam turbines and other large scale components.

I am a member of a Gunnison County committee on carbon emission reduction sponsored by ORE (Office of Resource Efficiency) , a local non-profit supported by Gunnison local governments. In discussions the idea of local energy generation has come up several times, as well as the usual efficiency/conservation measures. In fact moderate scale hydroelectric power generation (a few megawatts) is being considered for the Taylor reservoir in the county. However photovoltaic power, the usual "demonstration" project for local generation, is still quite expensive. If your system can be run effectively at a total of from less than a megawatt to a few megawatts we would be very interested in more information about the possibility of a small "farm" or even perhaps an initial demonstration of one or two units. The self contained electricity source and no need for water cooling are very attractive. (Air cooling may be a matter of concern at our high altitude of 8000 – 10,000 ft. but on the other hand our air is relatively cool in the daytime even during the summer.)

We would appreciate any information, even fairly rough estimates, about the cost and when these generators might become available at this scale. I would think the scalable feature would lead to a market for your products you might find interesting!

D. McLeod
etc.

Stirling Engine capital costs ($2,000 to 50,000 /kW)

Average Home Electrical Usage
under 9000 kWh a year. 750 kWh per month
24.38 kWh a day
Space heating 48%

725 kWh per month

Colorado Energy Usage per capita
10,463 871.9 kWh per month.

Homes - poor construction
$/ft²/yr
$.60 at 3.7 cents/kWh
at $1.25/ft²/year for 1,500 sq/ft = $1,875

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Stirling Engines for Low-Temperature Solar-Thermal-Electric Power Generation

Artin Der Minassians

Electrical Engineering and Computer Sciences
University of California at Berkeley

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Stirling Engines for Low-Temperature Solar-Thermal-Electric Power Generation

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Figure 1.8: Solar Dish-Stirling system. Image courtesy of Stirling Energy Systems (SES).

concentrator must track the sun in two axes. Tracking in two axes is accomplished in either azimuth-elevation tracking or polar tracking [15]. In azimuth-elevation tracking, used for larger systems, the dish rotates in a plane parallel to the earth (azimuth) and in another plane perpendicular to it (elevation). In the polar tracking method, used for the smaller systems, the collector rotates about an axis to the earth's axis of rotation. The collector rotates at a constant rate of 15°/hr to match the rotational speed of the earth. The other axis of rotation, the declination axis, is perpendicular to the polar axis. Movement about this axis occurs slowly and varies by ±23.5° over a year. Tracking should be performed with a high degree of accuracy in order to achieve high efficiencies.

At the focus is a receiver which is heated up to over 700 °C. The absorbed heat drives a thermal engine which converts the heat into motive energy and drives a generator to produce electricity [15, 22]. The solar-to-electric conversion efficiency of dish-engine systems can be as high as 30%, with large potential for low-cost deployment. For the moment, the

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SOLAR STIRLING POWER SYSTEMS

LINKS TO SOME USEFUL SOLAR WEB SITES

1. A very interesting Compendium of Solar Dish/Stirling Technology issued by Sandia National Laboratories, Alberquerque, can be found at **http://solstice.crest.org/renewables/dish-stirling/**

2. Sandia National Laboratories can be found at **http://www.sandia.gov/**

3. Information on joint venture between Science Applied International Corporation (SAIC) and Stirling Thermal Motors, Inc. (STM) can be found at **http://www.saic.com/energy/solar/**

4. Information on the Solar research complex at Almeria, Spain, can be found at **http://psaxp.psa.es/welcome.html**

5. Information on the National Renewable Energy Center at Golden, Colorado, can be found at **http://www.nrel.gov/**

6. Bomin Solar Research

7. The German company Sunmachine

8. Information on a proposed low temperature solar Stirling cycle engine can be found at **http://members.tripod.de/PeterFette/index.html**

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NEWS RELEASES

FOR IMMEDIATE RELEASE
February 12, 2008

Sandia, Stirling Energy Systems set new world record for solar-to-grid conversion efficiency

31.25 percent efficiency rate topples 1984 record

Sandia and Stirling Energy Systems set new world record for solar-to-grid conversion efficiency. The record establishes a new solar-to-grid conversion efficiency of 31.25 percent. The old record, which has stood since 1984, was 29.4 percent. (Photo by Randy Montoya)
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ALBUQUERQUE, N.M. —On a perfect New Mexico winter day — with the sky almost 10 percent brighter than usual — Sandia National Laboratories and Stirling Energy Systems (SES) set a new solar-to-grid system conversion efficiency record by achieving a 31.25 percent net efficiency rate. The old 1984 record of 29.4 percent was toppled Jan. 31 on SES's "Serial #3" solar dish Stirling system at Sandia's National Solar Thermal Test Facility.

The conversion efficiency is calculated by measuring the net energy delivered to the grid and dividing it by the solar energy hitting the dish mirrors. Auxiliary loads, such as water pumps, computers and tracking motors, are accounted for in the net power measurement.

"Gaining two whole points of conversion efficiency in this type of system is phenomenal," says Bruce Osborn, SES president and CEO. "This is a significant advancement that takes our dish engine systems well beyond the capacities of any other solar dish collectors and one step closer to commercializing an affordable system."

Serial #3 was erected in May 2005 as part of a prototype six-dish model power plant at the Solar Thermal Test Facility that produces up to 150 kilowatts (kW) of grid-ready electrical power during the day. Each dish unit consists of 82 mirrors formed in a dish shape to focus the light to an intense beam.

The solar dish generates electricity by focusing the sun's rays onto a receiver, which transmits the heat energy to a Stirling engine. The engine is a sealed system filled with hydrogen. As the gas heats and cools, its pressure rises and falls. The change in pressure drives the pistons inside the engine, producing mechanical power, which in turn drives a generator and makes electricity.

Lead Sandia project engineer Chuck Andraka says that several technical advancements to the systems made jointly by SES and Sandia led to the record-breaking solar-to-grid conversion efficiency. SES owns the dishes and all the hardware. Sandia provides technical and analytical support to SES in a relationship that dates back more than 10 years.

Sandia is a National Nuclear Security Administration laboratory.

Andraka says the first and probably most important advancement was improved optics. The Stirling dishes are made with a low iron glass with a silver backing that make them highly reflective —focusing as much as 94 percent of the incident sunlight to the engine package, where prior efforts reflected about 91 percent. The mirror facets, patented by Sandia and Paneltec Corp. of Lafayette, Colo., are highly accurate and have minimal imperfections in shape.

Both improvements allow for the loss-control aperture to be reduced to seven inches in diameter — meaning light is highly concentrated as it enters the receiver.

Other advancements to the solar dish-engine system that helped Sandia and SES beat the energy conversion record were a new, more effective radiator that also costs less to build and a new high-efficiency generator.

While all the enhancements led to a better system, one aspect made it happen on a beautiful New Mexico winter day — the weather.

2007 Solar Power Tower, Dish Stirling and Linear Fresnel Technologies Workshop

NREL hosted a concentrating solar power (CSP) technology workshop on March 7, 2007, in Golden, Colorado. It provided:

- An opportunity for industries developing solar power tower, dish Stirling, and linear Fresnel technologies to update attendees on the current status of their technologies
- Input to the U.S. Department of Energy on recommended R&D program directions.

The workshop featured panel discussions and presentations on the following concentrating solar power technologies:

- Central receivers
- Dish Stirling engines
- Linear Fresnel systems

Parabolic trough technology was covered in a separate workshop on March 8-9, 2007.

Note: if a presentation isn't listed below, NREL hasn't received permission to post it.

The following documents are available as Adobe Acrobat PDFs. Download Adobe Reader.

Attendees List: (Excel 77 KB)

Central Receivers

UTC-Molten-Salt Power Towers
Presentation Posted with Permission: (PDF 2.5 MB)
Presenter/Author: Rogers, D. (UTC)

Solar Tres - First Commercial Molten-Salt Central Receiver Plant
Presentation Posted with Permission: (PDF 928 KB)

Presenter/Author: Martin, J. (SENER)

PS 10 and PS 20 Power Towers in Seville, Spain
Presentation Posted with Permission: (PDF 3.5 MB)
Presenter/Author: Osuna, R. (Solucar)

Bright Source Energy - Distributed Power Towers
Presentation Posted with Permission: (PDF 801 KB)
Presenter/Author: Gilon, Y. (Luz2)

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Dish Stirling Engines

Stirling Energy Systems - Solar Dish Stirling Systems Report
Presentation Posted with Permission: (PDF 2.3 MB)
Presenter/Author: Liden, R. (SES)

Dish Stirling Activities at Schlaich Bergermann und Partner
Presentation Posted with Permission: (PDF 2.8 MB)
Presenter: Geyer, M. (SolarPACES)
Author: Schiel, W. (SBP)

Infinia Corporation - Dish Stirling Development
Presentation Posted with Permission: (PDF 5.5 MB)
Presenter/Author: Smith, T. (Infinia)

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Linear Fresnel Systems

Compact Linear Fresnel Reflector
Presentation Posted with Permission: (PDF 565 KB)
Presenter/Author: O'Donnell, J. (Ausra)

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Advisor: Seth R. Sanders

BibTeX citation:

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- Up to 90% efficient with heat recovery.

Fuel Types

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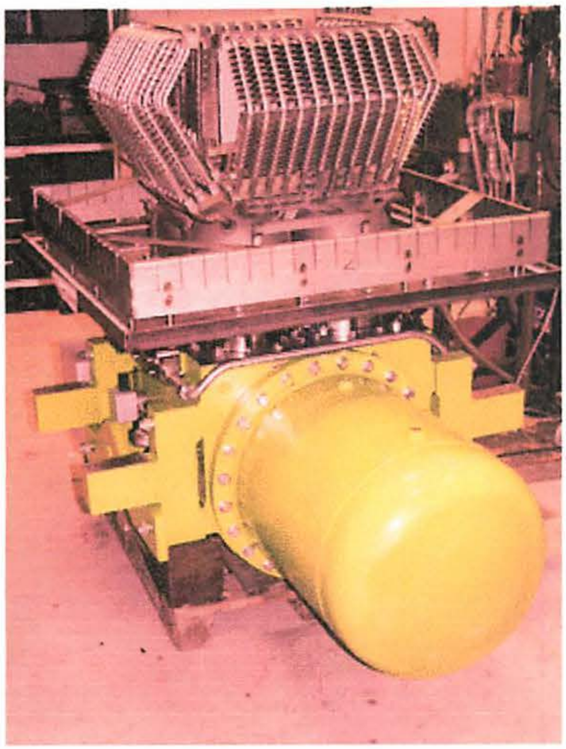

Pictured is a Sterling Engine technology designed to run on biomass.

Source: Stirling Denmark

Application Types

Residential, Rural

- Stirling engines are suitable for residential or portable applications. The small size and quiet operation mean that they would integrate well into a domestic environment;
- There is the possibility of using a solar dish to heat the Stirling engine eradicating the need for combustion of a fuel.

Advantages and Disadvantages

Advantages

- Few moving parts, limiting wear on components and reducing vibration levels;
- Constant burning of fuel as opposed to pulsed

Disadvantages

- High cost and reliability issues;
- Low electrical

combustion reduces noise; efficiency.

- Low emissions of NOx and unburned fuel;
- Fuel versatility.

Economic Performance

Cost Range for Stirling Engines	
Installed Capital Cost ($/kW)	2,000 – 5,000
Operating and Maintenance ($c/kWh)	0.1 – 3.5
Levelized Cost ($c/kWh)	
8000hrs/year	5.0 – 9.5
4000hrs/year	8.0 – 19.0
Source: WADE, 2006	

As with other emerging technologies, the ultimate commercial success of Stirling engines depends upon economies of scale being achieved through mass production. There are a number of material-related issues specific to the design architecture that must be addressed. Once this has been achieved, costs of Stirling engines, and other emerging DE technologies, will fall. The high costs and small size of Stirling engines limits the applicability of this technology in developing regions.

accurate and have minimal imperfections in shape.

Both improvements allow for the loss-control aperture to be reduced to seven inches in diameter — meaning light is highly concentrated as it enters the receiver.

Other advancements to the solar dish-engine system that helped Sandia and SES beat the energy conversion record were a new, more effective radiator that also costs less to build and a new high-efficiency generator.

While all the enhancements led to a better system, one aspect made it happen on a beautiful New Mexico winter day — the weather.

"It was a 'perfect storm' of sorts," Andraka says. "We set the record on Jan. 31, a very cold and extremely bright day, a day eight percent brighter than normal."

The temperature, which hovered around freezing, allowed the cold portion of the engine to operate at about 23 degrees C, and the brightness means more energy was produced while most parasitic loads and losses are constant. The test ran for two and a half hours, and a 60-minute running average was used to evaluate the power and efficiency data, in order to eliminate transient effects. During the testing phase, the system produced 26.75 kW net electrical power.

Osborn says that SES is working to commercialize the record-performing system and has signed power purchase agreements with two major Southern California utilities (Southern California Edison and San Diego Gas & Electric) for up to 1,750 megawatts (MW) of power, representing the world's two largest solar power contracts. Collectively, these contracts require up to 70,000 solar dish engine units.

"This exciting record shows that using these dishes will be a cost-effective and environmentally friendly way of producing power," Osborn says. "SES is actively engaged in the commercialization of the system, called the 'SunCatcher,' including continuing to prepare it for mass production, completing project site development and preconstruction activities, and establishing partnerships with substantial manufacturing and industrial organizations to develop a cost-effective manufacturing process and supply chain. The demonstrated high efficiency means more energy is generated for the given investment, lowering the cost of the energy delivered."

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SES was formed in 1996 to develop and commercialize advanced solar technology. The company maintains its corporate headquarters in Phoenix, Ariz, project and technical development offices in Tustin, Calif, and engineering and test site operations at Sandia National Laboratories in Albuquerque.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin company, for the U.S. Department of Energy's National Nuclear Security Administration. With main facilities in Albuquerque, N.M., and Livermore, Calif., Sandia has major R&D responsibilities in national security, energy and environmental technologies, and economic competitiveness.

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Sandia news media contact: Chris Burroughs, coburro@sandia.gov, (505) 844-0948
SES media relations contact: Lori Hecker, SES@stirlingenergy.com, (602) 957-1818

SMUD - 3.8 Solar Dish Concentrating with Stirling Engine

Energy Production from Renewable Resources Research
>Solar Research

The Problem

Solar-dish Stirling-engine systems concentrate sunlight onto heat powered Stirling engines which then generate electricity. These sun driven electric generators have been under development for the past 10 years by Science Application International Corporation (SAIC) as a contractor to the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories. The barriers to marketability are currently (2001) achieving reliability and cost reductions.

Proposed Research

Science Application International Corporation (SAIC) will continue developing two photovoltaic (PV) solar concentrating systems: 1) a 25 kilowatt (kW) hybrid solar-dish powering an advanced STM Power Stirling engine, and 2) a 20 kW solar concentrating dish (PV) system using a high concentration silicon PV receiver powering a 25 kW Kokums 4-95 Stirling engine. This work expands upon previous SAIC dish-PV programs.

Research Results

Demonstrated the SAIC advanced fixed-focus mirror facet concept by successfully producing and testing facets for both a dish-Stirling and a dish-PV system. Demonstrated the integration and operation of a hybrid solar dish-Stirling power system for electric power generation, and demonstrated improved reliability of this system compared to prior systems. Due to the failure of Arizona system, the Sacramento demonstration was cancelled.

Research Justification and Goals

Adds a project to the Energy Commissions research portfolio that emphasizes innovative energy supply and end use technologies, focusing on their reliability, affordability, and environmental attributes as mandated by the Warren-Alquist Act; and has the potential to enhance the reliability, peaking power, and storage capabilities of renewable energy as mandated by the Warren-Alquist Act by:

- Testing a 25 kW hybrid solar-dish powering an advanced STM Power Stirling engine.
- Testing a 20 kW solar concentrating dish (PV) system using a high concentration silicon PV receiver to power a 25 kW Kokums 4-95 Stirling engine.
- Achieving 25% and 18% solar conversion efficiencies for the respective systems with 90% availability.
- Selecting the system with the most potential for performance and low cost for installation as a demonstration system in Sacramento.

Contractor Sacramento Municipal Utility District

Contract # 500-00-034 Project # 15 (Status: Active)

Site Location Sacramento, CA

Contact Hassan Mohammed M.E., Energy Generation Research Office, Renewable Energy Technologies Program (916) 651-9312

This project is part of the research portfolio of the California Energy Commission. The Energy Commission supports energy research and development that improves the quality of life in California by bringing environmentally sound, safe, reliable, and affordable energy services and products to the marketplace.