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Technical and economical evaluation of solar thermal power generation

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Abstract

This article presents a feasibilty on a solar power system based on the Stirling dish (SD) technology, reviews and compares the available Stirling engines in the perspective of a solar Stirling system.

The system is evaluated, as a parameter to alleviate the energy system of the Cretan island while taking care of the CO_2 emissions. In the results a sensitivity analysis was implemented, as well as a comparison with conventional power systems.

In the long-term, solar thermal power stations based on a SD can become a competitive option on the electricity market, if a concerted programme capable of building the forces of industry, finance, insurance and other decision makers will support the market extension for this promising technology.

Keywords: Technical and economical evaluation; Solar electricity generation; Solar thermal power; Stirling engine

1. Introduction

The electrical generating demand has increased in the island of Crete due to the economic growth during recent years. The rate of this increase becomes dramatical during the summer. Conventional fossil fuel plants generate the electricity and this

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energy production cost is very high (Table 1); this cost can be higher in other Greek islands [1].

The power generation should be increased over the next years in order to satisfy the power demand. The new power plants should be environmentally since there already exist some conventional fossil fuel power plants in the island.

Crete is very rich in renewable energy sources. In this paper the option of the establishment of solar thermal power station based on Stirling dish (SD) technology is evaluated to alleviate the energy system of the island.

The system can be a clean and efficient solution to the major energy problem of the island[2].

2. Solar Stirling engines

2.1. Solar thermal electric technology

Solar thermal electric power generating systems incorporate three different design alternatives:

- Parabolic trough collector: focus systems that concentrate sunlight onto tubes located along the focus line of a parabolic-shaped reflective trough.
- Power tower: focus central receiver systems that use large fields of sun-tracking reflectors (heliostats) to concentrate sunlight on a receiver placed on top of a tower.
- Parabolic dishes: focus dish systems reflect light into a receiver at the dish's focus [3,4].

Exceptional performance (almost 30%) has been demonstrated by SD systems, which belong to the third design type described above [5].

In general, meteorological, operational and demand side conditions are critical

Table 1
Costs of the conventional power supply systems in the island of Crete

Alternative power supply systems	Investment(€/kW)	Operating costs		
		Fuel cost (€/kWh)	O&M variable (€/kWh)	O&M fixed (€/kW/year)
Gas turbines	–	0.118	1.76	26.41
Diesel engines	34.37	0.026	1.17	22.01
Steam units	79.85	0.036	2.05	24.95
GT to CC conversion	50.03	0.079	1.46	17.61

Source: [1].

when comparing the alternative solar power systems directly [6]. The comparison shows that each technology has its strengths and weaknesses, and a final decision on the implementation of a particular project can only be taken by considering the special circumstances at each site [7]. Moreover each technology has advanced variants with different performance and costs [8]. In order to get an overview, a decision maker is forced to consult specialists on each technology.

2.2. Solar Stirling engines

Engine designs for SD applications are usually categorized as either kinematic or free-piston.

- Kinematic Stirling engines: both the power piston and the displacer (or the compression and the expansion pistons) are mechanically (kinematically) linked to a rotating power output shaft.
- Free-piston Stirling engine: they have only two moving parts, the displacer and the power piston, which travel back and forth between springs. A linear alternator is incorporated into the power piston to extract power from the engine. As electricity is generated internally, there is no sliding seal at the high-pressure region of the engine therefore no oil lubrication is required. These designs promise long lifetimes with minimal maintenance requirements.

The technical challenges of the kinematic Stirling engine are sealing problems and complicated power modulation. Sealing problems can be avoided if a rotating alternator is integrated in the crankcase. The power modulation problem can be solved: (a) by varying the pressure level of the working space; and (b) by varying the piston stroke. The second power modulation method requires a mechanism to vary the piston stroke, a so-called swash plate. Varying the angle between the swash plate and the outgoing axis of the engine varies the piston stroke. Each of these power modulation methods results in a complex engine design, which includes a large number of critical mechanical parts [9,10].

Free-piston Stirling engines have the advantages of kineatic Stirling engine, but avoid the technical problems. It can be hermetically sealed, eliminating the need for a working fluid make-up system typical of a kinematic Stirling engines. In addition there is no connection between the power piston and the displacer piston. Both the phase angle between them and the stroke of the power piston are therefore variable and the power developed by the engine depends on both. This means that, in principle at least, the power of the engine could be controlled without having to change the pressure. Therefore, free-piston Stirling engines have simple design [11].

The only disadvantage of the SD system is its cost. However, this cost is less than the cost of a photovoltaic unit and comparable to the cost of parabolic trough systems, which is used commercially in California. Furthermore, the combination of technical improvements and mass production could reduce this cost by over 50% [7].

2.3. The Stirling engine and the environment

The Stirling engine is an environmentally very clean engine, because, when the heat comes from solar energy, the polluting emissions are almost zero. When the heat comes from hydrocarbon (HC) combustion, the emissions are also very low, because the fuel is burnt continuously and at near atmospheric pressure, in remarkable contrast to the interrupted, explosive combustion in petrol and diesel engines with relatively cold walls.

The combustion of fuel in a Stirling engine takes place in a space surrounded by hot walls, under adiabatic conditions. Because of this and because of the latitude in the choice of the air-to-fuel ratio the quantities of the CO produced and of the unburnt HCs are very low. Unfortunately, the more efficient combustion of a Stirling engine results in proportionately more CO_2 being produced than with an equivalent internal engine. However, the CO_2 is one of the most important contributors to the greenhouse effect. Therefore, if the Stirling is to maintain its position as an environmentally friendly engine, then some techniques for removing the exhaust CO_2 must be used.

The preheating of combustion air leads to a high flame temperature (~2000°C), which favors the formation of NO_x, yet these emissions are lower than expected. This is due to relatively short residence time of the gases at the high temperature, lower peak temperatures than in the internal combustion engine and the continuous combustion. The production of NO_x can be reduced more: (a) by recirculating part of the flue gasses along with the incoming combustion air; and (b) by lowering the flame temperature. The Stirling cycle is not effected detrimentally due to the external heating of the engine.

Regarding the emission of toxic or other polluting substances, the Stirling engine is inherently cleaner than all other current heat engines [11].

2.4. Description of the SD solar electric generating system

The SD electric systems, providing net solar-to-electric conversion efficiencies reaching 30%, can operate as stand-alone units in remote locations or can be linked together in groups to provide utility-scale power [12].

Individual units range in size from 10–25 kW. They consist of a solar concentrator, and a power conversion unit located at the focal point of the dish. The unit consists of a cavity receiver and a Stirling heat engine with an electric generator or alternator. The concentrator reflects and concentrates solar radiation, which is then delivered to the receiver. The receiver absorbs concentrated sunlight, transferring its heat energy to a working fluid, in the Stirling engine. The working gas (typically H_2 or He) is alternately heated and cooled. The engine works by compressing the working gas when it is cool and expanding it when it is hot. Expanding the hot gas that is required to compress the cool gas produces more power. This action produces a rising and falling pressure on the engine's piston, the motion of which is converted into mechanical power. An electric generator or an alternator converts the mechanical power into electricity [13].

Solar SD engines have advantages over more conventional power generation options because they:

- produce zero emissions when operating on solar energy;
- operate more quietly than diesel or gasoline engines;
- are easier to operate and maintain than conventional engines;
- start up and shut down automatically; and
- operate for long periods with minimal maintenance.

Solar concentrators used for SD applications are generally point-focus parabolic dish concentrators. Because of the parabolic shape, the dishes have concentrations ratios ranging from 600–2000 and they can achieve temperatures in excess of 1500°C.

The size of the solar collector for SD systems is determined by the power output desired at maximum insolation levels (1000 W/m^2) and the collector and power-conversion efficiencies. With current technologies, a 5 kW SD system requires a dish of *ca* 5.5 m, in diameter, and a 25 kW system requires a dish *ca* 10 m in diameter.

Concentrators can typically account for *ca* 25% of the cost of a SD system. Concentrating reflectors can be divided in three categories as follows.

- Glass-faceted concentrators use spherically curved individually align glass mirror facets, mounted on an approximate parabolic-shaped structure.
- Full-surface parabolic concentrators: the entire surface forms an approximately parabolic shape.
- Stretched-membrane concentrators: can be a single-facet or multifaceted. The designs incorporating thin membranes stretched over both sides of a metal ring. The membranes may be thin plastic sheeting or thin metal sheeting with a reflective coating applied to one of the membranes.

Tracking the sun's path increases the efficiency of the concentrator. There are two ways of implementing this:

- Azimuth-elevation tracking: in which the dish rotates in a plane parallel to the earth (azimuth) and in another plane perpendicular to it.
- Polar tracking method: in which the collector rotates about an axis parallel to the earth's axis of rotation and about the declination axis which is perpendicular to the polar axis.

3. Characteristics of the solar power plant

The design characteristics of a typical system (solar electricity system SD 25 kW) are shown in Table 2 [14].

Important performance advantages of the SD are its ability to operate earlier and later each day and it can also operate on cloudy days when solar energy is <2 kWh/m^2. In addition, due to its low thermal inertia, it can generate power between passing clouds as a photovoltaic unit can. Central receiver and parabolic trough require 1–2 h of steady insolation between clouds for successful start-ups. During

Table 2
Design characteristics of a solar electricity system SD 25 kW

Concentrator	
Glass area	91.01 m^2
Aperture area	87.67 m^2
Focal length	7.45 m
Glass type	No. 82 Commercial grade float. Thickness: 0.7 mm
Radius of curvature	599, 616, 667, 698”
Waviness	<0.6 mr
Reflectivity	>90%
Module dimensions	11.89 mH, 11.28 W
Module weight	6.934 kg
Stirling engine (kinematic)	
Engine dry weight	225 kg
Displacement	380 cc
Engine dimensions	66 cm W, 71 cm H, 58cm L
Number of pistons	4. double acting
Working fluid	H_2 or He
Working fluid pressure	20 MPa
Operating temperature	720°C
Power control	Fluid pressure
Cooling	Water/forced air fan
Output power	27 kW (max), 22 kW (rated)
Rated power efficiency	38–40%
Power conversion unit	
Weight	>680 kg
Alternator	Induction, 1800 rpm
Alternator efficiency	92–94%
Electrical power	480 V, 60 Hz, three phase
Gross power rating	25 kW at 1.000W/m^2
Peak net power efficiency	29–30%
Minimum insolation	250–300 W/m^2
Dimensions	*W*=168 cm, *H*=122 cm, *L*=183 cm

Source: [10].

frequent cloud passes for such systems the start up efforts consume more power would then be generated [15] (Figs. 1 and 2).

The size of the solar power plant for this analysis is 50 MW and it’s going to be located at a region with high solar radiation and low cost of land. The location of the solar thermal power plant for this study will be in southeast side of Crete (Lasithi) (Table 3), where the average annual solar radiation is high (1.728 kWh/m^2) and land cost is low (23.5–29.0 k€/ha).

4. Cost estimation

The selected economic indicators are: the net present value (NPV) and electricity generation cost.

Fig. 1. Stirling Energy Systems, Inc. (SES)/Boeing, 25 kW SD system at sunset. Source: [15].

$$\mathrm{NPV} = (E-O)\frac{1-(1+i)^{-N}}{i}-\mathrm{CC},$$

where E is the annual income, O is the annual operating and maintenance cost, i is the discount rate and CC is the capital cost.

$$\text{Electricity generation cost} = \frac{\mathrm{NPV}}{\text{Total electricity production}}.$$

The energy inflation is considered negligible.

NPV and electricity generation cost are estimated for two different annual production levels of 10 000 and 2000 SD systems (Tables 4 and 5). Other issues, such as siting as well as the optimal solar power plant size, were not covered by the current analysis.

A series of sensitivity analyses is undertaken in order to investigate the magnitude of the effect of the parameters variation on cost calculation. The parameters are:

Fig. 2. McDonnell Douglas (currently Boeing) SD system. Source: [15].

Table 3
Weather conditions in Crete

	Iraklio	Ierapetra	Rethimno	Chania
Annual solar radiation (kWh/m^2) (slope 0°)	1785.4	1728.0	1739.9	1700.6
Annual sunlight (h/year)	2816	3108	2694	2809
Average temperature per year (°C)	19.0	20.0	19.6	18.5

Source: [3].

- system capital purchase price;
- discount rate;
- annual solar radiation;
- lifetime;
- annual efficiency of the system;
- market price of the electricity; and
- size of the power plant.

5. Discussion and conclusions

The technology system, which was described, is a considerable alternative to deal with the energy problems of the island of Crete. It is also essential the timing of

Table 4
Assumptions and data

Annual production rate of SD systems	10 000	2000
Technical data		
Number of units	25	25
Total power (MW)	50	50
Annual solar radiation (kWh/m^2)	1.728	1.728
Annual generated electric energy (MWh)	69.711	69.711
Discount rate	10%	10%
Lifetime (years)	30	30
Sale price of electricity (€/kWh)	0.073	0.073
System purchase price (€/kW)	555[a]	1.611[a]
Fixed cost		
Procurement of equipment (M€)	22.40	64.89
Transport & installation (M€)	3.36	9.73
Land purchase (M€)	1.90	1.90
Earthworks etc (M€)	2.20	9.96
Other costs (M€)	7.46	2.16
O&M		
Labor cost (k€)	2.2	2.2
Consumables (M€)	1.01	1.01

[a] [8].

Table 5
Results

Annual production rate of SD systems	10 000	2000
Electricity generation cost (€/kWh)	0.071	0.178
Net present value (k€)	1.380	−69.479

the high demand (midday, summer) and the high insolation offering a solution during the summer period.

Furthermore the substitution of an imported liquid fuel, the avoidance of the CO_2 emissions, the creation of new jobs and the improvement of the living standard are essential benefits.

According to the results of the above analysis only the massive production of solar Stirling systems could provide a long-term economical feasible solution. The technical and economic evaluation shows that the SD technology offers a technical feasible and economic viable solution under the following conditions (Table 6):

- system purchase price <550 €/kW;
- discount rates $<10\%$;
- long lifetime (>25 years);
- solar radiation >1700 kWh/m^2;

Table 6
Sensitivity analysis

Scenario					
Scenario 1: Variation of system purchase price					
Power of plant (MW)	50	50	50	50	50
Annual solar radiation (kWh/m²)	1728	1728	1728	1728	1728
Annual generated electricity (MWh)	69711	69711	69711	69711	69711
Discount rate (%)	10	10	10	10	10
Lifetime (years)	30	30	30	30	30
Electricity sale price (€/kWh)	0.073	0.073	0.073	0.073	0.073
System purchase price (€/kW)	440	550	660	770	880
Results					
Capital cost (million €)	29.84	37.29	40.69	47.47	54.25
Operating and maintenance cost (million €)	1.012	1.012	1.012	1.012	1.012
Electricity generation cost (€/kWr)	0.060	0.071	0.076	0.087	0.097
Net present value (million €)	8.84	1.38	−2.01	−8.79	−15.57
Scenario 2: Variation of discount rate					
Power of plant (MW)	50	50	50	50	50
Annual solar radiation (kWh/m²)	1728	1728	1728	1728	1728
Annual generated electricity (MWh)	69711	69711	69711	69711	69711
Discount rate (%)	8	10	12	14	16
Lifetime (years)	30	30	30	30	30
Electricity sale price (€/kWh)	0.073	0.073	0.073	0.073	0.073
System purchase price (€/kW)	550	550	550	660	770
Results					
Capital cost (million €)	37.29	37.29	37.29	37.29	37.29
Operating and maintenance cost (million €)	1.012	1.012	1.012	1.012	1.012
Electricity generation cost (€/kWr)	0.062	0.071	0.081	0.091	0.101
Net present value (million €)	8.89	1.38	−4.24	−8.57	−11.95

(*continued on next page*)

Table 6 (*continued*)

Scenario					
Scenario 3: Variation of lifetime					
Power of plant (MW)	50	50	50	50	50
Annual solar radiation (kWh/m^2)	1728	1728	1728	1728	1728
Annual generated electricity (MWh)	69711	69711	69711	69711	69711
Discount rate (%)	10	10	10	10	10
Lifetime (years)	24	30	36	42	48
Electricity sale price (€/kWh)	0.073	0.073	0.073	0.073	0.073
System purchase price (€/kW)	550	550	550	550	550
Results					
Capital cost (million €)	37.29	37.29	37.29	37.29	37.29
Operating and maintenance cost (million €)	1.012	1.012	1.012	1.012	1.012
Electricity generation cost (€/kWr)	0.074	0.071	0.070	0.069	0.069
Net present value (million €)	−0.434	1.380	2.404	2.982	3.309
Scenario 4: Variation of annual solar radiation					
Power of plant (MW)	50	50	50	50	50
Annual solar radiation (kWh/m^2)	1728	1728	1728	1728	1728
Annual generated electricity (MWh)	69711	69711	69711	69711	69711
Discount rate (%)	10	10	10	10	10
Lifetime (years)	30	30	30	30	30
Electricity sale price (€/kWh)	0.073	0.073	0.073	0.073	0.073
System purchase price (€/kW)	550	550	550	550	550
Results					
Capital cost (million €)	37.29	37.29	37.29	37.29	37.29
Operating and maintenance cost (million €)	1.012	1.012	1.012	1.012	1.012
Electricity generation cost (€/kWr)	0.089	0.071	0.059	0.051	0.045
Net present value (million €)	−8.263	1.380	11.023	20.666	30.309

Table 6 (*continued*)

Scenario					
Scenario 5: Variation of annual efficiency of the system					
Power of plant (MW)	50	50	50	50	50
Annual solar radiation (kWh/m^2)	1728	1728	1728	1728	1728
Annual generated electricity (MWh)	55769	69711	83653	97595	1.12E+08
Discount rate (%)	10	10	10	10	10
Lifetime (years)	30	30	30	30	30
Electricity sale price (€/kWh)	0.073	0.073	0.073	0.073	0.073
System purchase price (€/kW)	550	550	550	550	550
Results					
Capital cost (million €)	37.29	37.29	37.29	37.29	37.29
Operating and maintenance cost (million €)	1.012	1.012	1.012	1.012	1.012
Electricity generation cost (€/kWr)	0.091	0.089	0.071	0.059	0.051
Net present value (million €)	−8.263	1.380	11.023	20.666	30.309
Scenario 6: Variation of the electricity sale price					
Power of plant (MW)	50	50	50	50	50
Annual solar radiation (kWh/m^2)	1728	1728	1728	1728	1728
Annual generated electricity (MWh)	69711	69711	69711	69711	69711
Discount rate (%)	10	10	10	10	10
Lifetime (years)	30	30	30	30	30
Electricity sale price (€/kWh)	0.059	0.073	0.088	0.103	0.117
System purchase price (€/kW)	550	550	550	550	550
Results					
Capital cost (million €)	37.29	37.29	37.29	37.29	37.29
Operating and maintenance cost (million €)	1.012	1.012	1.012	1.012	1.012
Electricity generation cost (€/kWr)	0.071	0.071	0.071	0.071	0.071
Net present value (million €)	−8.263	1.380	11.023	20.666	30.309

Table 6 (*continued*)

Scenario					
Scenario 7: Variation of the plant size					
Power of plant (MW)	40	50	60	70	80
Annual solar radiation (kWh/m^2)	1728	1728	1728	1728	1728
Annual generated electricity (MWh)	55769	69711	83653	97595	11153
Discount rate (%)	10	10	10	10	12
Lifetime (years)	30	30	30	30	30
Electricity sale price (€/kWh)	0.073	0.073	0.073	0.073	0.073
System purchase price (€/kW)	550	550	550	550	550
Results					
Capital cost (million €)	29.84	37.29	44.75	52.21	59.67
Operating and maintenance cost (million €)	0.810	1.011	1.213	1.416	1.618
Electricity generation cost (€/kWr)	0.071	0.071	0.071	0.071	0.071
Net present value (million €)	1.121	1.401	1.681	1.961	2.242

- annual generated electricity > 69.711 MWh;
- electricity sale price >0.073 €/kWh.

When the annual rate production of SD systems is low, the establishment of a SD solar power plant is worthwhile on many islands of Greece, which high cost of conventional electricity generation (0.18–0.29 €/kWh). The installation of a solar power plant in Crete is worthwhile only for high production rate of systems. The hybrid solar/fossil-fuel operation makes the system competitive with conventional fossil-fueled power plants in cost terms.

If externalities are included in cost estimation, the cost of electricity will be almost the same for both conventional and solar power generation. Therefore, if external costs are reflected in taxes, the SD system will be commercial.

In long-term period, solar thermal power stations based on a SD can become a competitive option on the electricity market, if a concerted programme capable of building the forces of industry, finance, insurance and other decision makers will support the market extension of this promising technology.

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