# Project Deliverable

| | |
|---|---|
| **Grant Agreement number** | 308952 |
| **Project acronym** | OMSoP |
| **Project title** | Optimised Microturbine Solar Power system |
| **Funding Scheme** | FP7-ENERGY.2012.2.5.1:RESEARCH, DEVELOPMENT AND TESTING OF SOLAR DISH SYSTEMS |
| **Work Package** | WP3 – Techno-economic analysis |
| **Deliverable number - title** | D3.4 Report on state-of-the-art dish-engine applications |
| **Lead Beneficiary** | RO3 |
| **Dissemination level** | PU |
| **Delivery month** | July 2013 |
| **Name, title and organisation of the scientific representative of the project's coordinator** | Abdulnaser Sayma<br>Professor of Energy Engineering<br>City University London<br><br>Tel: +44 (0)20 7040 8277<br>E-mail: a.sayma@city.ac.uk<br>Project website address: www.omsop.eu |

**Contents**

## Introduction

Sun can be seen as a Nuclear Fusion Reactor (NFR), the corresponding energy being delivered into the surrounding as matter and magnetic radiation.
The behavior of the thermal machines is based on thermodynamic cycles that take benefits from the cycle maximum temperature achieved by the working fluid (WF). Thus, the concentration of the solar radiation (energy) is a must to get the technologically possible power from the solar radiation impinging a square meter of reflecting surface.
One of the CSPs that have been studied and developed for terrestrial applications is based on a parabolic dish (Figure 1a) that allows to reach high temperatures concentrating the radiation in a focus.
The Stirling engine, based on volumetric mechanisms, has been the most important candidate to pursue the energy conversion from radiation to heat and electricity. In this way the Dish/Stirling (Figure 1b) has been deeply investigated and it has achieved good thermodynamic performance in comparison with other CSP Systems.
Since the OMSoP Project is aimed at the development of an alternative thermodynamic engine based on turbomachines working according to Brayton Cycle, this report gives the State of the Art of the Dish/Stirling CSP technology, the main achievements and the critical issues.

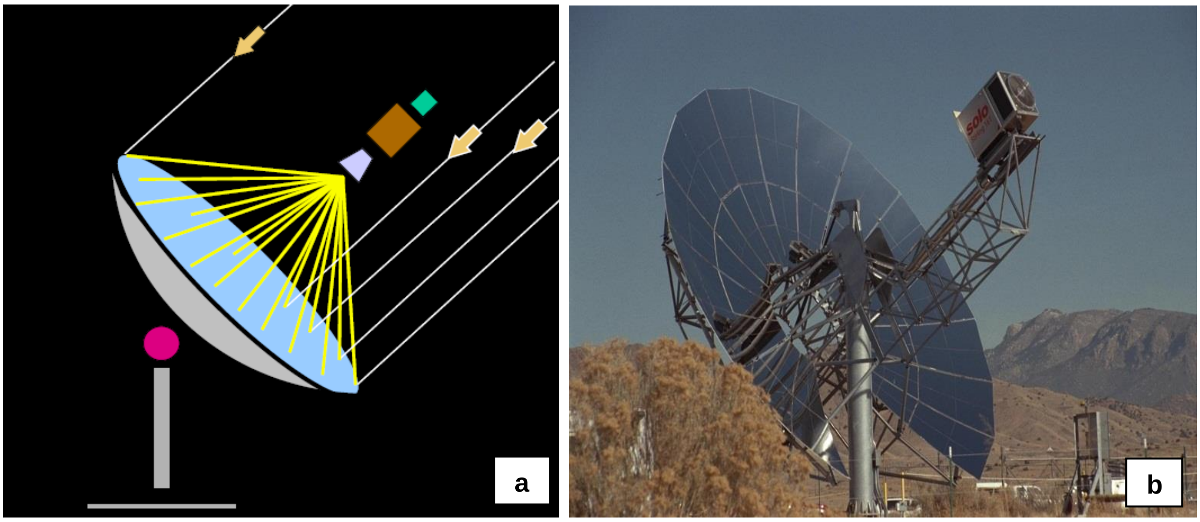



*Figure 1- a) Schematic view of a Parabolic Dish System;*
*b) Example of Dish/Stirling System (SES/SOLO Prototype)*

**Scientific and Technical Background**

The Sun surface temperature is estimated to be around 6000 to 10000 K, the related radiation energy flux being about 63 $MW/m^2$. The energy flux that arrives out of the Earth atmosphere is about 1300 $W/m^2$, the distance from the Sun being $1.5 \cdot 10^{11}$ m. The Sun diameter is about $1.39 \cdot 10^{9}$ m, thus the Sun surface heat flux is about $4.6 \cdot 10^{4}$ times than that out of the Earth atmosphere (Figure 2).
To achieve high temperature by the solar radiation means that it must be concentrated. A theoretical study [1] shows the relationship between achievable temperatures and concentration factors.

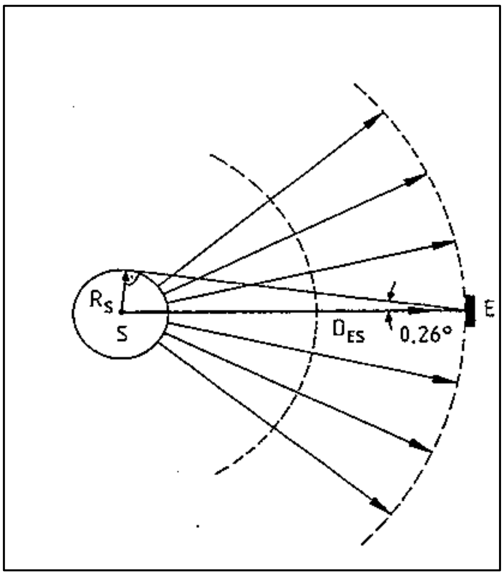



*Figure 2 – Sun-Earth geometry. Assuming a Sun spherical surface of radius Rs,Esc is the Solar Constant observed at distance $D_{ES}$ between Earth and Sun [1].*

For a given concentrator surface, there are various physical phenomena that bound the power of a solar energy fed engine. One of the most relevant is connected with the re-irradiation from the energy receiver.
A black body reaches the maximum temperature re-irradiating all the received energy, thus no energy can be used to feed an engine.
Other losses are related to:

1. Concentrating systems can utilize only direct irradiation;
2. Optical losses (i.e. imperfect reflection, reflector absorption)
3. Atmospheric losses (e.g. beam attenuation by haze or dust under large focal lengths);
4. Spillage losses (e.g. imperfect tracking and beam aiming under windy conditions);
5. The inability of the reflecting surface to concentrate over a small area (receiver opening) all the intercepted radiation;
6. Thermal re-radiation, conductive and convective losses at receiver/absorber device;

Moreover inoperability due to the irradiance that stays below a certain threshold needed for operation has to be taken into consideration.
Figure 3 represents a typical Sankey diagram for a CSP Sun Energy Capturing System.
Thermal machines to convert heat into work take benefits from the high temperatures of the WF heat injection and from the low temperatures of the WF heat rejection. Also the internal sources of entropy connected with irreversibilities play an important role.
The above can be easily summarized [2,3] by:

1. The Carnot Number $\tau = T_{max}/T_{min}$ that is the ratio between the maximum WF temperature ($T_{max}$) and the minimum WF temperature ($T_{min}$);
2. The Thermal Sources Concentration Index $\xi = \xi_n/\xi_p$

   $\xi_p$ being the positive thermal source concentration index that takes into account the WF heat weighted averaged temperature of the positive heat sources that warm up the WF. It is the ratio between Tmax and such a positive heat source average temperature (Th) (i.e. $\xi_p = T_{max}/T_h$)

$\xi_n$ being the negative thermal source concentration index that is the ratio between Tmin and the WF heat weighted averaged temperature of the negative heat sources ($T_c$) that cool the WF (i.e. $\xi_n = T_{min}/T_c$).

3. The Cycle Reversibility Factor $\sigma = \Delta S_n / \Delta S_p$

   $\Delta S_p$ and $\Delta S_n$ being the entropy variations corresponding to the positive addition of heat into the cycle WF and to the negative rejection of the heat from the cycle WF. Such an index, being higher than one takes the cycle irreversibility into account.

The cycle efficiency can be expressed as

$$\eta = 1 - \frac{\sigma}{\tau\xi}$$

T takes the engine technological bounds into account and it is typical of any kind of engine. In particular, for the Stirling engines τ can be up to 3-3.5.
The Concentration Factors ξp and ξn are improved by the internal heat recuperation and become 1 for iso-temperature both positive WF heat injection and negative WF heat rejection.

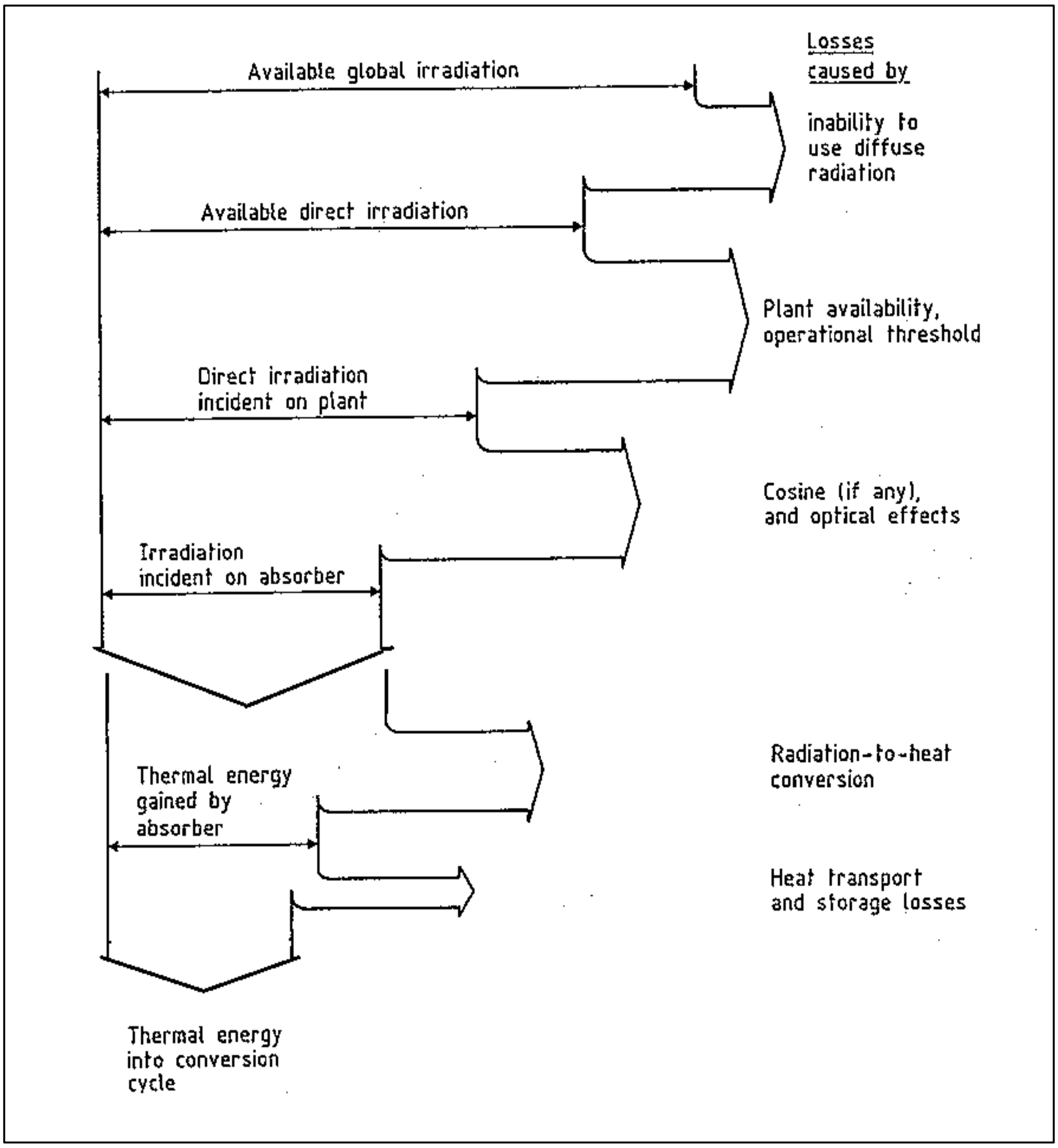



*Figure 3 – Simplified Sankey Diagram for the Dish/Receiver System*

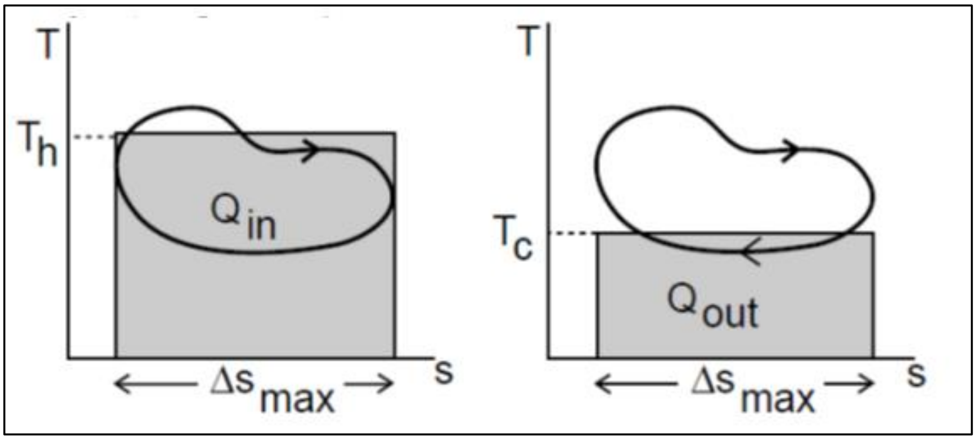



*Figure 4 – Temperature-Entropy generic direct cycle representation*

In [4] an amply description of the Stirling engine technologies and their applications to solar-powered systems are given.
The engine operation in shown in Figure 5. It consists in:

- an isothermal compression process (1-2): the WF is in the cold space. The power piston, which is approaching the Top Dead Center (TDC), compresses the working fluid from 1 to 2 at constant temperature;
- a constant-volume heating process (2–3): the displacer moves from TDC to the Bottom Dead Center (BDC). There is a WF transfer from the cold space to the hot space, while the power piston remains stationary at the TDC. The displacer pushes the WF into the hot space, passing through a regenerator which has stored heat. Heat given up by the regenerator raises the WF temperature and pressure at constant volume. Heat stored in the regenerator is given to the WF.
- an isothermal expansion process (3–4): after the displacer has pushed all the WF into the hot space, it is then kept at rest at its BDC. The WF is in the hot space and expands at constant temperature. The power piston is pushed from TDC to BDC by the increased pressure giving a mechanical power to a shaft.
- a constant-volume cooling process (4–1):the power piston remains stationary and it is ready to travel back to TDC under flywheel momentum and the sucking action of the partial vacuum created by the falling pressure. The displacer moves from BDC to TDC and transfers the to the cold space, where the pressure decreases and a partial vacuum is created, through the regenerator, decreasing the WF temperature and pressure at constant volume. Heat is transferred from the WF to the regenerator.

As shown in Figure 6 and reported in [4], “three different configurations (alpha, beta, and gamma) are commonly used. Each configuration has the same thermodynamic cycle but different mechanical design characteristics”.

- In the alpha-configuration the displacer is not used. Two pistons (hot and cold pistons) are used on either side of the heater, regenerator, and cooler. These pistons move uniformly in the same direction to provide WF constant-volume heating or cooling processes. When all the WF has been transferred into one cylinder, one piston is fixed and the other piston moves to expand or compress the WF. The expansion work is done by the hot piston while the compression work is done by the cold piston.
- In the beta-configuration, displacer and power piston are in the same cylinder. The displacer moves the WF between the hot and the cold space of the cylinder through heater, regenerator, and cooler. The power piston, located at the cold space of the cylinder, compresses the WF when this one is in the cold space and expands the WF when this one is moved into the hot space.
- The gamma-configuration uses separated cylinders for the displacer and the power piston, with the power cylinder connected to the displacer cylinder. The displacer moves the WF between the hot space and the cold space of the displacer cylinder through the heater, regenerator, and cooler. In this configuration, the power piston both compresses and expands the WF. The gamma-configuration with double-acting piston arrangement has theoretically the highest possible mechanical efficiency.

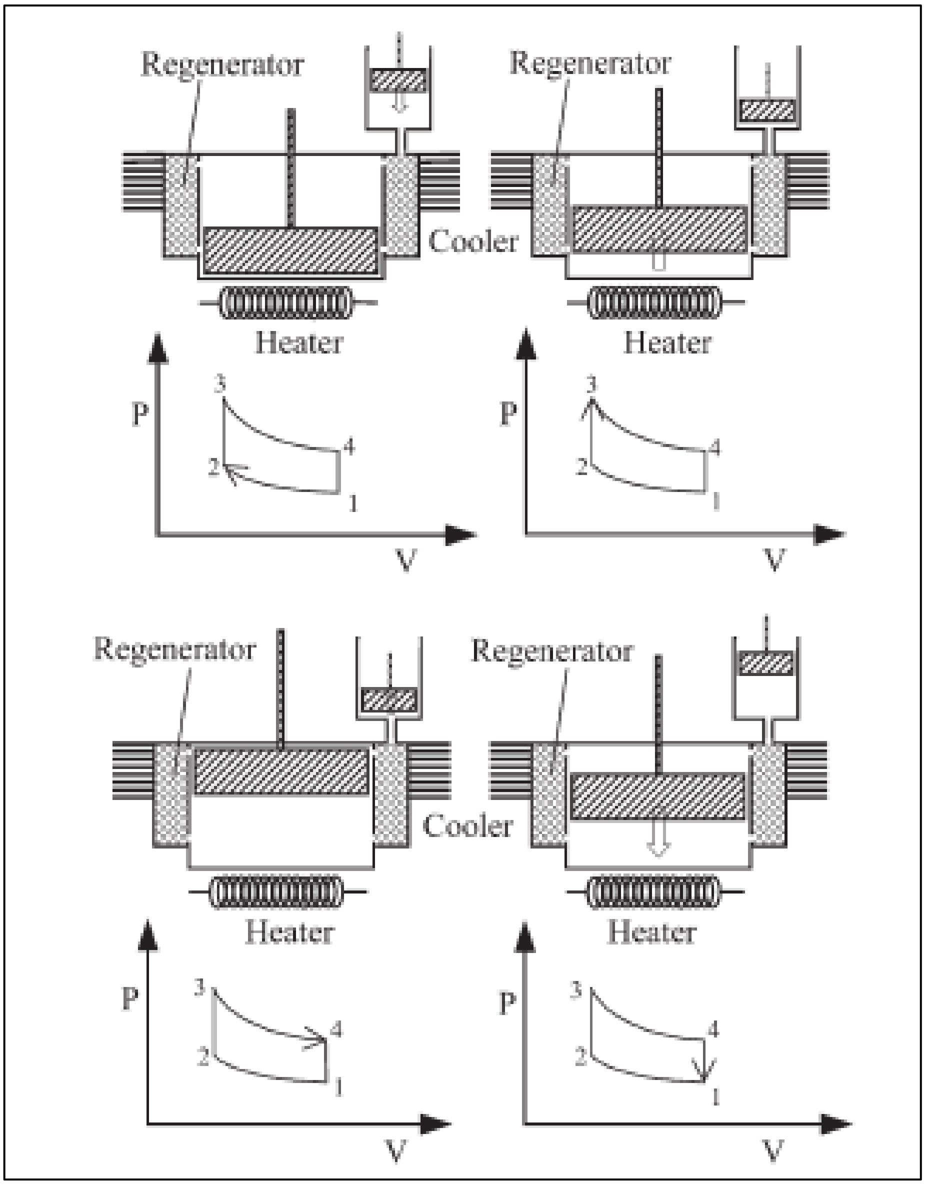



*Figure 5 – Stirling engine operation [4]*

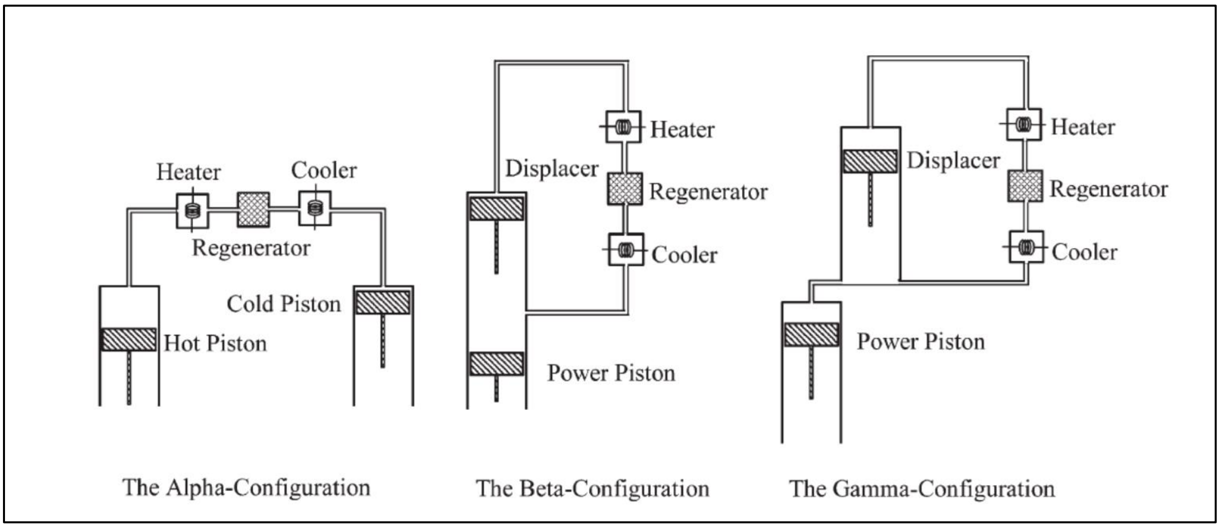



*Figure 6 – Mechanical configuratios for Stirling engines [4]*

In [4] there is also a review of the main formulas for the calculation of the indicated work, power and efficiency of the engine. The growth in interest for the Stirling engine is connected with the development of new materials and the application of WFs like helium and hydrogen which have a low viscosity. It allows the reduction of pumping losses

According to such characteristics, Stirling engine is a good candidate for CSP Systems based on Dishes and it competes with the Brayton cycle based engines that are the subject of the OMSoP Project.

Various developments have been performed and the present Deliverable reports the State of the Art of Dish/Stirling CSP Systems.

**Bibliographical Review**

The major literature that has been analyzed to extract the information is listed in the last chapter and the main papers are summarized in the following.

The main components of a Dish/Stirling engine Systems are:

1. The solar concentrator (Dish) with the sun-tracking system;
2. The solar receiver;
3. The Stirling engine with the electric generator/alternator.

Solar Concentrator (Dish)

In [5,6] a complete description of such components is given. The solar concentrator is generally a point-focus dish with a parabolic or a quasi-parabolic shape, but there are examples of point-focus concentration systems based on flat mirrors overlapped radiation [7,8].

In Figure 7 some configurations developed for the Dish are shown.


*Figure 7 – a)McDonnell Douglas Corporation Concentrator (1984) [6]; b)EnviroDish (2006)[9] c) DOE Faceted Stechde-Membrane Dish, 1992 [6] d) Heliofocus concentrator prototype 2013 [8] e)Dish-Stirling Prototype, Gardenshow in Pforzheim (1989/1991) [27]*

In [6] concentrators are divided into three main categories:

1. Glass-Faceted Concentrators: they use spherically curved, individually alignable glass mirror facets mounted on parabolic-shape structures. An example is given in Figure 6a. This desigh guarantees high concentration ratios but it has not been implemented for Dish/Stirling Farms Projects because it is heavy, expensive and requires accurate alighment of a large number of mirrors. In Figure 8 an example of curved glasses mirror is given;
2. Full-Surface Paraboloid Concentrators: the entire surface forms a paraboloid. Two proptotypes have been developed in the past for Dish/Stirling applications, but tests showed a low optical efficiency (about 60%);
3. Stetched-Membrane Concentrators: Membranes are made of thin metal or plastic sheeting with a reflective coating. Such membranes are stretched over both sides of a metal ring. Various designs have been developed. In the Single Faceted-Stretched Membrane Dishs the surface shape approximation to a paraboloid is given by initially forming the membrane and using the pressure difference between  front and back to support the shape and maintain its shape. For Multiple Faceted-Stretched Membrane Dishs the same technique is used to obtain parts of the reflector. The main advantage of these solution is the reduction of costs maintaining good performance. Examples are shown in Figue 6 b and e.

*Figure 8 - Segmented Dishs (Curved Glasses)[27]*

Moreover, in order to have a good radiation concentration, a two-axes tracking system is necessary. In [6] a description of the two ways used to implement this is given.

1. Azimuth-elevation tracking: the Dish rotates in a plane parallel to the earth (azimuth) an in another plane perpendicular to it (elevation). Thi gives the collector up/down and right/left rotations;
2. Polar tracking method: the collector rotates about an axis parallel to the earth's axis of rotation, while the other rotational axis (declination axis) is perpendicular to the polar axis.

In Figure 9 examples of the two tracking systems are shown.

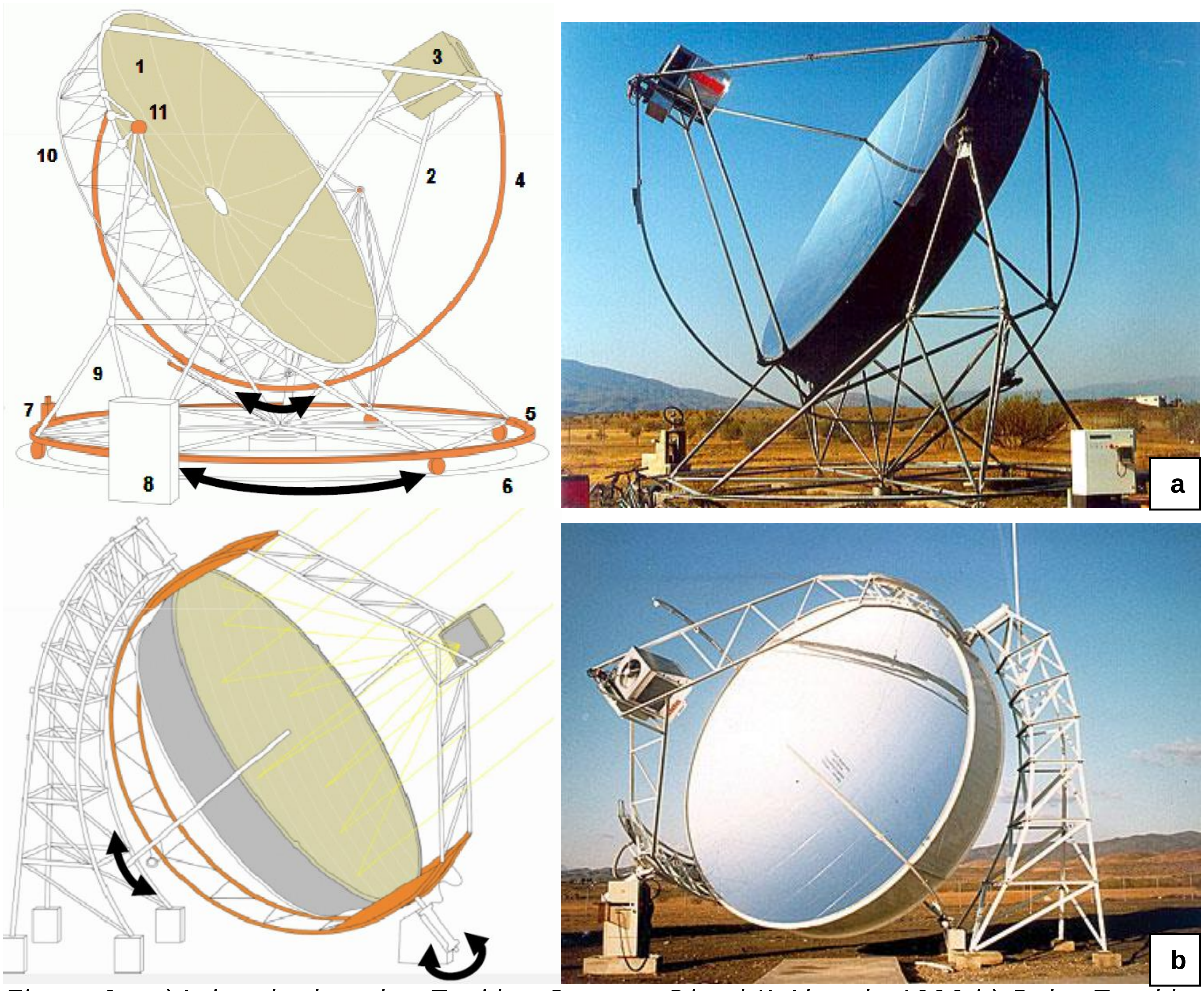
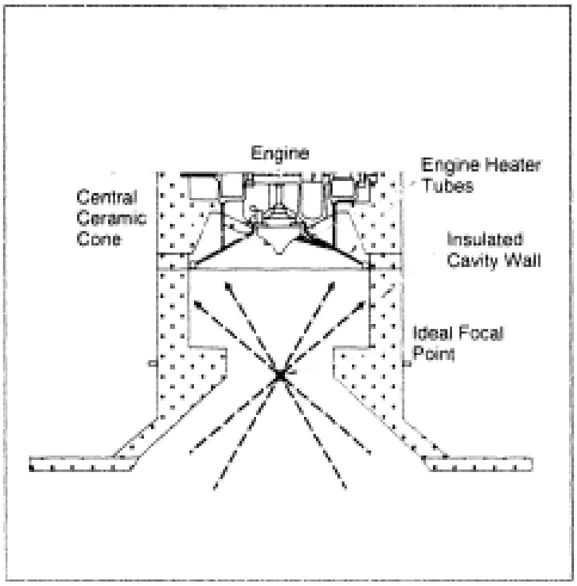


*Figure 9 - a)Azimuth elevation Tacking System- Distal II Almeria 1996 b) Polar Tracking System- Distal I Almeria 1992*

<u>Solar Receiver</u>
The receiver has to absorb the reflected and concentrated solar radiation and has to transfer the heat to a WF. In [6] there is a description of the concepts applied in the design of receivers for Dish/Stirling Engine Systems.
Such components have a cavity with a small opening through which the concentrated sunlight enters. The receiver aperture geometry has to limit radiation and convection losses. To transfer the absorbed radiation to the WF various methods can be adopted. In particular, directly illuminated tube receivers use small tubes through which the WF flows are placed directly in the concentrated solar flux region. Tubes form the absorber surface. Otherwise other receiver use a liquid-metal intermediate heat-transfer fluid. The liquid metal is vaporized on the absorber surface and condenses on tubes carrying the WF (Reflux Receiver). In Figure 10 the two concepts are illustrated.
In Figure 11 details of modern solar receivers for Solar Stirling engines are shown.

<u>Stirling Engines</u>
Stirling engines used for Dish Solar Systems are derived from aerospace applications. In 70s and 80s various concepts have been developed and proposed for terrestrial purposes. In [10] a review of such designs is given and some technologies are illustrated in Figures 12,13 and 14. Solar Stirling engines generally operate at a maximum temperature of 650-800°C according to material thermal limits, with an engine conversion efficiency of around 30-40%.
Usually helium and hydrogen are used as WF: helium has fewer material compatibility problems that hydrogen and it is safer but on the thermodynamic point of view, hydrogen allows a higher engine efficiency value.
Dish/Stirling Systems are equipped with two kind of engines:

1. Kinematic engines;
2. Free-piston engines.



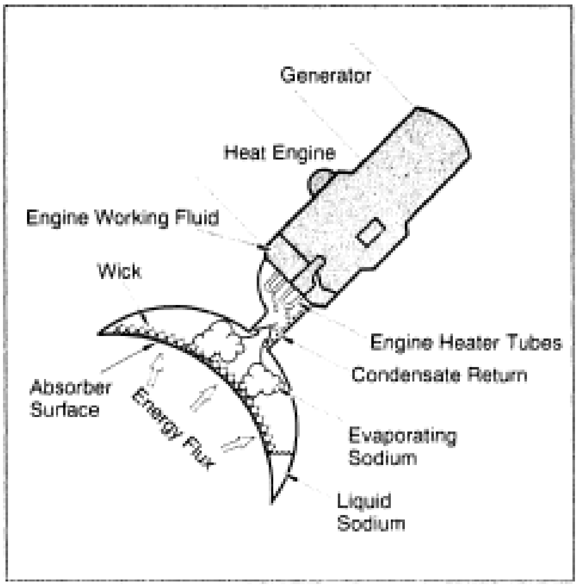



*Figure 10 – a) Directly illuminated Tube Receiver b) Reflux heat-pipe Receiver*

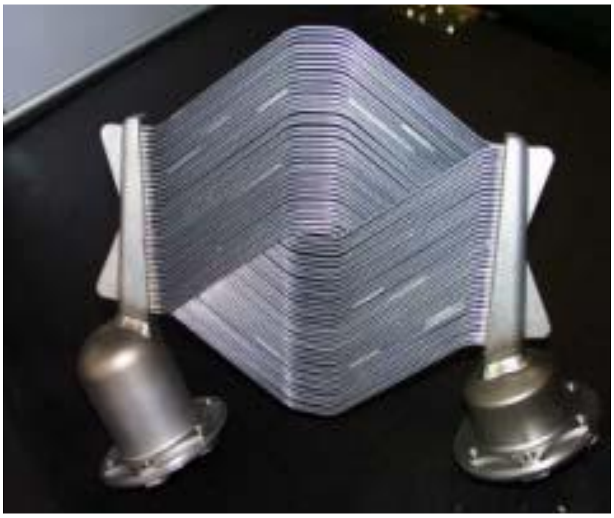



*Figure 11 - Details of modern solar receivers for Solar Stirling engines*

In a kinematic engines the power piston is mechanically connected to a rotating output shaft (Figures 15 and 17). As shown in Figure 16 for the STM 4-piston engine, some prototypes have been designed also in a hybrid configuration (they are equipped with a combustor) [11,18].

The free-piston engine is based on another concept. It is not mechanically connected to an output shaft, but bounces alternately between the space containing the WF and a spring that usually contains a gas. Dynamics of the spring/mass systems determines piston frequency. A magnet is attached to the power piston and electric power is generated as it moves past stationary coils. In Figure 18 a scheme of the INFINIA free-piston engine is shown [12].

In [6] are reported design and performance specifications for the main components of Dish/Stirling Systems prototype developed and tested before 1994. The table is shown in Figure 19.

In the next chapter information collected for prototype and commercial modules are illustrated.

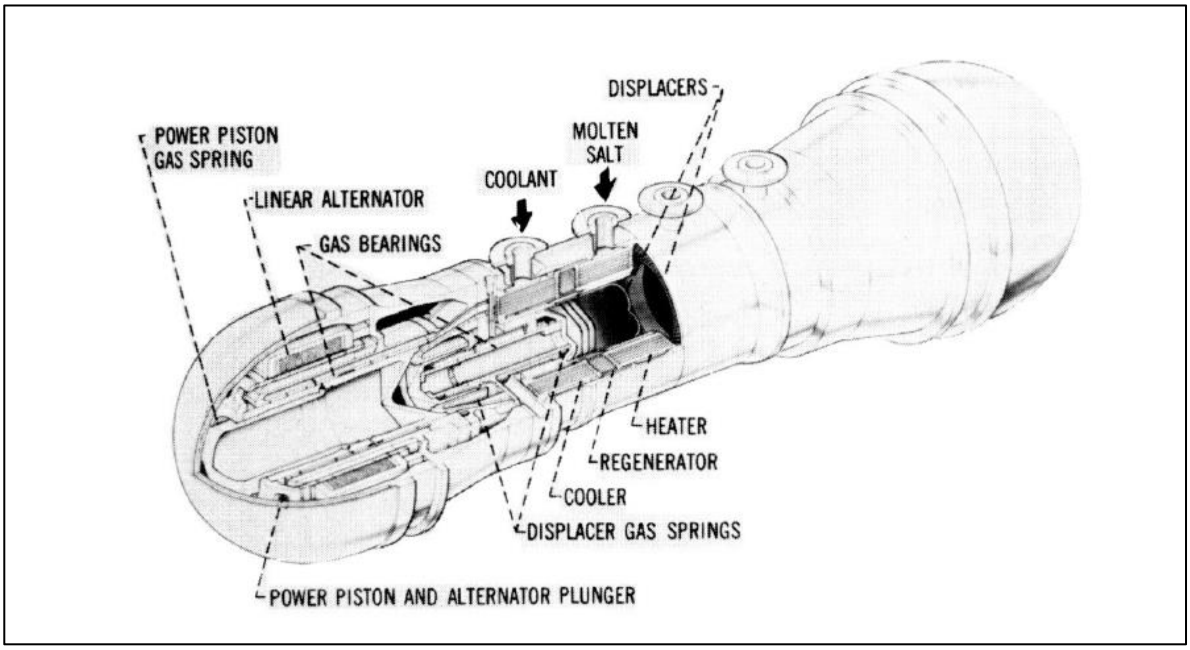



*Figure 12 - 25 kWe Space Power Demonstrator Engine*

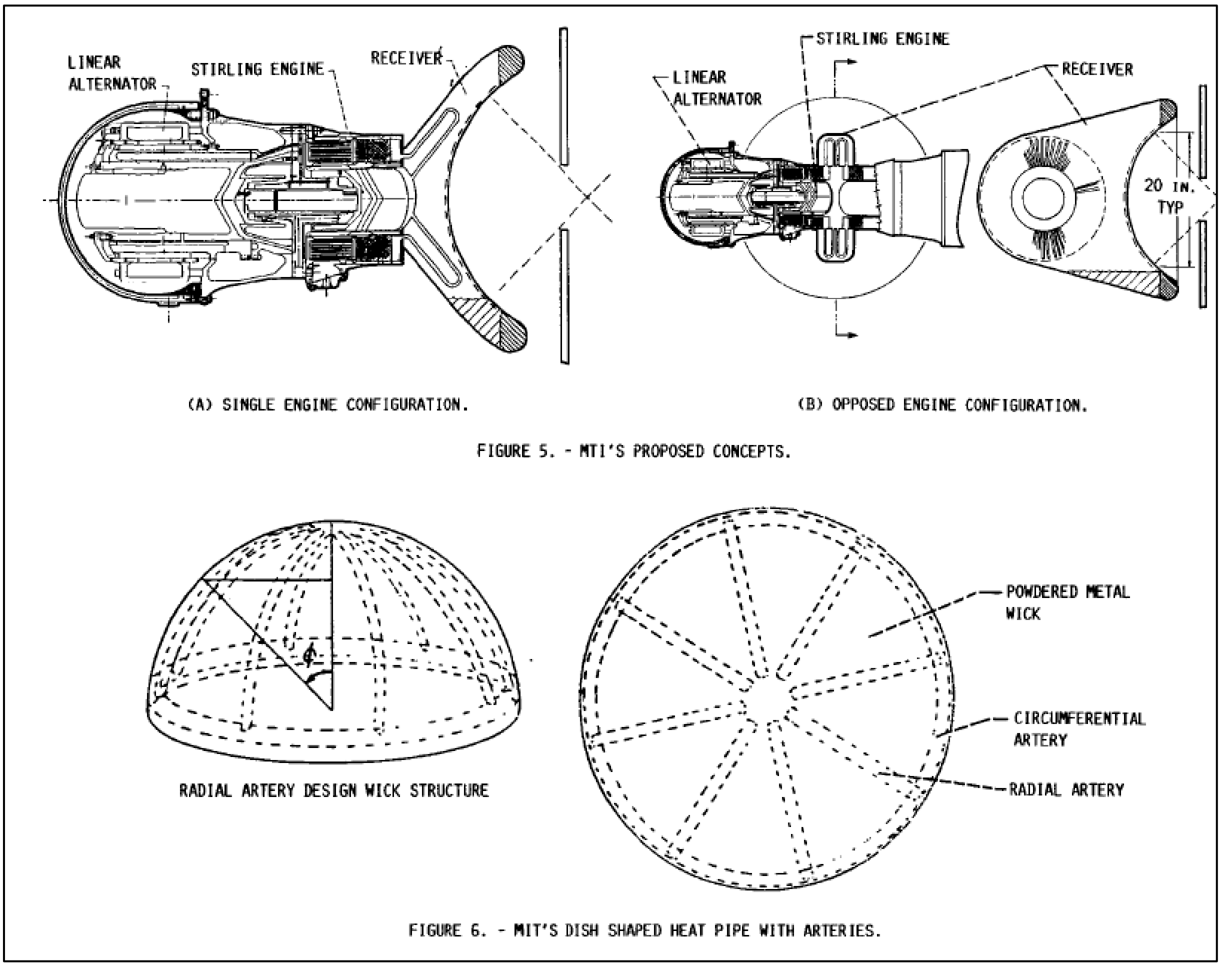



*Figure 13- MIT's preliminary Dish-Stirling engine*

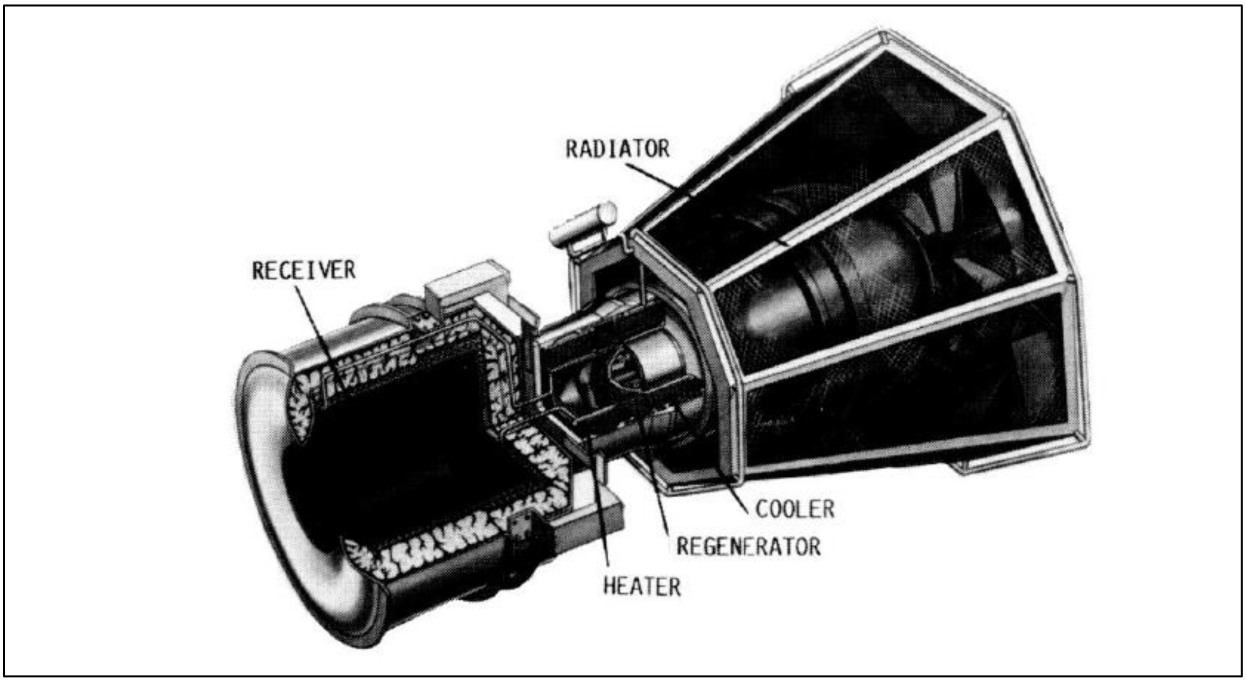



*Figure 14 – Conceptualized Free-Piston Stirling engine conversion system*

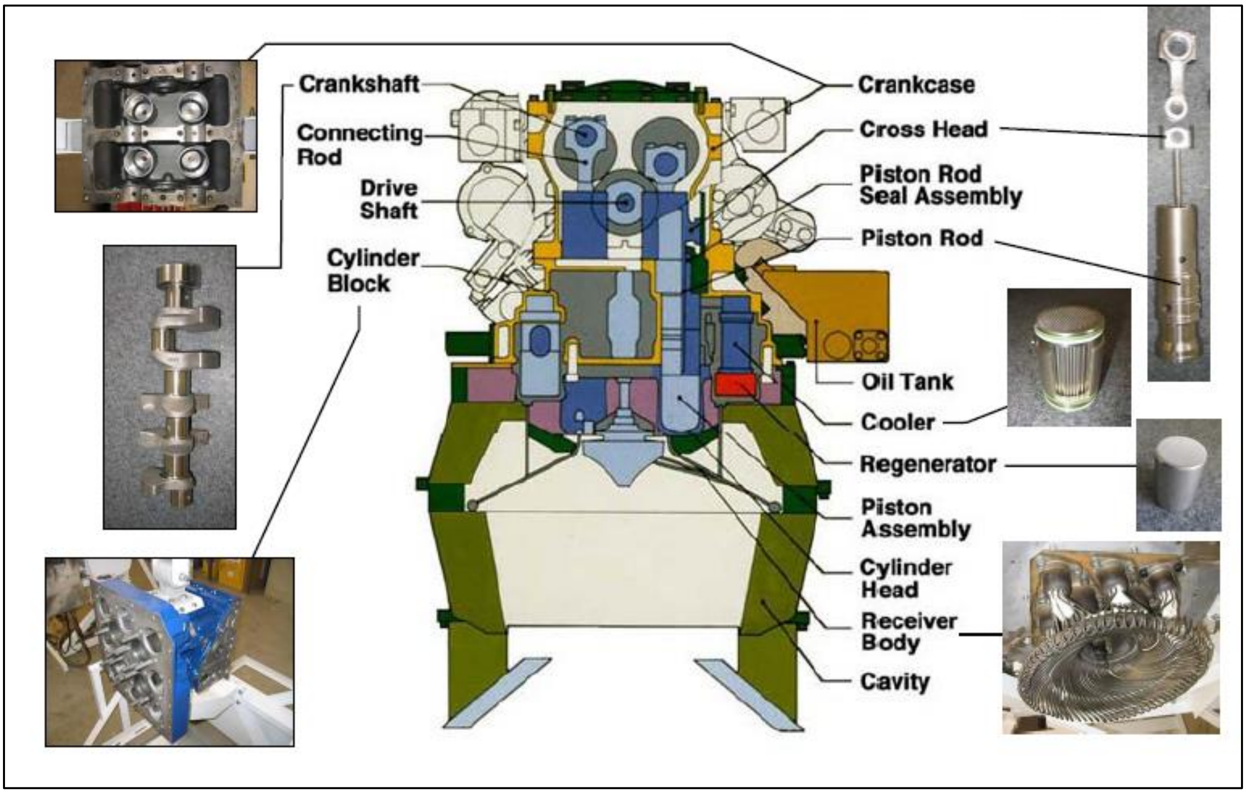



*Figure 15 – Scheme of a kinematic engine and its main components*

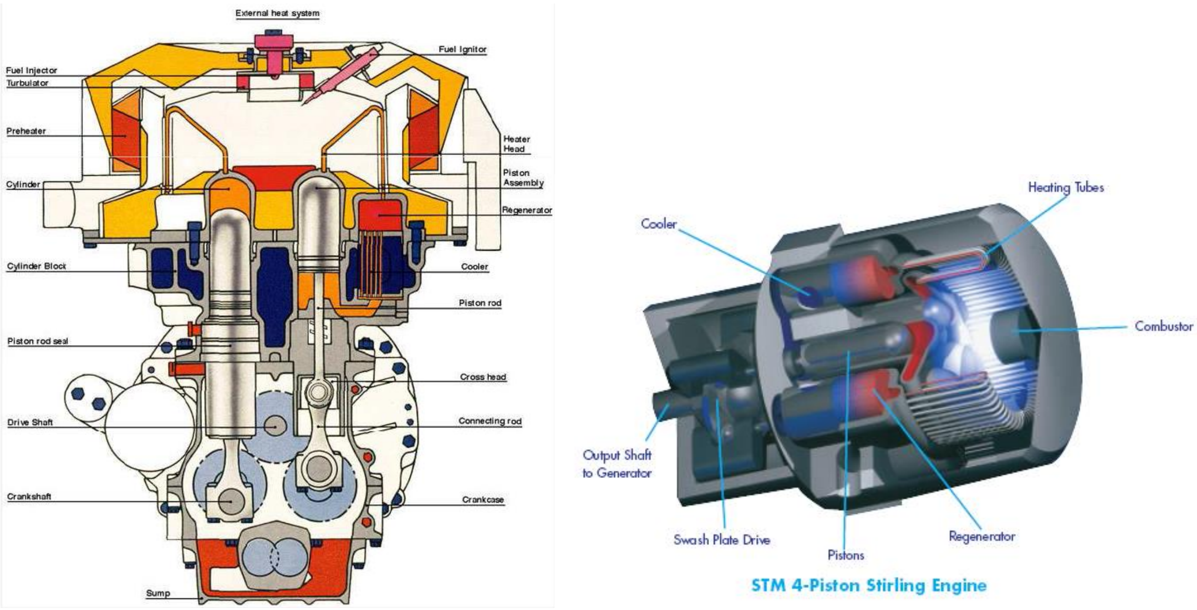



*Figure 16 - 4-Piston hybrid kinematic Solar Stirling engine*


*Figure 17- SES kinematic Solar Stirling engine. It is a 4 cylinder, each with a 95cc displacement engine (4-95 engine) that evolved from the Philips engines of the 1960's*

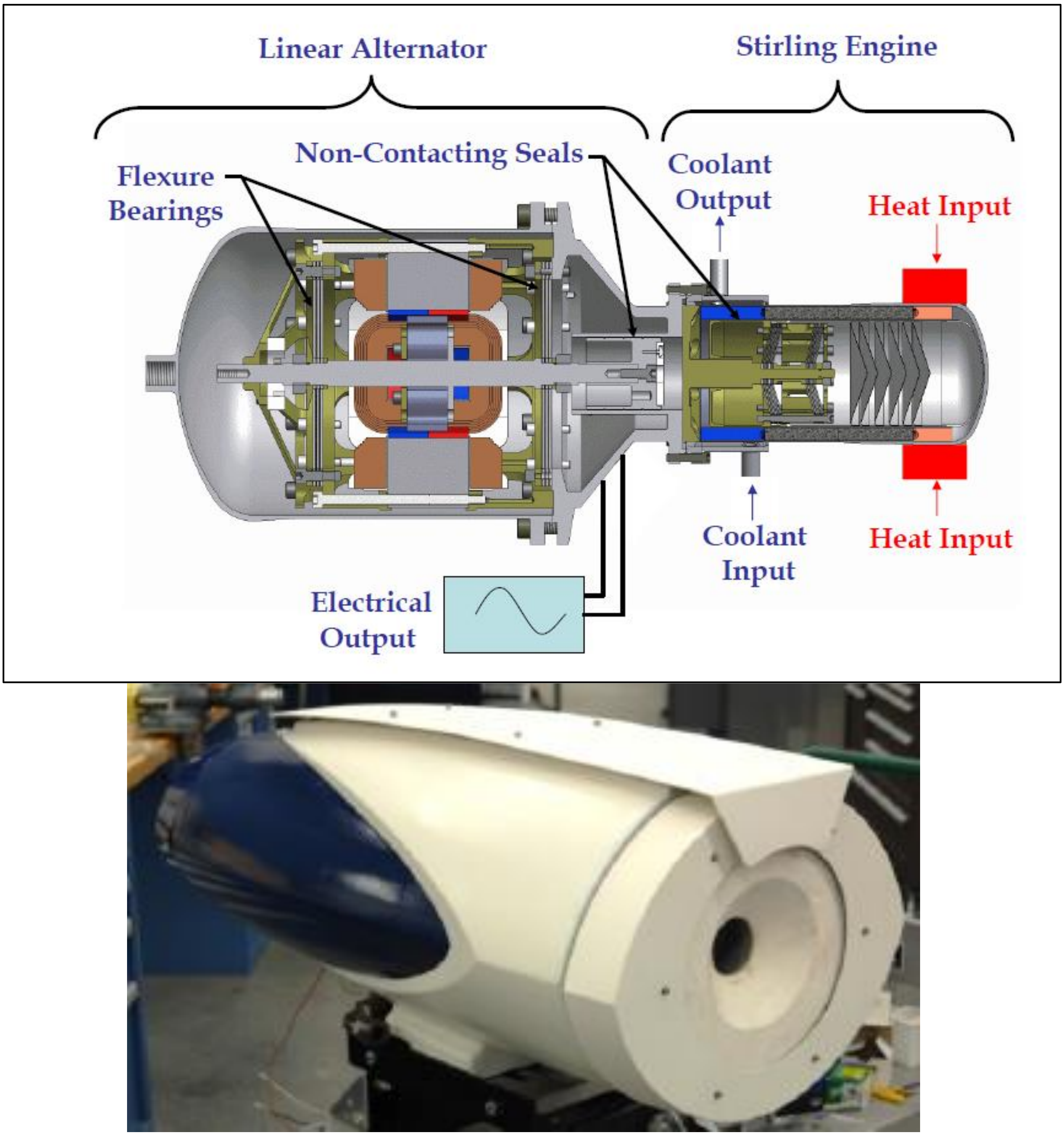



*Figure 18 - INFINIA Free Piston Engine: scheme and picture [12]*

| SYSTEM | | | | | | | |
|---|---|---|---|---|---|---|---|
| Name | Vanguard | MDAC | German/Saudi | SBP 7.5-m | CPG 7.5-kW | Aisin/Miyako | STM Solar PCS |
| Year | 1984 | 1984-88 | 1984-88 | 1991- | 1992- | 1992- | 1993- |
| Net Electricity* | 25 kW | 25 kW | 52.5 kW | 9 kW | 7.5 kW @ 950 $W/m^2$ | 8.5 kW @ 900 $W/m^2$ | 25 kW (design) |
| Efficiency* | 29.4% @ 760° C gas temp. | 29% - 30% | 23.1% | 20.3% | 19% @ 950 $W/m^2$ | 16 % @ 900 $W/m^2$ | —+++ |
| Number | 1 | 6 | 2 | 5 | 3 built, 14 planned | 3 planned | 1 |
| Location (no.) | CA | CA (4), GA, NV | Riyadh, Saudi Arabia (2) | Spain (3) Germany (2) | CA, TX, PA, | Miyako Is, Japan | SNL-TBC |
| Status | Testing completed | Testing completed | Occasional ops. | Testing now | Initial testing of 5-kW prototype | Fabrication | — |
| **CONCENTRATOR** | | | | | | | |
| Manufacturer | Advanco | MDAC | SBP | SBP | CPG | CPG | — |
| Diameter** | 10.57 m | 10.57 m | 17 m | 7.5 m | 7.3 m | 7.5 m | — |
| Type | Faceted glass mirrors | Faceted glass mirrors | Stretched membrane | Stretched membrane | Stretched membrane | Stretched membrane | — |
| No. of Facets | 336 | 82 | 1 | 1 | 24 | 24*** | — |
| Size of Facets | 0.451x0.603 m | 0.91x1.22 m | 17 m dia. | 7.5 m dia. | 1.524 m dia. | 1.524 m dia. | — |
| Surface | Glass/silver | Glass/silver | Glass/silver on stainless steel | Glass/silver on stainless steel | Aluminized plastic film | Aluminized plastic film | — |
| Reflectance (initial) | 93.5% | 91% | 92% | 94% | 85% to 78% | 85% to 78% | — |
| Concentration+ | 2750 | 2800 | 600 | 4000 | 1670 | 1540 | — |
| Tracking | Exocentric gimbal | Az-el | Az-el | Polar | Polar | Polar | — |
| Efficiency | 89% | 88.1% | 78.7% | 82% | 78% | 78% | — |
| **ENGINE** | | | | | | | |
| Manufacturer | USAB | USAB | USAB | SPS/Solo | Sunpower/ CPG | Aisin Seiki | STM / DDC |
| Model | 4-95 Mk II | 4-95 Mk II | 4-275 | V-160 | 9-kW | NS30A | 4-120 |
| Type | Kinematic | Kinematic | Kinematic | Kinematic | Free-piston | Kinematic | Kinematic |
| Power (elect.) | 25 kW | 25 kW | 50 kW | 9 kW | 9 kW | 30 kW (derated to 8.5 kW)*** | 25 kW |
| Working Gas | Hydrogen | Hydrogen | Hydrogen | Helium | Helium | Helium | Helium |
| Pressure (max.) | 20 MPa | 20 MPa | 15 MPa | 15 MPa | 4 MPa | 14.5 MPa | 12 MPa |
| Gas Temp. (high) | 720°C | 720 C | 620°C | 630 C | 629°C | 683 C | 720°C |
| Peak Efficiency | 41% | 38% - 42% | 42% | 30% | 33%++ | 25% | 42% |
| **RECEIVER** | | | | | | | |
| Type | Direct tube irradiation | Direct tube irradiation | Direct tube irra[illegible]n | Direct tube irradiation | Sodium heat pipe | Direct tube irradiation | Direct tube irradiation |
| Aperture Diameter | 20 cm | 20 cm | 70 cm | 12 cm | 18 cm | 18.5 cm | 22 cm |
| Peak Flux | 75 $W/cm^2$ | 78 $W/cm^2$ | 50 $W/cm^2$ | 80 $W/cm^2$ | 30 $W/cm^2$ | 30 $W/cm^2$ | 75 $W/cm^2$ |
| Tube Temp. (max.) | 810°C | — | 800°C | 850 C | 675°C++++ | 780 C | 800°C |
| Efficiency | 90% | 90% | 80% | 86% | 86% | 65% | 85% to 90% |

* At 1000 $W/m^2$ unless otherwise noted
** Equivalent disk
*** 32 for temporary high output
\+ Geometric concentration ratio, defined in Chapter 3
\++ Includes alternator
\+++ Depends on concentrator used
\++++ Heat pipe internal temperature (Na vapor)

*Figure 19 - Specifications of Dish/Stirling prototype systems(till 1994)[6]*

**Developed Dish/Stirling Systems**

Prototypes

As reported in [13], Modern Stirling engines coupled with directly-illuminated solar receivers were developed in the late 1970s and early 1980s by United Stirling AB, Advanco Corporation, McDonnell Douglas Aerospace Corporation (MDA), NASA’s Jet Propulsion Laboratory, and DOE. They born initially for aerospace purposes, but, after a few years, they were applied also for terrestrial electic power generation with Dish/Stirling engine Systems.

In 1984, the Advanco Vanguard 25 kW prototype recorded a solar-to-electric conversion efficiency of 29.4% (net) using the United Stirling PCU. This efficiency is defined as the net electrical power delivered to the grid, taking into account the electrical power needed for parasitics, divided by the direct normal insolation incident on the mirrors. In Figure 20 the prototype is shown.

MDA subsequently attempted to commercialize a system using the United Stirling PCU and a dish of their own design. Eight prototype systems were produced by MDA before the program was canceled in 1986 and the rights sold to Southern California Edison (SCE). The cancellation of the dish/Stirling program was part of MDA’s decision to cancel all of their energy related activities, despite the excellent technical success of their dish/Stirling system. The MDA systems routinely converted sunlight incident on the concentrator’s mirrors to electricity with net efficiencies of about 30%. Southern California Edison Company continued to test the MDA system on a daily basis from 1986 through 1988. During its last year of operation, it achieved an annual efficiency of about 12%, including system outages and all other effects such as mirror soiling, and an annual efficiency of over 23% was determined to be achievable excluding outages.

In the early 1990s, Cummins Engine Company attempted to commercialize Dish/Stirling systems based on free-piston Stirling engine technology. The Cummins development efforts were supported by SunLab through two 50/50 cost shared contracts. The Dish/Stirling Joint Venture Program (DSJVP) was started in 1991 and was intended to develop a 5 to 10 kW dish/Stirling system for remote power applications. The Utility Scale Joint Venture Program (USJVP) was started in late 1993 with the goal of developing a 25 kWe dish/engine system for utility applications. However, largely because of a corporate decision to focus on its core diesel-engine business, Cummins canceled their solar development in 1996. Technical difficulties with Cummins’ free-piston Stirling engines were never resolved.

In 1993, another USJVP contract was initiated with Science Applications International Corporation (SAIC) and Stirling Thermal Motors (STM) to develop a dish/Stirling system for utility-scale applications. The SAIC/STM team successfully demonstrated a 20-kW unit in Golden, Colorado, in Phase 1. In December 1996, Arizona Public Service Company (APS) partnered with SAIC and STM to build and demonstrate the next five prototype dish/engine systems in the 1997-1998 time frame. SAIC and Stirling Thermal Motors, Inc. (STM) worked on next-generation hardware including a third-generation version of the STM 4-120, a faceted stretched-membrane dish with a face-down-stow capability, and a directly-illuminated hybrid receiver. The overall objective is to reduce costs while maintaining demonstrated performance levels. Phase 3 of the USJVP calls for the deployment of 1 MW Dish/engine systems in a utility environment.

Then, other developers continued to develop such systems. For example, Stirling Energy Systems (SES) purchased the rights of the MDA technology and improved the system recording a conversion efficiency up to 31% (Figure 21) [9].

In Figure 21 a Table from [13] with the major characteristics of some 80s-90s prototype is presented. They range in size from 5 to 50 kWe and they have been built in United States, Germany, Japan and Russia.

In 2000s other prototypes of interest have been developed and installed in addition to SES systems. The EnviroDish System installed at Odeillo – Spain in 2006 in just an example. It has been developed on the basis of the experience of Distal I and II prototypes and the EuroDish System. The Envirodish used a SOLO V161 Stirling engine with hydrogen as WF and it recorded a pick efficiency of 24%.

Another relevant example is the INFINIA 3,2 kWe Dish/Stirling System. It was marketed into 2006 and in 2010 about 100 systems have been installed in the world. The Company declares an engine efficiency of 32%, 86% of net reflectivity for the concentrator and a net efficiency of the system of 24% after inverter and parasitic losses [12] and, launches its product as the best commercial module comparing test results (Figure 23) [14]. On the basis of the 3.2 kWe Module, Infinia started the development of a 30 kW 6-cilinder configuration (a scheme is shown in Figure 24) based on the existing module [14]. The project was also funded by the Department of Energy (DOE) of the USA in

order to approach the target of 7-10 c$/kWh by 2015 and 5-7 c$/kWh by 2020 using economies of module size and high quantity production. After the 2008 announcement, no other information related to this project are available.
Since the WF has to be cooled, the Dish/Stirling System can have an interesting utilization where cogeneration is required. A commercial module available in the last years on the Italian market is the INNOVA Trinum: a Dish/Stirling system that provides 1 kWe and 3kWth. For such a system INNOVA declared an overall conversion efficiency of 55.2%, an electrical efficiency of 13.8%and a thermal efficiency of 41.4% based on 725 W/m2 DNI (Figure 25) [15].

*Figure 20 –ADVANCO Vanguard Dish/Stirling prototype system*


*Figure 21 - SES (Sandia Lab, Albunquerque, 2005)*

| Company | Concent Type | Optical Surface | Dish Area ($m^2$) | Rec Type | Total Hours/ (Nos. of systems) | Engine Company | Engine Type | Rated System Output ($kW_e$) | Steady, system Output ($kW_e$) | Steady, system Effic (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Advanco Vanguard System | Faceted Glass-Metal | Glass | 86.7 | DIR | 1996 (1) | United Stirling | Double-Acting 4-cyl, KSE | 25 | ~ 20 - 22 | 23 |
| Schlairch Bergermann und Partner | Stretched Membrane | Glass | 227 | DIR | NA (2) | United Stirling | Double-Acting 4-cyl, KSE | 50 | NA | NA |
| McDonnell-Douglas SES System | Faceted Glass-Metal | Glass | 91 | DIR | 13,852 (7) | United Stirling | Double-Acting 4-cyl, KSE | 25 | 20 - 22 | 23 |
| Schlaich Bergermann und Partner | Stretched Membrane Parabolic | thin glass | 44 | DIR | > 27,000 (6) | SOLO Kleinmotoren | 2 cylinder KSE | 10 | ~9.0 | ~ 18.0 |
| Cummins Power Generation | Faceted Stretched-Membrane | aluminum polymer | 44 | Heat Pipe | > 1000 (4) | Clever Fellows | 2 cylinder FPSE | 7 | 5.2 | 15 |
| Cummins Power Generation | parabolic gore | thin glass | 145 | Heat Pipe | ~ 25 (1) | Aisen Seiki | 4 cylinder KSE | 25 | ~ 20 | NA |
| Science Applications Int. Corp. | Faceted Stretched-Membrane | thin glass | 107 | $DIR^+$ | 400 (1) | Stirling Thermal Motors | 4 cylinder KSE | 20 | 18.5 | 22.4 |

Figure 22 – Details and performance of some Dish/Stirling prototypes

| | 10 watt (?) | 55 watt (NASA) | 350/450 watt (comm'l) | 1 kW (comm'l) | 3 kW (comm'l) Solar | Total |
|---|---|---|---|---|---|---|
| Units | 10 | 30 | 20 | 84 | 2 | 146 |
| Longest test | 100,000 | 35,000 | 30,000 | 25,000 | 300 | N/A |
| Cumulative test time at Infinia | 160,000 | 30,000 | 24,000 | 40,000 | 500 | 254,500 |
| Cumulative test time at Clients | 90,000 | 120,000 | 42,000 | 30,000 | n/a | 282,000 |
| Total Test Time | 250,000 | 150,000 | 66,000 | 70,000 | 500 | 536,500 |

*Figure 23 –Details and tests of various Stirling engine*

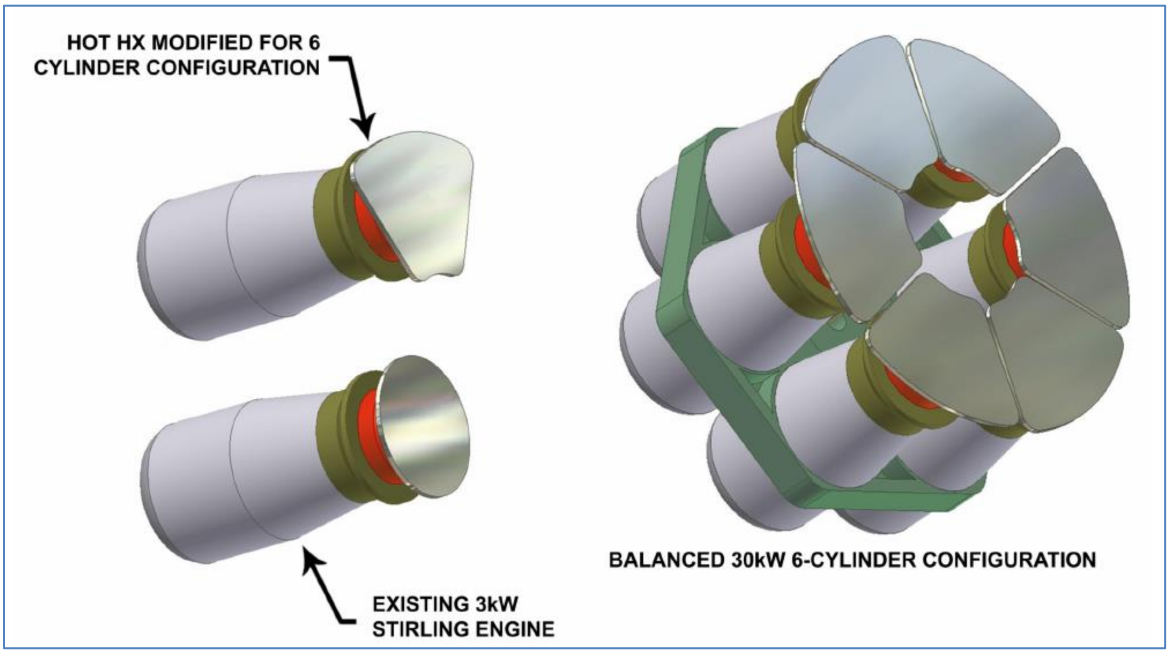



*Figure 24 – Infinia 30 kWe 6-cilinder project*

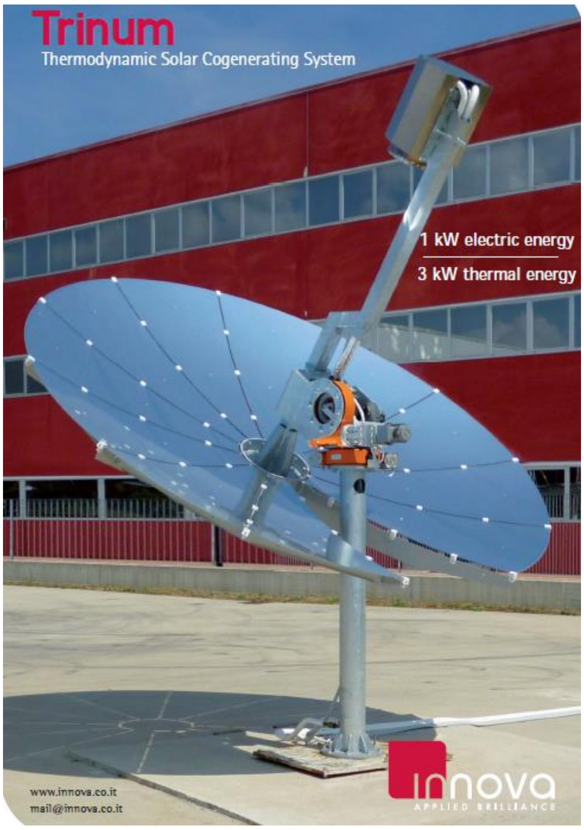



*Figure 25 – INNOVA Cogeneration Dish/Stirling System Trinum*

Concerning Dish/Stirling System costs and performance in [5] the table shown in Figure 26 is reported. System and component costs are from industry sources and independent SunLab analyses. The installed costs include the cost of manufacturing the concentrator and power conversion unit (PCU), shipment to the site, site preparation, installation of the concentrator and PCU, balance of plant (connection to utility grid). The component costs include a 30% profit.
Since costs are extremely sensitive to production rates and the installed costs are extremely dependent on the market penetration, it is not easy to give a “realistic” estimation. Moreover component costs are a strong function of production rates that have to be assumed. The economic life of a dish/engine power plant is 30 years.
As written in [[Solar Dish Engine], costs reported in 1980s prototype was based on the 25 kW dish-Stirling system developed by McDonnell Douglas (MDA) in the mid of 80s but they were in line with the STM 4-120 Stirling engine. Operation and maintenance (O&M) costs are of the prototype demonstration.
Costs reported for the 2000 took significant availability improvements into account, in particular resulting in an annual efficiency of 23% and assuming Stirling engines commercialized for other applications and spare parts and a dedicated staff available.
In addition a modest reduction in the cost of the dish concentrator simply was assumed.
On the basis of a production of 100 modules, resulting in installed costs were nearly $5,700/kW .
Performance for 2005 was largely based on one of the solarizable engines being commercialized for a non-solar application. A production rate of 2,000 modules per year was assumed.
Performance for years 2010 and beyond was based on an engine performance improvements of well over 10%. A production rate of 30,000 modules per year was assumed.
By 2010 dish/engine technology was assumed to be approaching maturity. So, in this scenario, a typical plant may include several hundred to over a thousand systems. In the table, a typical plant is assumed to be 30 MW.
For the higher production of 2020-2030, 50000 - 60000 modules per year were assumed. Evolutionary improvements in mirror, receiver, and/or engine designs were assumed.

Table 1. Performance and cost indicators.

| INDICATOR NAME | UNITS | 1980's Prototype 1997 | +/-% | Hybrid System 2000 | +/-% | Commercial Engine 2005 | +/-% | Heat Pipe Receiver 2010 | +/-% | Higher Production 2020 | +/-% | Higher Production 2030 | +/-% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Typical Plant Size, MW | MW | 0.025 | | 1 | 50 | 30 | 50 | 30 | 50 | 30 | 50 | 30 | 50 |
| Performance | | | | | | | | | | | | | |
| Capacity Factor | % | 12.4 | | 50.0 | | 50.0 | | 50.0 | | 50.0 | | 50.0 | |
| Solar Fraction | % | 100 | | 50 | | 50 | | 50 | | 50 | | 50 | |
| Dish module rating | kW | 25.0 | | 25.0 | | 25.0 | | 27.5 | | 27.5 | | 27.5 | |
| Per Dish Power Production | MWh/yr/dish | 27.4 | | 109.6 | | 109.6 | | 120.6 | | 120.6 | | 120.6 | |
| Capital Cost | | | | | | | | | | | | | |
| Concentrator | $/kW | 4,200 | 15 | 2,800 | 15 | 1,550 | 15 | 500 | 15 | 400 | 15 | 300 | 15 |
| Receiver | | 200 | 15 | 120 | 15 | 80 | 15 | 90 | 15 | 80 | 15 | 70 | 15 |
| Hybrid | | ---- | | 500 | 30 | 400 | 30 | 325 | 30 | 270 | 30 | 250 | 30 |
| Engine | | 5,500 | 15 | 800 | 20 | 260 | 25 | 100 | 25 | 90 | 25 | 90 | 25 |
| Generator | | 60 | 15 | 50 | 15 | 45 | 15 | 40 | 15 | 40 | 15 | 40 | 15 |
| Cooling System | | 70 | 15 | 65 | 15 | 40 | 15 | 30 | 15 | 30 | 15 | 30 | 15 |
| Electrical | | 50 | 15 | 45 | 15 | 35 | 15 | 25 | 15 | 25 | 15 | 25 | 15 |
| Balance of Plant | | 500 | 15 | 425 | 15 | 300 | 15 | 250 | 15 | 240 | 15 | 240 | 15 |
| Subtotal (A) | | 10,580 | | 4,805 | | 2,710 | | 1,360 | | 1,175 | | 1,045 | |
| General Plant Facilities (B) | | 220 | 15 | 190 | 15 | 150 | 15 | 125 | 15 | 110 | 15 | 110 | 15 |
| Engineering Fee, 0.1*(A+B) | | 1,080 | | 500 | | 286 | | 149 | | 128 | | 115 | |
| Project /Process Contingency | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | |
| Total Plant Cost | | 11,880 | | 5,495 | | 3,146 | | 1,634 | | 1,413 | | 1,270 | |
| Prepaid Royalties | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | |
| Init Cat & Chem. Inventory | | 120 | 15 | 60 | 15 | 12 | 15 | 6 | 15 | 6 | 15 | 6 | 15 |
| Startup Costs | | 350 | 15 | 70 | 15 | 35 | 15 | 20 | 15 | 18 | 15 | 18 | 15 |
| Other | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | |
| Inventory Capital | | 200 | 15 | 40 | 15 | 12 | 15 | 4 | 15 | 4 | 15 | 4 | 15 |
| Land, @$16,250/ha | | 26 | | 26 | | 26 | | 26 | | 26 | | 26 | |
| Subtotal | | 696 | | 196 | | 85 | | 56 | | 54 | | 54 | |
| Total Capital Requirement | | 12,576 | | 5,691 | | 3,231 | | 1,690 | | 1,467 | | 1,324 | |
| Total Capital Req. w/o Hybrid | | 12,576 | | 5,191 | | 2,831 | | 1,365 | | 1,197 | | 1,074 | |
| Operation and Maintenance Cost | | | | | | | | | | | | | |
| Labor | ¢/kWh | 12.00 | 15 | 2.10 | 25 | 1.20 | 25 | 0.60 | 25 | 0.55 | 25 | 0.55 | 25 |
| Material | ¢/kWh | 9.00 | 15 | 1.60 | 25 | 1.10 | 25 | 0.50 | 25 | 0.50 | 25 | 0.50 | 25 |
| Total | ¢/kWh | 21.00 | | 3.70 | | 2.30 | | 1.10 | | 1.05 | | 1.05 | |

Notes:
1. The columns for "+/-%" refer to the uncertainty associated with a given estimate.
2. The construction period is assumed to be <1year for a MW scale system.

Figure 26 – Evaluation of costs for Dish/Stirling engines

Dish/Stirling Plants

In the last decay some Dish/Stirling Solar Plants have been built on the basis of SES and INFINIA experience. [9]

- Maricopa Solar Plant
  In January 2010 Tessera inaugurated the Maricopa Solar Plant near Peoria (Arizona) [16]. It was an ambitious 1.5 MWe Plant based on 60 SES Suncatcher Dish/Stirling 25 kWe Systems (with SOLO Stirling engines) (Figure 27). The plant was decommissioned in September 2011 and no other information or details are available for such a plant.
- Renovalia – Villarobledo
  In 2009 Renovalia started the installation in Villarobledo of a 1 MWe Solar Power Plant based on 3 kWe INFINIA Dish/Stirling engine Modules (Figure 28) [9];
- PowerPlay Solar – GH Daily
  In 2010 PowerPlay Solar installed a cluster of 30 INFINIA Dish/Stirling Modules at YUMA (Arizona) (Figure 29),
- Deployment Plants
  In 2007 SES declared that two major contracts were under development for up to 1750 MW of peak capacity, both of them in South California [17].
  The first one with Southern California Edison (SCE) for a total capacity of 500 MW with expansion option to 850 MW that means 20000 or 34000 Dish/Stirling Modules.
  The second one with San Diego Gas & Electric (SDG&E), sited in the Imperial Valley near El Centro, for a total capacity of 300 MW with expansion option to 900 MW, that means 12000 up to 36000Dish/Stirling Modules.
  The construction was scheduled for 2009 for the first plant and for 2008 for the second one but the deployment has never started in both cases. Moreover SES and Tessera have downfallen. A political and economic view of what happened and why is reported in [19].

*Figure 27 - Maricopa Solar Power Plant*

*Figure 28 - Renovalia - Villarobledo*

*Figure 29 - PowerPlay Solar – GH Dairy Plant*

**Conclusions**

The Dish/Stirling System shows some undeniable advantages: an high efficiency (up to 32% in some cases) also when the insolation is low (Figure 30) [18], a highly modular design, the low requirement of water in comparison with other CSP technologies. But some drawbacks can be highlighted.
In [19] it is pointed out that Dish/Stirling Systems run without a storage system, so they deliver power as a PV and, at the moment, PV technology is cheaper and more reliable. “From an engineering point of view, there are some challenges to work around”.
In [20] some of them has been stressed. High efficiency Stirling engine use hydrogen or helium as WF, so the engine piston seals are a critical part. The Eurodish V161 Stirling engine presented a significant gas pressure drop in the motor due to seals leakeage after a few days as shown in Figure 31.The WF refilling and the piston seals replacement are, nowadays, a critical point to have a reliable system. Also the pistons (in particular the cooler ones) are a critical part of the Stirling engine because they can rapidly be damaged.
So, although the promising expectations, the reliability of the Dish/Stirling System has to be improved before consider its “real” commercial application.

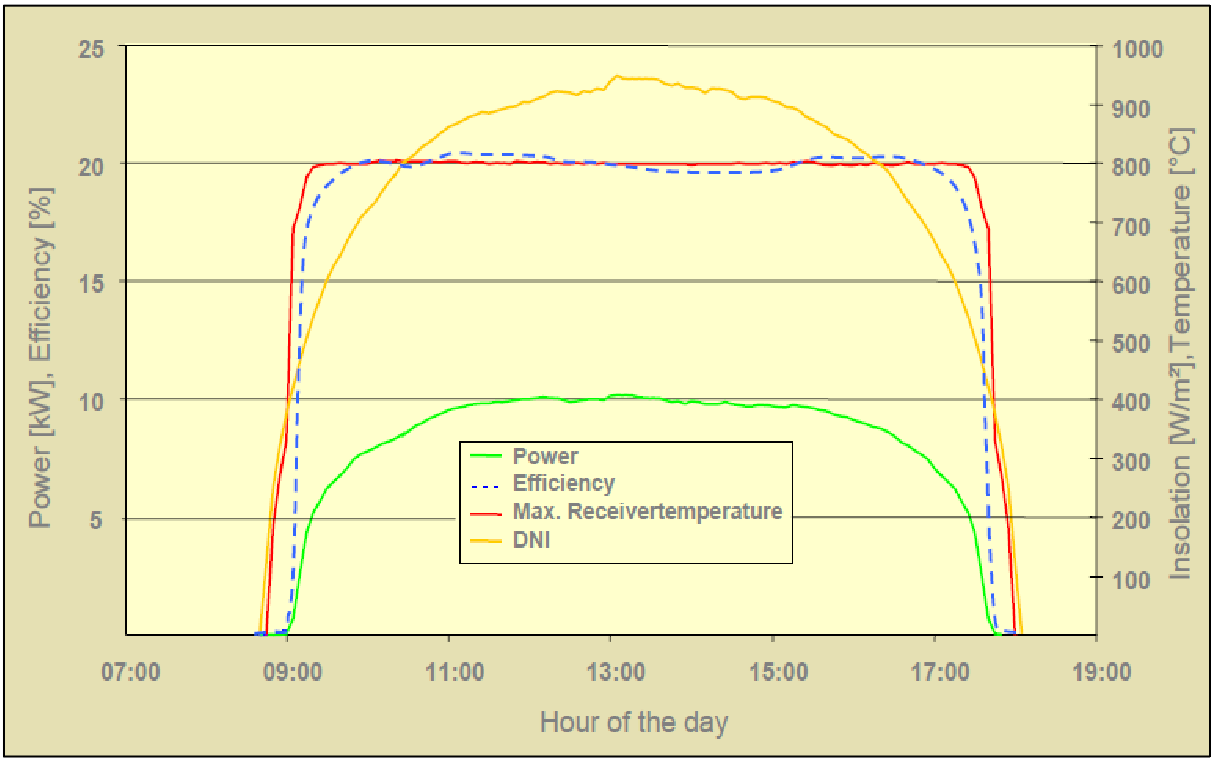



*Figure 30 - Typical operation day in Spring (Measured on Feb. 2005 in Seville) [18]*


*Figure 31 – Eurodish – WF pressure in the engine [20]*

**References**

[1] Winter C. J., Sizmann R.L., Vant-Hull L.L., Solar Power Plants – Fundamental, Technology, Systems, Economics, Ed. Springer-Verlag, 1991

[2] Caputo C., Un acifra di merito dei cicli diretti", Il Calore, No.7, 1967

[3] Cerri G., Parametric Analysis of Combined Gas-Steam Cycles, Journal of Engineering for Gas Turbines and Power, Vol. 109, 1987

[4] Kongtragool B., Wongwises S., A review of solar powered Stirling engines and low temperature differential Stirling engines, Renewable and Sustainable Energy Reviews, Vol. 7, 2003;

[5] Solar Dish Engine, from the web site: www.solarpaces.org;

[6] Stine W.B., Diver R.B., A Compendium of Solar Dish/Stirling Technology, SAND93-7026 UC-236, 1994;

[7] Smith R., Cohn L., Solar Support, Sun & Wind Energy 5/2010;

[8] Web site www.heliofocus.com;

[9] Il solare termodinamico, Le tecnologie dei Dish – Stirling, web site www.solaretermodinamico.it , 2012;

[10] Shaltens R. K., Comparison of Stirling Engines for Use with a 25-kW Dish-Electric Conversion System, DOE/NASA/33408-2, NASA TM-100111, AIAA-87-9069, 22nd Intersociety Energy Conversion Engineering Conference, Philadelphia, 1987;

[11] Greyvenstein G., Introduction to Dish Stirling CSP Technology, Solar South Africa, 2011;

[12] Smith T., Concentrating Solar Power Technology Workshops, Infinia Corporation Presentation, 2007;

[13] Mancini T.R., Solar-Electric Dish Stirling System Development, Sandia National Laboratories, USA, SAND-97-2924C, 1997;

[14] Infinia Corporation, 30-kW Maintainance-Free Solar Dish Engine, DOE Solar Programs Annual Review, Austin, Texas, 2008;

[15] web site www.innova.co.it , Trinum technical brochure, 2013;

[16] NREL Website, Marikopa Solar Project, 2013;

[17] SES – Stirling Energy Systems Inc., Solar Dish Stirling Systems Report, NREL CSP Technology Workshop, 2007;

[18] Rüdiger H., Dish Stirling, Seminar Alternative Energien;

[19] Deign J., The trouble with Dish Stirling CSP, CSP Today, 2012;

[20] Armanasco F., Brignoli V., Rossetti A., Miglioramento delle prestazioni del motore Stirling tipo V161 per applicazioni Dish/Stirling, Zeroemission Rome 2011;

[21] Abbas M., Boumeddane B., Said N., Chicouche A., Dish Stirling technology: a 100 MW solar power plant using hydrogen for Algeria, International Journal of Hydrogen Energy 36, 2011;

[22] Viebahn P., Kronshage S., Trieb F., Lechon Y., Final Report on Technical Data, Costs and Life Cycle Inventories of Solar Thermal Power Plants, EU Project NEEDS- New Energy Externalities Developments for Sustainability, 2008;

[23] Burrouhs C., Hecker L., Sandia, Stirling Energy Systems set new world record for solar-to-grid conversion efficiency, News releases, 2008;

[24] Videconomics, A Potential Role for an AMC in Supporting Dish/Stirling Concentrating Solar Power, Case study annex, 2010;

[25] IRENA-ETSAP and IRENA, Concentrating Solar Power, Technology Brief E10, 2013;

[26] Fraser P. R., Stirling Dish System Performance Prediction Model, PhD Thesis, University of Wisconsin-Madison, 2008;

[27] Schiel W., Geyer M., Dish Stirling Activities at Schlaich Bergermann und Partner, Workshop at NREL, 2007;

[28] Sanchez M., Concentrated Solar Thermal Power (CSTP): The road towards grid parity

[29] Jahromi M.Z., Bioki M.M.H.H. Fadaeinedjad R., Simulation of a Stirling Engine Solar Power Generation System Using Simulink, Acem – Electromotion 8-10 Sept. 2011. Istanbul, Turkey;

[30] Kaddour A., Benyoucef B., Simulation of Dish Stirling Solar Concentrator by Greenius Software, J Elec Electron 2012;

[31] Bittanti S., De Marco A., Farina M., Spelta S., Modelling and Simulation of Stirling Solar Engine, Dipartimento di Elettronica e Informazione, Politecnico di Milano;

[32] Howard D., Harley R.G., Modeling of Dish-Stirling Solar Thermal Power Generation, EFRI publication 1280258246;

[33] Howard D., Modeling, Simulation and Analysis of Grid connected Dish-Stirling Solar Power Plants, PhD Thesis, Georgia Institute of Technology, 2010;

[34] Mendoza S., Almazan O., Silva E., Guillen R., WREF 2012: Modeling generation systems from using solar stirling engines parabolic dishes (Solar/Dish), Solar 2013

[35] Diver R. B., Menicucci D.F., Dish/Stirling for Department of Defense Applications Final Report, SANDIA Report SAND97-0527, 1997;

[36] Roos C, Concentrating Solar Collectors, Solar Engineering, 2008;