S.E.P.P. - SOLAR ENERGY POWER PLANT

PROCESS HEAT AND ELECTRICITY
WITH
LARGE PARABOLIC DISH SYSTEMS - LPDS

Based on Study established for the
European Economic Community
Directorate 13, Brussels of June 21, 1983

Author:

TABLE OF CONTENTS

INTRODUCTION TO SOLAR THERMAL POWER CONVERSION

Various methods for capturing and converting solar energy in a useful way to man's requirements are known today, ranging from low temperature small domestic applications in flat plate collectors to concentrating devices such as parabolic troughs, bowls, heliostat-tower and dish systems as well as photovoltaic systems for electricity and process heat generation.

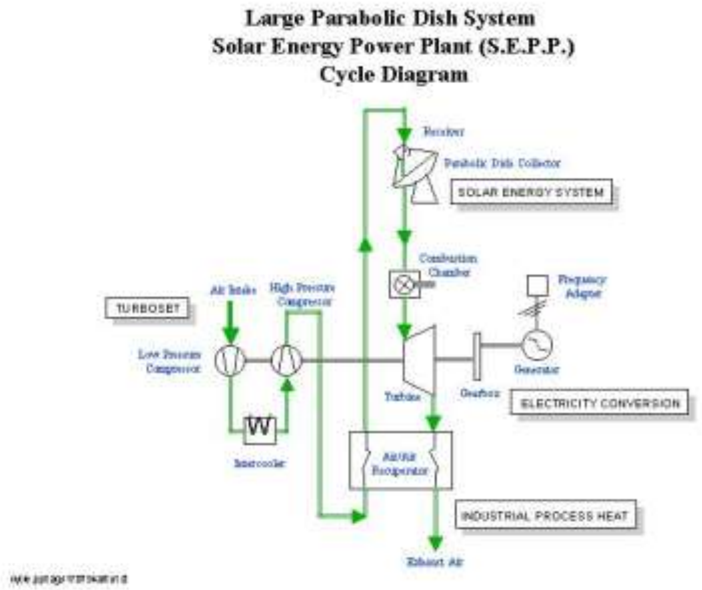
Solar thermal power systems utilize concentrated solar energy from direct radiation (as part of the entire solar insolation, i.e. diffuse and direct radiation) onto a surface normal in order to drive - via a suitable heat exchanging system - a heat conversion engine (prime mover) which produces either electric power or industrial process heat using steam, sodium, or gas (air, helium) as a working medium.

Advantages of Large Parabolic Dish Systems

In this paper we will confine our discussions to the smaller and medium scale solar thermal power plant for producing high temperature industrial process heat and/or electricity up to single dish systems for 2000 kW_{el}, using large parabolic dish collectors with an open cycle industrial gas turbine in the case where electricity production is implemented.

Comparisons with other types of solar thermal power plants show, that the Large Parabolic Dish System has considerable advantages over the heliostat-tower and farm concept:

- higher output in annual kWh(electric or thermal)due to constant two axis solar tracking without a cosine loss factor,
- higher conversion efficiency due to higher process temperatures,
- higher efficiency in electric power conversion due to constant heat flux distribution in receiver,
- high availability through the use of proven components,
- process heat availability in a wide spectrum of temperatures,
- waste heat utilization at temperature levels of 200^{o} Celsius in case of electricity production can bring plant efficiency up to 85%,
- service and maintenance requirements low,
- simple and reliable cycle using air as working medium,
- low thermal inertia for fast system start-up time,
- potential for even higher usable process temperatures through the use of ceramics in receiver and turbine for future generations of LPDS,
- compact, stand-alone system with 24 h system use due to hybrid mode (electricity generation).



This paper describes two kinds of parabolic dish collector systems:

(1) ***LPDS*** - 500 kW_{el} demonstration power plant with emphasis on electricity generation and the use of waste heat, applying a 56 m diameter large parabolic dish collector with a gas turbine, in hybrid firing mode for use in developing countries as a stand-alone power generation system for electricity and high temperature process heat.

(2) ***HIRST*** - High Intensity Radiation Solar Test Station - 15 m diameter dish for process heat generation (130 kW) in developing countries and demonstration unit for applications of high temperature materials research (ceramics) for receiver, storage, and turbine development and alternate solutions for optical configurations for use in the next generation solar energy power plants of the Large Parabolic Dish System type.

MARKETS AND USER PROFILE

The markets and user profile of this type of solar power plant today can be described as the isolated load market where the user is generally isolated from a national grid. The local utility plant, if there is one at all, consists of a few diesel generators with possibly a small transmission and distribution network. This application is typical of small communities on islands, remote military installations, isolated industrial sites, and villages in developing countries. It is certainly these markets that will allow the economic penetration of solar energy in the very near future, together with co-generation in suitable industrial countries with sufficient insolation per year to warrant the installation of costly solar energy conversion hardware.

A cost comparison of LPDS type solar power plants to the diesel generating set are described in a simulation model in “COST PARAMETERS FOR LPDS SOLAR ENERGY POWER PLANTS”.

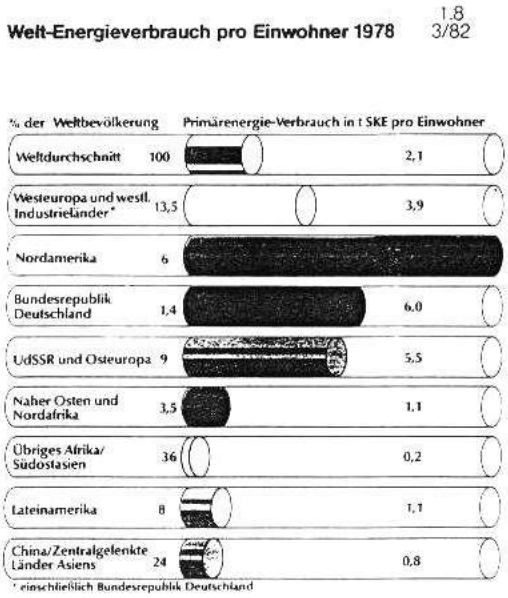


Fig 1 World Energy Consumption 1978

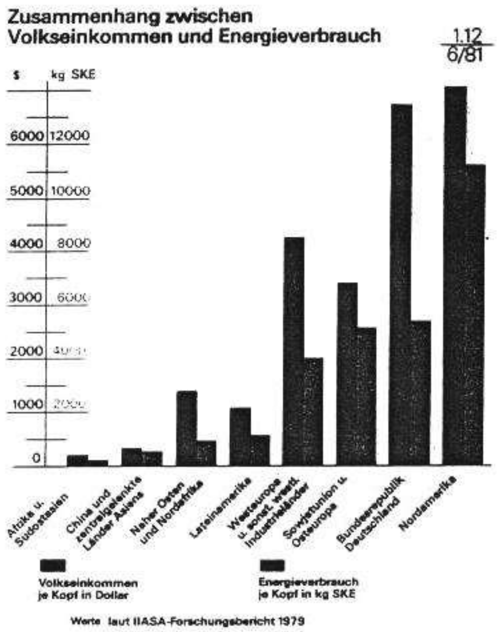


Fig. 2 Relationship between Public Income and Energy Consumption

The Isolated Load Market

Production cost of electric energy in the isolated load market is considerably higher than in large, grid-connected national networks. In these markets solar energy can provide competitively priced thermal and electric energy in utilities, industrial, and related applications for rural communities and farms, as well as municipal and industrial users through modular, individual stand alone systems of the Large Parabolic Dish System (LPDS) type.

Solar power plants today have been conceived as solar-mode-only plants. This may be adequate for experimental stations and in grid connected systems but is unacceptable for use in the isolated load market in developing countries where a stand-alone power plant is required. LPDS uses a hybrid firing mode to provide 24 hour system use.

From the experience gained up to now, it seems unlikely that solar power plants can compete with fossil and nuclear plants in the near future in grid connected systems; installation costs are considerably higher for solar power plants than conventional systems and, accordingly, the price per produced kWh. A dramatic increase in fossil fuel prices worldwide renders calculations very much more favourable for a plant life of 20 years in comparison to more than some 20 years ago when this paper was originally conceived.

The market and user profile in developing countries is entirely different from the industrial countries, with electricity consumption per capita decisively lower and the profile of energy use spread more into the application of high quality process heat especially in isolated load market conditions [Figures 1 and 2]. Conversely, fossil fuel cost can be extremely high due to important transportation costs in small quantities into such areas.

The application of the LPDS and HIRST type of solar power plant can be seen in either stand-alone or mini-grid configurations (arrays) in those markets.

SOLAR ENERGY POWER PLANT REQUIREMENTS

In general, a solar thermal power plant has to fulfill the following requirements:

1. cost-effective energy production
2. 24 hour system use
3. autonomous system
4. high plant availability
5. high thermal and electric conversion efficiency
6. operation and service with little man power
7. high temperature process heat production
8. electricity production and use of waste heat energy
9. clean and ecological system.

Line concentrators and heliostat-tower systems can only partially fulfill these requirements: it is important to keep the operation and the system as simple as possible within the above described markets where a solar power plant is to be installed since cost and maintenance is a major deterrent to the use of solar energy power plants in these areas. A LPDS employs standard components available in industrial applications: the dish technology is taken from radio astronomy and communication, the turbine and heat exchanger are standard industrial off-the-shelf proven products, receiver technology is applied from the experience gained in running more than a cumulated total of 500'000 hours in radiation heaters of gas turbine plants in West-Germany [Ref. 1].

Continuous production of energy is a user requirement that has been given far too little attention in the design and operation of present day solar power plants: only systems that can provide the user with a constant and guaranteed supply of the energy (thermal or electric) can be applied in areas with no grid support.

In the case of solar energy this means one of two or both things: (a) thermal storage for night and cloud periods or (b) hybrid operation, i.e. fossil fuel operation as an addition to solar radiation or in the absence of solar insolation.

Emphasis, therefore, has been placed on this requirement in the case of the Large Parabolic Dish System - LPDS: the demonstration power plant described in detail in this paper is equipped with hybrid firing through the use of a burner (combustion chamber) at the turbine inlet to assure continuous 24 hour electricity production. Solar power plants built in the very near future will have to resort to this hybrid firing method as suitable energy storage is not yet available, if they want to compete with existing energy production systems in the defined markets.

The 15 m parabolic dish - the High Intensity Radiation Solar Test Facility (HIRST) places emphasis on high temperature storage with simple media, as well as demonstrating the use of ceramic materials for higher conversion efficiencies through the use of high process temperatures. A 15 m dish can be applied as an energy production unit for high temperature process heat in developing countries. It would be prohibitive - cost-wise - to test ceramic equipment in the focal area of the Large Parabolic Dish System demonstration plant producing in excess of 1'500 $kW_{thermal}$.

GENERAL SYSTEM DESCRIPTION

This paper discusses both types of parabolic dish collectors - HIRST (High Intensity Radiation Solar Test Station) and LPDS (Large Parabolic Dish System); their different uses are described and their development potential explained.

HIRST - 15 m Dish Collector

The 15 m diameter dish collector will be primarily used for high temperature process heat 15 m diameter dish producing 130 $kW_{thermal}$ as such small engines do not warrant the production of electricity due to their low efficiency. As we are concerned primarily with state-of-the-art materials and available system components, we cannot recommend a suitable prime mover for this size of dish at the present time; future development of the Stirling principle and organic Rankine engine [Ref. 3] could become a choice in this size but can only be considered experimental prototypes at this time and, therefore, are not suited for applications in developing countries. The process temperature spectrum in this size of dish is interesting today to make this collector size desirable for industrial processes on a small scale in developing countries for the range of 900 – 200^o Celsius (higher temperatures in future generation collectors possible).

Dish technology in this size is widely used for communication and there is experience with hundreds of such structures available. A topographically sheltered location (see SITE SELECTION) allows a low cost structure on an equatorial mount with only one axis moving while tracking the sun to yield a cost-effective plant, the dish being app. 50% of total plant cost. Depending on the process temperature required, the use of steel alloys like Inconel or Incoloy being very expensive may not even be necessary. Only in applications where very high temperatures in the range of 800^o are used these alloys have to be applied.

Fig. 3 Solar Test Station at Crosbyton, Texas

As a first installation HIRST should be placed near a technology center where data acquisition computers and personnel can conduct the experiments in well-prepared test surroundings; a site in a third world country would not be advantageous for this research facility.

HIRST forms an important step in high intensity radiation experiment stations: the Jet Propulsion Laboratories Test Bed Concentrators (JPL TBCs) [Ref. 2] have a nominal 95 m^2 of reflective surfaces and deliver 83 $kW_{(thermal)}$ at 1000 W/m^2 solar radiation; the HIRST with its 175 m^2 surface would deliver 150 $kW_{(thermal)}$ under similar conditions. This forms an acceptable scaling step towards the Large Parabolic Dish System and still keeps cost to a minimum for hardware tests.

The HIRST will also test and demonstrate the SPHER receiver [Ref. 4] using ultra fine coal particles and regular stainless steel in all parts of the receiver for use in a next generation LPDS. The receiver outlet temperature from the SPHER can be as high as 1’000^o Celsius, the mass of carbon particles is minimal even for large power sizes; the simple design promises very high efficiency with minimal losses and high process temperatures.

One study program for the HIRST is a compound system for the optical configuration, the Cassegrainian arrangement (Fig. 4) with a secondary mirror in front of the focal area to reflect the partly concentrated beam down into the vertex of the dish, placing the receiver and power conversion system very close together to avoid heat transport losses. The trade-off in this system is the increased focal length and heat losses from the second mirror surface. In order to arrive at a high intercept factor, the secondary has to be manufactured to very high precision for optical reflection; against this cost stand the costs for the long hot gas duct and its heat losses. A very substantial advantage besides unloading the struts from heavy weight of the receiver is the small rim angle of the secondary beam in this Cassegrain configuration, making the RADIS CONE simpler in optical design and manufacture.

The HIRST will test secondaries and receivers to fulfill this condition; for relatively "low" receiver outlet temperatures involving steel alloys, this might represent a very interesting solution as the high focal plane temperature resulting from the high concentration ratio has to be degraded by the Radiation Distribution Cone (RADIS) in the demonstration power plant; physically speaking one creates undesirable entropy.

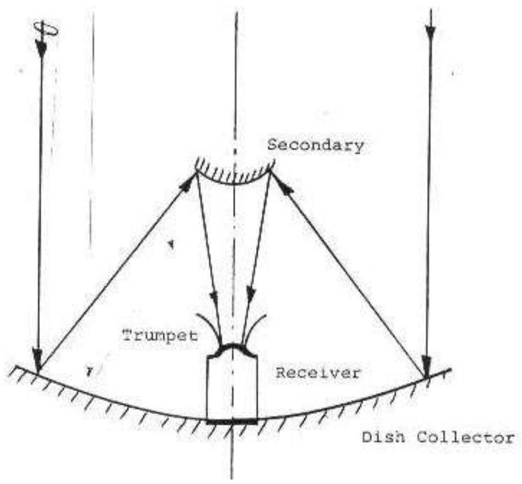


Fig. 4 Cassegrain Configuration for LPDS

Another HIRST program is to test RADIS - CONES (Radiation Distribution Cones) in ceramics for receivers of the LPDS type used in the demonstration power plant.

500 kW_{el} Demonstration Plant

The demonstration Large Parabolic Dish System is conceived as a 500 kW_{el} power plant in hybrid firing mode, i.e. the open-cycle gas turbine used to generate electric power is running on hot air coming from the receiver in the focal area of the 56 m diameter dish collector; in the absence of solar radiation (or insufficient radiation to maintain the power level required) the combustion chamber of the turbine is fired to maintain design power output at terminals.

The working medium is ambient air, which is heated to 800^{o} C in the receiver of this demonstration power plant. The hot air is led via a concentric hot gas duct to the turbine. The turbine used is a standard industrial gas turbine, normally running at 930^{o} C. In view of the application of high-temperature steel alloys in the receiver tubes and in order not to push to the limits of the material, maintaining the Bammert Criterion for the tubes, this "low" turbine inlet temperature has been chosen for the demonstration power plant.

A very interesting trade-off study can be performed in this connection: the industrial gas turbine chosen for this demonstration power plant has an inlet temperature of 930^{o} C, therefore running in this application on a reduced temperature level. The excess hybrid firing to bring the turbine inlet temperature to 930^{o} C represents a high level of exergy with a high efficiency for the fuel burnt. It should be considered, therefore, whether it would not be advantageous to the running of the plant to input this extra fuel into the cycle constantly and achieve an even higher efficiency of the cycle and the entire plant.

In the specific application the quantity of fuel used against the increase in electric power efficiency must be weighted. The result depends entirely on the price of fuel in the given location.

Optimized design data of the hybrid-mode solar gas turbine plant

CYCLE			
Enthalpy drop of the turbine	Δh	=	335.2 kJ/kg
Enthalpy rise of the LP compressor	$\Delta h'_{co}$	=	90.7 "
Enthalpy rise of the HP compressor	$\Delta h''_{co}$	=	91.8 "
Effective enthalpy drop	Δh_e	=	152.7 "
Enthalpy increase in the receiver and combustion chamber	$\Delta h_{r,c}$	=	393.5 "
POWER			
Power at terminals of alternator	P	=	500 kWe
Thermal power transferred to the working air	$\dot{Q}$	=	1,464.4 kW
Thermal power (recuperator)	$\dot{Q}_{re}$	=	1,312.7 kW
Cooling power (intercooler)	$\dot{Q}_i$	=	345.5 kW
Exhaust or reject heat	$\dot{Q}_w$	=	539.1 kW
EFFICIENCY			
Cycle efficiency	$\eta_{cy} = 1 - (\dot{Q}_i + \dot{Q}_w)/\dot{Q}$	=	39.6 %
Net efficiency	$\eta_{net} = P/\dot{Q}$	=	34.1 %
Efficiency of receiver incl. combustion chamber	$\eta_{r,c}$	=	83.0 %
Collector efficiency	ρ	=	81.0 %
Total efficiency	$\eta_{tot} = \eta_{net} \cdot \eta_{r,c} \cdot \rho$	=	23.0 %

Table 1 – Design Data of a Hybrid Solar Gas Turbine Plant

Considerations for Hybrid Firing

Ideally, a solar power plant should have energy storage to overcome cloud and night periods. Up to now, no simple and cost effective system is available for use for a reliable industrial application in the markets in question.

One of the goals for the 15 m HIRST is testing a storage system with high temperature thermal storage presently under study at the institute that could be applied to the next generations LPDS. The storage module uses the same cycle air and is conceived as a low maintenance system with MgO spheroids as storage material.

As an industrial gas turbine is always equipped with a combustion chamber it was a logical step to leave the combustion chamber in the system and use it for firing the turbine in cloudy periods or during the night to assure 24-hour electricity production. Depending on the cycle, the combustion chamber could be in series or in parallel with the receiver. The solution has become the parallel firing mode as the turbine unit is mounted in a counterweight configuration in the back of the dish; this has become necessary due to the fact that an industrial gas turbine cannot be tilted more than +/-15 degrees from the horizontal for lubrication reasons. The original design called for the turboset to be mounted directly behind the receiver up behind the focal area; in order to maintain this configuration, an aircraft turbine would have to be used with the disadvantage of a lower service and maintenance interval. An industrial gas turbine today has a service interval of once a year, whereas this time is much shorter in the case of aircraft turbines and not within the overall philosophy of the project.

Site Selection - Experience

All sites of solar energy power plants have reported 20 - 30% worse weather conditions - and consequently less hours of usable solar radiation - than assumed in their site selection studies. Some blame the volcano activities around the world for the increase in dust in the atmosphere or generally worse weather than expected.

The main problem is that site selection has not been given the proper attention in solar energy. A comparison with astronomy shows, that astronomers measure the weather and transparency of the atmosphere for years before an instrument is erected at a site; data collection on long range weather data is between 5 to 10 years in astronomy.

There is, of course, a direct influence of the local weather conditions for economic assessment of a solar power plant; even more so, since only the direct radiation part of the entire solar insolation can be transferred in thermal power plants. The thermodynamic cycle and component efficiencies are squeezed to the very last 1/10 of a percentage point - bad meteorological conditions at the site can destroy 20 - 30% of all calculated usable sunshine hours and thus influence performance by far greater than the thermodynamic cycle does.

From this experience we conclude that it is of prime importance to select a site for a solar thermal power plant with utmost care before any projections are made.

Meteorological Data Evaluation

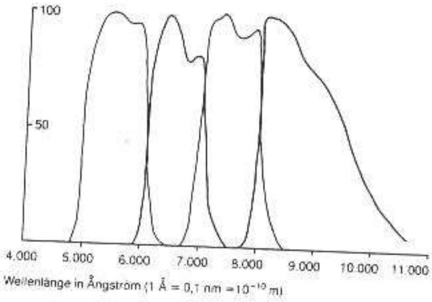
Meteorological data are most of the time inconclusive as to the usable sunshine hours at a given site since they do not split the radiation into direct and diffuse counterparts. The relationship of direct to diffuse radiation can be up to 50/50. High contents of water vapor and/or dust in the air can degrade performance of a solar plant by the given figures. Obviously, these sites are not suited for placing a solar power plant. Attention has to be given to the micro-climate of an area. In general, high altitudes must be preferred due to their lesser contents of water vapor. A site selection program has to include ground-based radiometers for measuring direct insolation and the comparison with locally available meteorological data as to weather patterns over many years.

Satellite Weather Observation

An important aspect for site selection is the use of satellite weather information from such satellites as METEOSAT, TIROS and LANDSAT. METEOSAT produces constant images of the entire European area with many parts of Africa, being in geo-stationary orbit. The resolution of METEOSAT is app. 20 x 20 km which is sufficient for a general weather pattern structure; data on tape is available easily back to 1979, with earlier data also accessible. By efficient use of algorithms, the resolution of METEOSAT data can be interpreted down to +/-2 km. Dust content in the atmosphere cannot be determined by METEOSAT data evaluation.

For more precise resolution and water vapor contents in the atmosphere, LANDSAT satellites provide very high-resolution images up to 80 x 80 m on the ground. LANDSATs have been in orbit since 1972 and provide continuous data from 14 revolutions per day (5). As an example, mapping all of Germany takes 7 days of LANDSAT images. The Multi Spectral Scanner "sees" the ground in the wavelengths as shown in Figure 5. This data permits interpretations - after digital image processing in the computer - for climatic studies, and micro climates in particular for a pre-selected site.

The combination of LANDSAT, METEOSAT and radiometric data from ground based direct insolation measurements yields a conclusive argument for a particular site for a solar power plant.



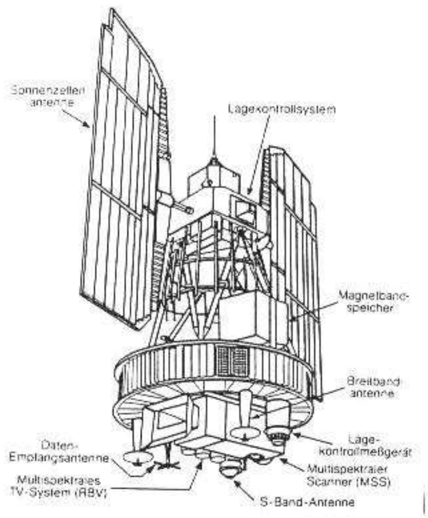


Fig. 5 Landsat Multi-Spectral Scanner

A study in the institute has been proposed to calibrate the sensors aboard the satellites via the reflection of Laser light scattering in order to achieve direct insolation data: a laser mounted alongside the telescope is aimed at the satellite and the amount of reflected light off the satellite measured through the telescope. The beam divergence of the Laser is known, the strength of the received signal in the telescope directly proportional to the absorption coefficient in the air mass. Combined with ground based radiometric data, this yields a value for extrapolating past and future satellite data.

Collector Placement

In the interest of a light-weight (cost-effective) collector structure, the collector has to be placed in a topographically sheltered position. Any structure that is exposed to high wind loads has to be more expensive in construction and upkeep. The site for a sheltered collector placement, therefore, is on the slope of a hill, facing south on the northern hemisphere (and north on the southern hemisphere). The mount and dish structure should be built into the hill slope as much as the turning angle for viewing the sun at all times throughout the year permits. Excavation work is cheaper than adding stiffening members to a free standing dish.

The slope of the hill and "burying" of the dish structure into the ground is a function of site latitude. The dish only has to access an area +/-23.5^{o} north and south of the celestial equator; it is easy to see from the drawings that an equatorial mount placed into the side of a hill provides the correct placement for such a structure. Theoretically, the dish could be placed as far into the ground as the annual solar ecliptic movement permits; in latitudes close to the equator, this is shown in figure [8] thus protecting the collector from high wind loads.

Flying sand and dust are a major obstacle to solar collector panels; dust degrades the reflective surface coefficient of a panel considerably; values of non-washed panels are in excess of 30% less radiation reflection from the reflector surface - and the corresponding amount usable for power conversion. One solution to this problem is frequent washing of the panels which is manpower intensive, the first step, however, is trying to avoid excessive flying sand in the air: plant the surroundings of the solar power plant with grass, shrubs, or cover with concrete or asphalt - this still does not away with washing the panels for maximum reflectivity but stretches the time interval between washing cycles. An automatic washing system around the top rim of the collector dish with a spray down in the morning before sunrise is still the easiest and least costly affair, the water being filtered and regained to a large extent, collected at the bottom of the dish and re-used in areas where water is scarce. The addition of a solvent to reduce water surface tension prevents streaking of the drying surface. The automatic wash is the cheaper solution in the long run and guarantees optimum results for reflectivity which is the first requirement for a solar thermal power plant.

Mount

As discussed in a previous paper (Ref. 15), the basic principles of mounting a large parabolic dish for tracking the sun continuously are the Azimuth-over-Elevation mount with one axis pointed to the site zenith and the elevation axis perpendicular to the former; this system is used for heliostat mountings and primarily in communication where no specific guiding on a celestial object is required (a heliostat guides on the angle between the sun and the tower). AZ-EL mounts, as they are called, have the advantage of directing the load at all times onto their azimuth bearing. Dishes that are AZ-EL mounted require constant two axis tracking due to the movement of the sun in the sky being a function of the earth's axis and the equatorial distance; this is accomplished under computer control.

This mount encounters driving problems when the sun gets close to the site zenith: the azimuth axis has to turn with very high speed to accomplish the transition from an east to west position. For some sites in northern/southern latitudes where the sun passes through or toward of the zenith (latitudes <= +/-23.5^{o}) very high speed gear motors are required (cost considerations).

The Equatorial Mount

The mount type chosen for the Large Parabolic Dish System is the equatorial or polar axis mount: as the name implies, one axis is pointed towards the north pole with the declination axis at a right angle to the polar or right ascension axis. This mount has the advantage of having to acquire the sun once in driving both axes to the location (right ascension and declination coordinates of the sun) in the sky and from that time on only has to drive the polar axis to follow the sun throughout its diurnal cycle in the sky. Corrections in delta are only necessary for refraction and daily motion in declination by the sun, which does not exceed 1' in one hour (around the time of the equinox) [Figure 6]. The speed for driving the polar axis is constant (with the exception of small corrections for flexure and refraction) so that a quasi-constant speed gear motor can be applied for cost considerations. Guiding on the sun is done via a microcomputer to precision dictated by the gear trains. Tracking and guiding with walk-on/ walk-off procedures is discussed in the chapter "TRACKING".

The polar axis rests on two pillars with hydraulic bearings to take up the forces directed perpendicular to the polar axis and due to the site latitude into the south pad (in northern latitudes). Steel bearings (ball, rollers, etc.) cause too much friction, which in turn would require stronger motors for driving. This way, the load rests on a thin film of oil thus reducing friction to an absolute minimum; a 300 ton structure can be driven by a 1 kW motor using hydraulic bearings due to the slow speed required to follow the sun.

Alpha axis positioning is done via incremental encoders resolving to 3" mounted on the north and south polar bearing pads; they are interpreted by the driving control computer to filter mount flexure under wind and temperature conditions and shifting loads throughout the day. A non-repeatability positioning error of <30" can be achieved after calibration of the installation under different load conditions.

A lightweight structural design to minimize cost for placement in a sheltered area was discussed in a paper before. In an area where the mount can be placed into a hillside, the north and south polar bearing pads can be mounted directly into the hillside (rock, if available) to save erecting a support structure.

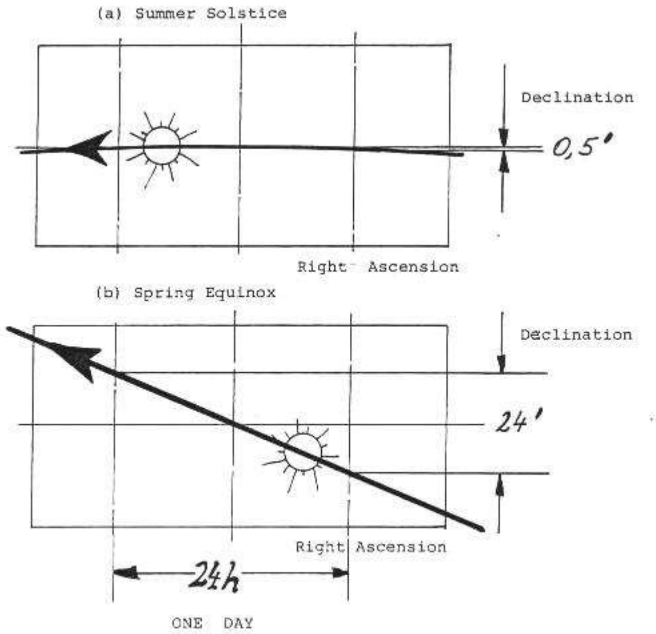


Fig. 6 Solar Motion at Solstice and Equinox

Motion of the delta axis is restricted to +/-23.5^{o} from the equatorial plane plus small corrections for mechanical flexure and refraction. The gearing can be simple with one motor and an arc of a helical spur gear app. 50^{o} wide. A study involving hydraulic push rods for the declination adjustments is currently being carried out. This would make a motor and gear train unnecessary and could save cost, as a hydraulic system is already existing for the north and south bearing pads. There is one hydraulic push rod on either side of the delta axis, enabling the dish to be held securely.

Dish Structure

The dish structure is divided into the following parts:

- delta axis
- parabolic reflector panel support structure
- reflector panels
- counterweight
- turboset container
- hot gas duct
- support struts.

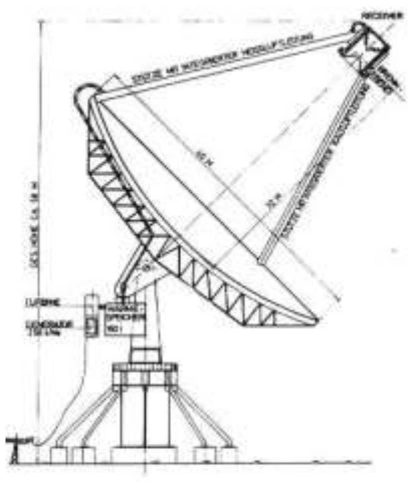


Fig. 7 LPDS Artist Concept, Free Standing

Delta Axis

The delta axis has been dealt with briefly before; it is permitting an access to the sky band +/- 23.5° from the celestial equator with an extra +/-1° for flexure and refraction when in low horizon position.

The two axes stubs are held in axial thrust ball bearings that take up the varying directional loads throughout the daily motion with preloads to prevent shifting of position when load reversal occurs at the meridian.

Delta movement is effected either by a helical spur gear section of 50° of an arc with one positioning motor and preloads via cable and weights or two hydraulic push rods to achieve the desired positioning. Another method that can be used instead of the hydraulic push rods is a pair of lead screws driven by motors and preloaded to assure stable positioning.

Position is input via incremental encoders located on both ends of the delta axis and interpreted by the computer to filter out mechanical flexure; the guiding and electronic specifications are giving in section TRACKING. Positioning accuracy in the sky is <30" for repeatability and only limited by the mechanical flexure parameters of the dish; computer positioning control is one magnitude greater and can filter out mechanical flexure after test runs under varying temperature and wind load conditions.

Parabolic Support Structure and Reflector Panels

The reflector panel support structure has the form of a paraboloid, segmented into equal truss arms to distribute the loads onto the bearings. This design is a standard dish design with parameters for maximum deviation from the true paraboloid to be defined with the manufacturer ("best fit paraboloid" method). The structure flexes to the shape of a paraboloid during the motion from east to west, with deviation from an ideal paraboloid held to a minimum.

Different approaches in reflector panels are being studied in combination with results from existing hardware. A selection of various approaches is given below with their advantages and disadvantages. The reflector panels can be adjusted individually to the desired flux distribution in the focal area. Surface precision is 1 mrad.

Aluminium Paraboloid Panels

Aluminium paraboloid panels 4 mm thickness overcoated with aluminium under high vacuum and SiO coated for protection from dust and sand to permit washing.

Advantages:

1. minimum transmission losses (<=1%) for reflected light.
2. true paraboloid shape for maximum concentration in focal area and highest temperatures,
3. no differential thermal expansion coefficients between support and reflective coating,
4. easy mounting on support structure by bolts (as in communication and radio astronomy),
5. Large panel sizes possible with light weight
6. Re-aluminizing possible by keeping original panel,

Drawbacks:

1. high cost for manufacture of masters,
2. careful cleaning required (automatic wash),
3. abrasive effects of sand stronger than on glass surface.

Foam Glass Panels

Foam glass panels as used by JPL Test Bed Concentrators 1 and 2. A substructure of foam glass is formed on a master. Panel thickness is app. 50 mm, size is 61 x 71 cm, mirror surface is 60 x 70 x 0.15 cm silvered and bonded with adhesive to foam glass, sealed at the edges, painted white (6).

Advantages:

1. tested material, working well in solar applications,
2. sturdy panel.

Drawbacks :

1. experience with relatively small panels,
2. heavier compared to (A),
3. bonding and adhesive can cause problems with delamination, blinding mirror surface due to water intrusion,
4. expensive process; price per square meter was app. US$ 250 for test bed concentrators (in quantities price would be greatly reduced).

Thin-glass Panels with Back-silvered Reflector Surface

Panel size app. 1 m x 1 m, cut to form concentric rings on dish structure. As with JPL panels, three different focal lengths are provided for inner, middle and outer panel radius. The panels are hot-formed glass on masters previously cut to size and back-silvered in a conventional way to reduce cost. Precision <= 1 mrad, thickness 3 mm. Manufacturing methods are well understood from making heliostat mirrors.

Advantages:

1. light weight
2. proven technology
3. good optical properties
4. cost effective process
5. low cost replacement
6. maintenance free.

Drawbacks:

1. thin glass - risk of breaking from strain and ice (hail),
2. have to be adjusted and held strain free.

The thin glass panels can also be arranged in square sections on the support structure, as in the case of JPL TBCs or Crosbyton Bowl. A study is underway to determine whether the square panels are cheaper to manufacture and their cost impact on the reflector surface total cost with support structure differences.

Panels are held in flexible mounts with sufficient distance between panels for temperature expansion and strain due to flexure of structure (typically 3 mm). Adjustments are made on three points.

Turboset Container and Counterweight

The dish structure requires a counterweight to balance the mount when turning during the day. Part of that counterweight function is absorbed by placing the turboset container behind the dish, hanging from the inner truss structure to allow the turbine to run horizontally (requirement of an industrial gas turbine) for lubrication reasons.

The gas turbine with its own control electronics (analog) is supplied as a complete unit by the manufacturer, including silencer and heat exchanger; this unit is a standard, off-the-shelf gas turbine unit with one-year service intervals and well suited for applications in the isolated load market.

Hot Gas Duct

Placing the turboset container behind the dish requires a hot gas duct to lead the air from the heat exchanger placed close to the turbine, to the receiver and feed the hot air down to the turbine. The system of concentric gas ducts is being used, as it is in operation for the Helium Turbine Plant Oberhausen [Figure 8], (8). The two gases - hot and cold - have minimal pressure differences and allow the inner skin of the hot gas duct to be very thin as it does not have to absorb the atmospheric pressure. This saves cost on the expensive material with insulation between the two concentric tubings.

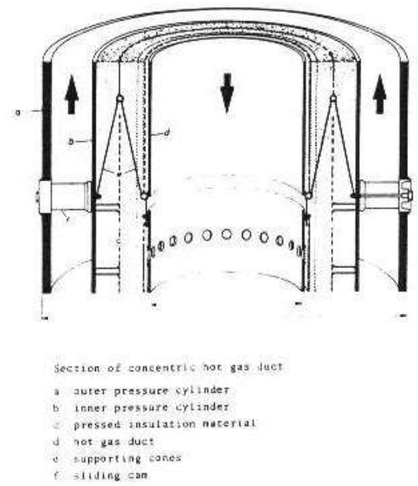


Fig. 8 Hot Gas Duct Oberhausen

A flexible joint between the hot gas duct and the turboset container allows movement of the axes alpha and delta while the container is hanging in a perpendicular position all the time throughout the day.

Thermal losses and pressure losses encountered are much less influential on price and performance of the entire plant than using an aircraft turbine with modifications and its short service time intervals; the added load of the turbine and generator at the focal area creates a high additional momentum that has to be absorbed by the dish structure, thus making it more expensive again.

Using the turboset container behind the dish has drastically reduced the total weight at the focal plane. The manufacturer is giving a total weight of the turboset assembly at app. 15 tons, excluding heat exchanger, but including generator (Ref. 8).

Support Struts

The receiver cage assembly is being held in place by three supporting struts that also house all the cabling for instrumentation and control electronics for data acquisition in the receiver and emergency shut down covers.

The struts are divided into a south strut, which includes the hot gas duct, and an east and west strut. The top portion of the struts holds a platform for the attachment of the receiver. The struts are designed to distribute the load of the receiver cage to the stiffening members of the dish structure and lead the forces into the bearings.

OPTICAL ANALYSIS

General Optical Data

The tradeoff between focal length and rim angle (receiver angle of incidence) is closely coupled with the intercept factor as well as momentum considerations of stiffness for the entire structure of the dish and receiver support struts; the longer the focal length, the greater the momentum of the receiver at the platform off the end of the struts, the more counterweight is required, the heavier and larger the struts have to be, etc.

In agreement with other project realizations, the JPL TBCs in particular, the optimum F/D ratio (focal length to diameter) has been set to F/D = 0.6; this results in a focal length of 33 m for the demonstration power plant collector (Ref. 10).

Panels used are spheroids of hot-formed glass with three radii for inner, middle, and outer circles. Optical manufacturing proposals are being studied at the present time to check for the most cost-effective solution. The decision parameters for the optical configuration coincide with the philosophy adopted by the JPL, Pasadena for their TBCs; experience throughout the past two years of running shows a satisfactory optical behavior.

The manufacture of spheroids is of course much less costly than off-axis paraboloids of glass; these would only warrant the investment of the masters if very large numbers of panels could be produced (series production of LPDS and HIRST).

In most cases up to now, insolation values have been used that turned out to be overly optimistic; when basing the dish and receiver configurations on too little values of insolation, however, overload of such components can result much of the time which then forces to walk off the sun to prevent damage; an example shall demonstrate this condition:

Insolation value (layout)	700 W/m^2
Receiver overload factor:	1.15 (= 805 W/m^2)(maximum)
Actual direct radiation	1000 W/m^2
Receiver overload	24%
Control Decision	permanent sun walk-off, start hybrid firing.

This has various financial implications: a large part (24%) of the solar power is not being used, the plant having been designed for lower insolation values, the receiver cannot be subjected to a constant overload, neither to increased thermal cycling by walk off/walk-on condition and, therefore, the control decision must be made to resort to hybrid firing, which on top of not having made use of the available solar energy costs money in fossil fuel firing for the entire net power (500 kW_{el}).

It is in this example - such insolation variation values are more common in good sites and have been witnessed by the author numerous times at Edwards AFB (JPL), SCRTF, Albuquerque/USA, and THEMIS, Targasonne / France - that the hybrid firing mode shows its operational advantages: the plant is laid out for 870 W/m^2 for the receiver net power value (without overload), resulting in a maximum receiver (with overload factor 1.15) load of 1000 W/m^2 In cases of lower insolation values, the combustion chamber is fired to add the energy required for net load; as mentioned before, this additional firing represents a very high value of fuel utilization and is financially sound practice as the most costly component, the dish, is kept smaller when laid out for 870 W/m^2 instead of 700 W/m^2 (24% reduction in surface area).

Adopting this philosophy, the demonstration LPDS plant for 500 kW electric output has the following parameters for the dish (Usable Dish Surface is defined as the net dish surface for radiation reflection from a surface normal to the incident solar radiation after subtracting receiver shadowing, struts, and panel gaps):

Dish Focal Length	33 m
F/D ratio	0.6
Diameter	56 m
Usable Dish Surface	2370 m^2
Shadowing (struts, receiver, panels)	<4%
Direct Radiation Layout Value	870 W/m^2
Maximum Direct Radiation assumed	1000 W/m^2
Receiver Overload Factor	1.15
Concentration Factor	3000 - 5000
Collector efficiency (reflective losses combined)	0.83
Panel accuracy	1 mrad.

Collector Efficiency

Losses of radiation are incurred in various parts after striking the surface of the panels. Long-term tests (3 years) on the TBCs have shown that the following data on reflective glass panels can be assumed to be realistic, provided the panels are washed in regular intervals:

Initial panel reflectivity	0.95
degrading to (assumed value)	0.91
Transmission losses into panel	0.96
Dust correction factor	0.975
Re-radiation losses	0.97
Collector Efficiency	0.83
(Power arriving at receiver opening)	

The above values are achieved with a surface accuracy for panels of 1 mrad at the TBC's.

RECEIVER

General Considerations

The receiver plays an important role in any solar thermal power plant design; it is the primary heat exchanger that transfers the visible solar radiation into infrared radiation and forms the critical link between the optical system (sun) and thermodynamic cycle. Many percentage points are lost in this conversion that influence overall plant efficiency directly; it is for this reason that the receiver must be considered the prime complex of the interface solar to thermodynamic cycle.

Very special attention has been given to receiver design [Figure 9]. The complexity of a receiver can be understood when looking at results from solar receivers built: the performance variations from design to actual test data vary as widely as 50%. This is due to two very difficult assessments, the thermodynamics of a receiver and its optical counterpart. While it is acceptable to transfer conventional heat exchanger techniques, the primary problems arise with optical configuration: how to get the incident radiation into the cavity so that the reradiation losses in the visible and infrared are minimal.

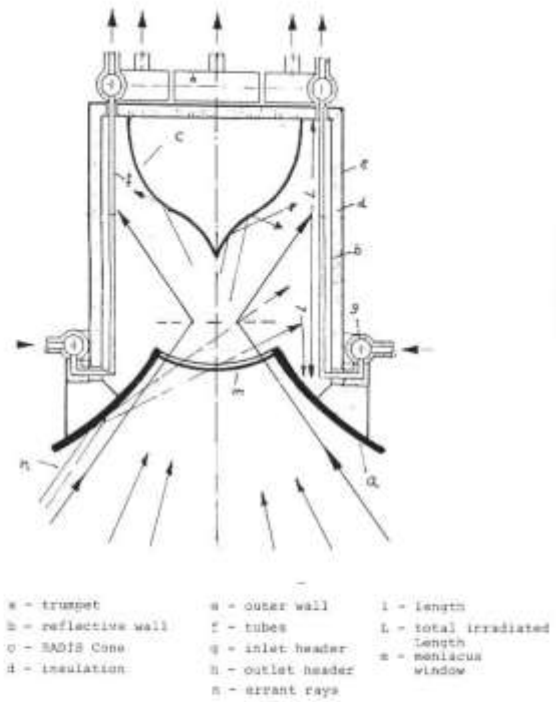


Fig. 9 Receiver

Causes for losses in and around a receiver are:

- capture geometry
- absorptivity of surfaces
- emissivity of surfaces
- aperture size
- convection losses
- radiation losses (external and through aperture)
- conduction losses to mount
- spillage
- heat exchanger characteristics
- insulation properties.

Test results with Brayton receivers (hot air from 800 – 1100° C) at the JPL TBCs have given the following test data for loss spectra (for a receiver efficiency of 85%):

* radiation	50 %	Improvement goal	15 %
* cavity convection	25 %	"	8 %
* conduction	20 %	"	5 %
* external convection	4 %	"	3 %
* reflection	<1 %	"	<0.5 %
* external radiation	<1 %	"	<0.5 %

Improvement must be made in the above figures and is to be seen primarily in radiation, cavity convection, and conduction. These developments are a major program point in HIRST and applicable with sensible scaling parameters for larger LPDS systems. Receiver efficiencies lie generally in the 75 - 85% range for hardware tested over the past years in Brayton or other cycles. Improvement in these figures by up to 10 percentage points can be achieved with the considerations for primary radiation control and careful receiver design, together with real tests from units installed in the HIRST.

Optical Properties

The receiver design for the Large Parabolic Dish System has been carefully studied and optical improvement results are presented here that should raise receiver efficiency considerably above the mentioned values.

Radiation arriving from the collector will be "spilled" by the amount of slope error on the panels, misalignment of panels, and tracking errors of the entire dish structure. Special attention has been given to these factors in the design of the LPDS receiver: this is why high accuracy for panels, their support, and driving of the collector are required.

The intercept factor is defined as the amount of radiation energy arriving at the receiver aperture and total solar energy arriving in the focal plane area. Careful consideration, therefore, has been given to bring as much energy arriving at the receiver into the aperture. A much widely used definition for concentration ratio is the aperture area versus the collector area. This stems from designs of heliostat systems, where the focal area is not well defined and due to large open cavities, the smallest aperture has to be adhered to. In a highly concentrating LPDS this is not possible. Walk-ons and walk-offs would damage the aperture mouth considerably due to the extremely high temperatures of the focal plane ($t > 3000^{o}$ C).

Window

The focal plane area lies well within the receiver cavity; the radiation enters the receiver through a window of fused silica of high purity silicate glasses (Corning No.7913 - Vycor No.7940 - Fused Silica, No. 7971 - Titanium Silicate). These glasses have maximum operating temperatures of 1170 K, 1170 K, and 1070 K, respectively. Cooling the glass can be achieved by blowing air onto its exterior or interior surface, if found necessary by air from the heat exchanger (the air that also cools the ceramic Radiation Distribution Cone).

To reduce glass reflectivity, two methods are employed: making the incoming angle of radiation perpendicular to the surface tangent (i.e. providing a meniscus lens design as a window shape and treat the glass by selective etching technique (as distinct from coating); this process reduces reflectivity to 0.25% per surface, as measured test data (Ref. 10) have shown. Absorbance in these fused silica glasses is <= 1.5%; the glass has a very low coefficient of thermal expansion, therefore, not being subjected to strain from temperature differences inside and outside of the receiver (see manufacturer's specification sheet).

The window has 2 cm in thickness, is meniscus shaped to the same radius as the dish and can be made large enough to accommodate a comfortable receiver opening in order to reduce spillage and increase the intercept factor; calculations by A. Hunt (Ref. 11) were based on a window with a diameter of 1.6 m.

Cavity Convection

One major consideration for the window is the closed cavity. One design also employs two windows for increased radiation reflection back to the inside; an analysis is presented by A. Hunt in (Ref. 11). With this technology, improvement as indicated for re-radiation and convection losses should be important and increase overall receiver efficiency substantially. Further testing of these concepts is done in the HIRST. Wind has been a known factor for convection losses in receiver cavities; the windowed receiver does not suffer from these phenomena.

Cavity convection has been the second most underestimated factor in receiver losses; natural convection and induced air currents can carry considerable amounts of heat out of the receiver opening of a cavity without window. Due to the many different, non-controllable factors (such as wind speed, direction) variations in amplitude of these influences can change from 0 - 50% in a short time interval and are difficult to impossible to control. Site-specific winds contribute to up to 50% of the receiver losses through convection. It is here that the window really is worth its investment!

Geometrical View Factor

The geometrical view factor is another important aspect of receiver design: once radiation is inside (the entering radiation is in visible wavelengths), it must be trapped in order not to be able to escape from the cavity aperture in the form of reflection in the visible or infrared spectrum. This is fulfilled by one function of the Radiation Distribution Cone (RADIS). Once solar radiation has entered the cavity, it is "trapped" by the optical surface geometry of the receiver to remain locked inside until transformed into infrared radiation. The selective etching process and the low IR-transmissivity of the window material ascertain good re-radiation properties.

Trumpet

In order to improve the intercept factor further, i.e. reduce spillage around the receiver aperture window in order to collect as much of the delivered solar flux into the cavity, a so-called "trumpet" is employed. The trumpet is a secondary concentrator as shown in Figure 10 and can assume both shapes (a) and (b), an open hyperboloid of revolution or a closed one; simple ray tracing shows, that both types can be considered when using cone optics. The hyperbola is shaped in such a way that the maximum spillage encountered due to bad tracking and panel inaccuracies still forces the radiation inside the aperture window. As this secondary reflector is well ahead of the focal plane and the radiation is grazing, heat does not play a role and it can be manufactured of simple sheet aluminium coated for maximum reflection. The trumpet is an item not requiring servicing or maintenance and not costly in manufacture but contributes considerably to the intercept factor performance of the receiver.

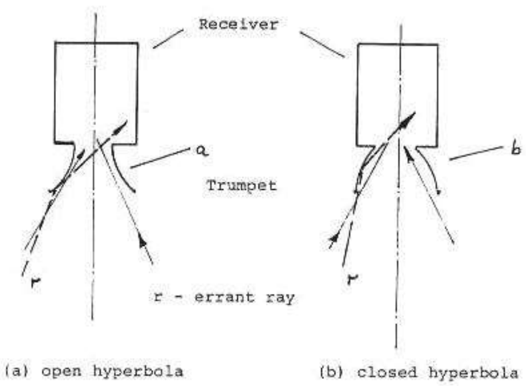


Fig. 10 Trumpet

Spillage around the receiver can be seen in the enclosed photograph of the THEK dishes (10m diameter) at THEMIS, France [Figure11] and the TBCs at JPL.

Fig. 11 Spillage at THEMIS, France

Emergency Aperture Closure System - EACS

A very important aspect for material safety of the receiver and its associated components, including struts, is the Emergency Aperture Closure System - EACS [Figure 12]. In case of a guiding and tracking motor or program error, receiver damage, power failure etc., it is extremely important to have an emergency shut-down of the impinging radiation into the thermal cycle system as quickly as possible. Due to the nature of the tracking motors - or their failure in an emergency, one cannot rely on fast slew speeds but must provide other means to prevent radiation from entering the receiver.

The EACS consists of a positive closure contact relay system holding two radiation reversal cones analogous to the thrust reversal system of a jet engine: in case of an emergency or power failure, the relays open, and the two spring-loaded doors normally parked alongside of the receiver exterior fall shut and close off the receiver aperture from receiving any radiation.

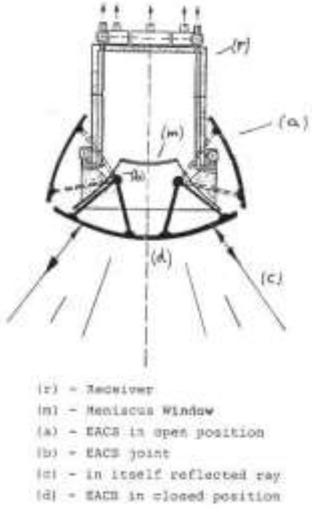


Fig. 12 EACS Emergency Aperture Closure System

The EACS surface geometry is designed in such a way that the impinging radiation from the dish is reflected into itself, i.e. the surface radius of the EACS system is equal to the parabola of the dish; the radiation is reflected back onto the dish and leaves the dish as it came in. In a power fail emergency (see TRACKING AND CONTROL), the overbalanced dish structure moves northward and brings the beam out of the strut and receiver area in order to avoid damage due to overheating by the beam walk-off.

The EACS is well inside the focal area of the dish and, therefore does not overheat from the radiation. It can be manufactured from aluminium and coated for maximum reflection of radiation. The system is self-closing through gravity and spring-loaded in the event of a power failure.

Interior Receiver Geometry

The functioning of the receiver as a thermal unit serving as the heat exchanger is described in the next chapter; here, its inside optical properties are discussed. They are primarily the Radiation Distribution Cone - RADIS made of ceramics and the reflective wall surfaces of the receiver cavity serving to reflect the incident radiation in such a way that the steel alloy tubes are loaded as equal as possible in their circumferential angle (phi) Φ (Ref. 13).

At first, the impinging radiation into the windowed cavity is in visible wavelengths and has to be treated with geometrical optics through ray tracing of cone optics behavior in order to distribute the radiation well before being absorbed by the heat exchanger tubing and transformed into infrared. It is then treated as a black (more precisely "gray") body radiation problem in thermodynamics. This important step was often overlooked in receiver geometry and forms the part called the "geometrical view factor".

One of the decisive advantages of parabolic dish systems over other types of solar power plants is the controlled and even heat flux distribution allowing the use of the Bammert-Criterion for loading the steel alloy tubes with radiation along their entire length in a specific fashion as dictated by the internal stresses in the tube material due to differential temperature gradients along the length of the tubes and their circumference.

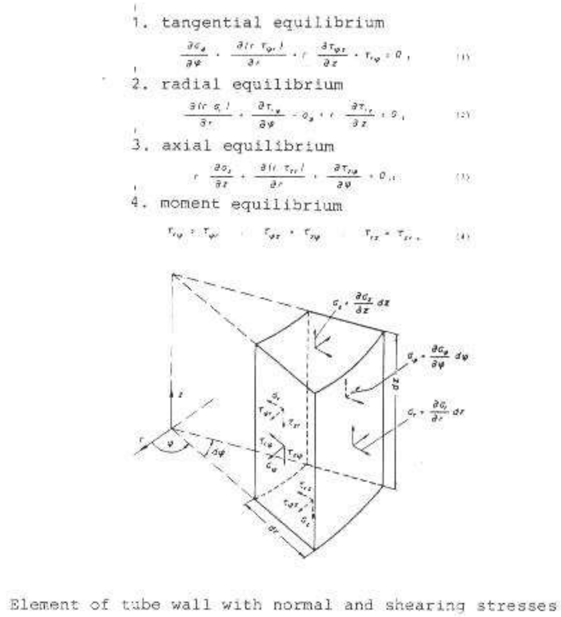


Fig. 13 Tube Load in Solar Receivers

The tubes are arranged in a circle with inlet and outlet headers on the top and bottom of the receiver. There is a defined tube spacing ratio (gaps) between the individual tubes to allow radiation to hit the reflective rear walls and permit re-radiation of the energy to the back of the tubes that otherwise would only receive IR radiation from the insulated wall surface [Figure 13].

RADIS Cone

After entering the receiver through the window, the focal plane area is inside the receiver cavity, the rays diverge and hit the RADIS CONE to be geometrically distributed to enable the desired load on the tubes [Figure 14] This involves complex cone geometry depending on the receiver physical layout and shape factor, forming concentrating and diverging surfaces to achieve the desired effect for the Bammert-Criterion. Due to the high inside temperature and proximity of the RADIS CONE to the focal area, it is manufactured of ceramics and cooled with cycle air entering the receiver coming from the heat exchanger, being preheated and led into the inlet header. The ceramics is glazed and coated for optimum visible and IR reflection, analogous to high power Laser optics coatings in fusion research.

Reflective Wall

Radiation that passes through the gaps in the tubes (tube spacing ratio) hits the rear wall of the receiver; still being in the visible light wavelengths, the radiation is reflected back onto the rear of the tubes in order to reduce the circumferential stresses in the material (Incoloy or Inconel) due to temperature gradients in axial, radial, and circumferential direction; the more even the radiation load can be distributed, the better the Bammert-Criterion can be fulfilled and higher total tube loading implied. All this reduces stresses and increases tube life for a very costly material - increasing at the same time the heat transfer properties and, therefore, the overall receiver efficiency, being a direct measure for plant efficiency.

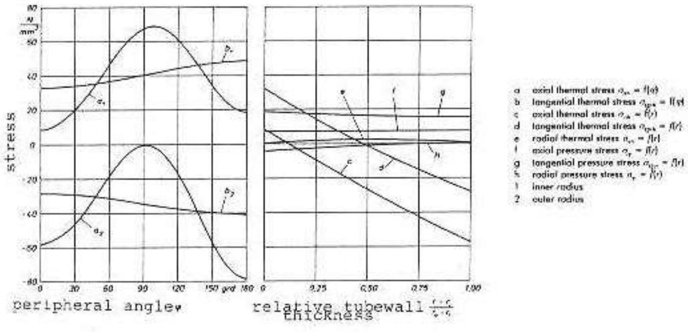


Fig. 14 Circumferential Load on Receiver Tubes

The bottom parts of the receiver around the window opening are also shaped to reflect the radiation coming off the tubes and the rear wall reflection back into the cavity to retain all radiation inside; the positive geometrical view factor of the receiver is a strong contribution to its efficiency. The reflective surfaces in the visible spectrum all reflect the infrared radiation and help diminish radiation losses.

Receiver Thermodynamics

As stated before, receiver technology has been transferred from more than 500'000 working hours of radiation heaters in German closed-cycle gas turbine plants. Bammert has reported on various occasions and described in great detail the underlying thermodynamic properties for the selection of the principle for the receiver in the LPDS (Ref. 11)ff.

The specific layout and cycle data for the Large Parabolic Dish System demonstration plant for 500 kW_{el} are presented in this section.

Basic Thermodynamic Layout Parameters of LPDS:

- electric power 500 kW
- working medium air
- turbine inlet temperature 800^{o} C
- open cycle industrial air turbine
- hybrid firing with combustion chamber
- a recuperator is used
- cycle calculations given for system with and without intercooling
- receiver efficiency calculated to 83% including combustion chamber
- net cycle efficiency 34.1%.

Detailed data for components are given in Table 5.

Receiver Layout

In the receiver for a 500 kW_{el} solar gas turbine, thermal power of 1'464 kW must be transferred by radiation to the working air. The heat flux distribution inside the receiver was varied so that the quotient of the maximum stress and allowable stress in the tubes achieves the permissible value of 1.0 (Bammert-Criterion). The maximum stress is defined as the combined stress resulting from three-dimensional thermal stresses and pressure loading. The allowable stress is obtained from creep properties of the tube material and is a function of the local tube temperature. The quotient of maximum stress and allowable stress is called the coefficient β (beta). Based on these principles, Table 5 gives the design values of the receiver. The optimum cases (β = 1 for the entire tube length) were calculated for two spacing ratios (t/d = 2.7 or 2.0) with the shape factor D/L in case two being the more attractive one.

A cylindrical cavity receiver is described below. Working air enters the inlet header (g), flows through the tubes (f) located in front of the receiver inner wall (b), and leaves the unit through the outlet header (h). The total irradiation length is (L) with the current irradiated length (l). The tubes have an outer diameter d(o) and are arranged at a spacing (t) on the pitch diameter (D).

CYCLE LAYOUT

Selection of the Basic Cycle

The cycle diagram of a gas turbine process incorporating a recuperative heat exchanger and an intercooler is shown in Figure 15 (recuperative process). The atmospheric intake air compressed in the low-pressure compressor (a) is re-cooled in the intercooler (b) and raised to the maximum process pressure in the high-pressure compressor (c). The compressed air is preheated to the receiver inlet temperature in the recuperator (d) by heat input from the hot turbine exhaust gas. The upper process temperature is reached in the receiver (e) by means of solar radiation input. A combustion chamber (f) downstream of the receiver is able to substitute fossil fuel for the missing solar radiation. The air expands in the turbine (g) releasing mechanical energy to drive the compressors and generator (h). From the turbine outlet the exhaust gas passes to the low-pressure side of the recuperative heat exchanger in which it transfers heat to the high-pressure side. The remaining reject heat (waste heat) is discharged to the atmosphere via the chimney or can be used for process heat generation. Reference points 1 to 8 denote the entry of the working fluid into the respective cycle component.

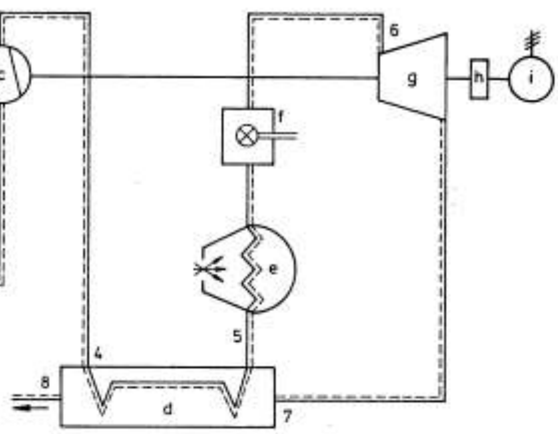


Fig. 15 Cycle Diagram LPDS

Thermodynamic Optimization

The cycle concept is followed by thermodynamic optimization. For this operation, a number of layout parameters have to be selected. The predetermination of realistic values for these parameters requires a lot of experience. Table 2 shows the layout parameters, which influence the net efficiency of the gas turbine plant. Net efficiency is defined as the quotient of power available at the generator terminals and heat absorbed by the working air in the receiver and combustion chamber. The maximum limit temperatures for air as a working medium are app. 800^{o} C for high-alloyed tube metals in the receiver. The minimum process temperature, i.e. the compressor inlet temperature is strongly dependent on climatic conditions. The temperature difference of the recuperator has a pronounced effect on the cycle efficiency and on the size of this component. In order to cool the blade roots in the thermally high stressed first turbine stages and to cool the rotor, cycle air is tapped from the HP-compressor. The cooling air-flow rate is two percentage points of the mass flow rate of the HP-compressor. It has a strong influence on the output power and efficiency.

With these layout parameters a thermodynamic optimization was carried out taking into account the real gas behavior. The net efficiency and the turbine mass flow rate are plotted against the turbine expansion ratio for a 500 kW_{el} plant with air as a working medium. It can be seen that the maximum cycle efficiency is at a lower pressure ratio than the minimum mass flow rate. Due to smaller sized cycle components with decreasing mass flow rate, the design point of the turbine expansion ratio has been chosen just above the one leading to maximum efficiency.

Table 3: Layout parameters of optimized gas turbine cycle

output at terminals		500	kWe
working fluid		air	
turbine inlet temperature		800	°C
" " pressure		4.63	bar
pressure ratio of expansion		4.5	
isentropic turbine efficiency		88	%
cooling coefficient		2	%
number of intercoolers		1	
compressor inlet temperature	LP	20	°C
" " "	HP	20	°C
pressure ratio of compression	LP	2.24	
" " " "	HP	2.24	
isentropic compressor efficiency	LP	84	%
" " "	HP	83	%
temperature difference of recuperator		40	°C
efficiency of heat exchanger		87	%
recuperator inlet temperature (cold)		111	°C
" " " (hot)		489	°C
receiver inlet temperature		449	°C
sum of relative pressure drops		10.4	%
from ambient to 1 0.6 %	see Fig. 2		
" 2 " 3 0.8 "			
" 4 " 5 1.2 "			
" 5 " 6 5.0 "			
" 7 " 8 2.14 "			
" 8 " ambient 0.66 "			
mechanical efficiency		99	%
gear "		96	%
alternator "		93	%
turbine mass flow rate		3.8	kg/s
volume flow rate at turbine inlet		9,009	m^3/h
" " " " LP compressor		11,591	"
" " " " HP compressor		5,222	"

Table 2 Layout Parameters of Optimized Turbine Cycle

Layout Data

The expansion ratio of the turbine was chosen to be 4.5, which makes all necessary data of the cycle available. Table 3 lists the temperatures and pressures for the inlet points. The detailed layout parameters of the cycle are compiled in Table 3 and the final design data of the hybrid mode solar gas turbine plant are presented. All data are based on a net power of 500 kW_{el} at alternator terminals. A thermal power of 1'464 kW has to be transferred to the working medium inside the receiver tubes. The net efficiency of the gas turbine plant is 34.1%. Taking into account receiver efficiency and combustion chamber efficiency, with optical collector efficiency, a total efficiency of (eta) η_{plant} = 23 % is obtained. This figure is based on very conservative assumptions and should come out even better with the additions mentioned to the receiver under RECEIVER after refined calculations.

Maximum continuous rating 500 kWe		design data	
inlet spot	Component	temperature °C	pressure bar
1	LP compressor	20	0.994
2	intercooler	110	2.223
3	HP compressor	20	2.205
4	recuperator HP	111	4.932
5	receiver/combustion chamber	449	4.873
6	turbine	800	4.630
7	recuperator LP	489	1.028
8	exhaust or reject heat	160	1.006

Table 3 Working Air Conditions in Air Turbine Cycle

TURBO MACHINERY

For an output of 500 kW_{el} an open cycle gas turbine offers a reliable and cost-effective solution; overall dimensions and blade heights lead to reasonable efficiency values.

In accordance to the above mentioned cycle optimization, a standard off-the-shelf gas turbine has to be selected for the plant. Offers requested from several suppliers have shown that various manufacturers offer a suitable solution to the turbo-machinery requirements. An offer and data sheets from KHD comes closest to the desired optimum layout parameters with the least amount of changes (Ref. 8). The company has developed a T-joint to accommodate the combustion chamber and solar firing as required under the project. Actual engineering has to be finalized but is not considered a problem. GEA have offered to supply a heat exchanger that has already been coupled to that turbine arrangement. The entire unit is mounted conveniently in a container including control electronics (analog) for the turbine and generator; the installation serves normally as a mobile power generation station and can be transported by truck due to its compactness. The entire power conversion unit would be mounted in its container in the back of the dish, with the hot gas duct coupled on the T-joint with the combustion chamber.

TRACKING AND CONTROL SYSTEM

General

For the HIRST and demonstration LPDS power plant, many functions are displayed and monitored that would not be given attention to in a series production LPDS or HIRST; it is through the wide range of display possibilities and interaction with control functions - mechanically and thermodynamically - that a better understanding for visitors and operators of solar power plant operation can be achieved and the operation of a hybrid plant explained. Series production HIRST and LPDS will run under automatic computer control with the input for parameters from the two projects proposed here. In the isolated load market, little attention can be given to plant control; therefore, automatic operation is an essential feature for remote sites.

The tracking and control system are subdivided into a mechanical/electric and electronic part subsystem.

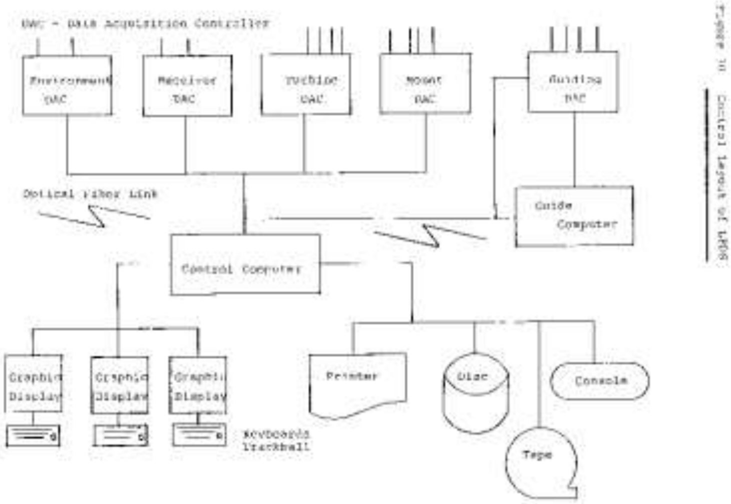


Fig. 16 Tracking and Control

The mechanical parameters are the driving motors of the dish in both right ascension and declination (or their hydraulic counterparts), the emergency aperture closure system EACS with its receiver and mount components, the turbine control valves as supplied by the manufacturer for flow and pressure, and thermal control with firing of the combustion chamber.

The electric components for the individual mechanical subsystems consist of relays and power switches, as standard equipment in power plant machinery control.

Electronics

The electronics for the solar power plant control are subdivided into the solar tracking micro-computer as a stand-alone unit, the data display system for environmental conditions (wind, insolation, etc.), and the data acquisition and display subsystem for the thermal and electrical, as well as mechanical parameters of the plant [Figure 30]. All data acquisition is processed in the data accumulators and preprocessors, located as close as possible to the data acquisition site; preprocessed data is then transferred via optical fiber cables to the main control and data acquisition computer for logging and display in quasi-real time (i.e. very short time intervals before new data set update is displayed on the graphic screens).

Guiding

The tracking and control system is laid out in a redundant form, as is usually found with power plant computer control; there is a backup system available for tracking should the primary guiding computer fail. The data logging and display computer will take over guiding the dish in addition to its job as data logger and display system; return times of data on the display screen may be somewhat slower in this case, solar power production, however, is not interrupted and notice is given to the operator to check the problems of the guiding computer without initiating an EACS task.

The solar coordinates are calculated by the computer and checked against the sensor position of the sun for optimum guiding parameters. Dish positioning is achieved through refraction tables and astronomical ephemeris. Guiding is only limited by the mechanical structure stiffness and its flexure under wind loads. These parameters are logged constantly and serve to initiate correction tasks for maximum precision guiding of the dish.

With the encoders used, precision of 3 arc-seconds can be achieved, one magnitude smaller than the mechanical guiding specification, interpretation of mechanical parameters leads to a tracking precision of <30" for both axes.

Emergency Walk-off

Emergency walk-off procedures are pre-programmed for various positions of the dish assembly in the sky to allow safe walk-off for the receiver and struts, complemented by the EACS; as mentioned before, the positive closure contact relay system assures mechanical functioning in case of computer error or power failure.

The sun avoidance path is such that the collector is (on the northern hemisphere) always north-heavy (overbalanced to the north) with the struts south, east and west, the beam on emergency walk-off passes through the "empty" north zone and is reflected harmlessly into the air. As with heliostat power systems, there is a danger zone on beam walk-off defined around the collector.

An emergency walk-off causes the EACS to initiate and is triggered by the following events:

- power failure,
- alarm inputs from dangerous levels of temperatures inside and outside of receiver,
- main computer failure,
- alarm inputs from cycle (turbine, hot gas duct, generator, valves, pressure drop, etc.).

Graphic Displays

The plant status with all parameters important to plant control is constantly monitored and displayed in the control room on color graphic display monitors. The programming is such that the operator can have an interactive dialog with the screen function in question and descend into levels of display for more precision in the monitored data without interrupting the on-going operation of plant control.

The displays are refreshed in quasi real time for all important plant data on environment, optical parameters, tracking, and the thermodynamic cycle with a status of switches, valves, etc. The operator can transfer control to mechanical guiding or system operation via analog instrumentation as in conventional power plant design.

The graphic display systems serve as a backup computer and thus can also assume tracking in case of a guiding computer failure. Colour graphics contribute much to increased understanding of power plant control functions and are of the intelligent type, i.e. they have to be fed data and commands from the main computer only for their display functions.

COST PARAMETERS FOR LPDS SOLAR ENERGY POWER PLANTS

General Considerations

Cost predictions for large quantities of solar energy power plants are very difficult; a reasonable approach is to take the present data and parameterize these data for the specific site values, particular installation parameters of the individual plant and give advice to future builders of similar plants what to look out for: this was the result of a constituting meeting at the DLR, Cologne Germany of a Working Group called "On the Economic Assessment of Solar Thermal Power Plants", in May 1983 where the author was a member. The difficulty lies in the experimental nature of all present day solar energy power plants: to apply regular industrial parameters would be non-conclusive. It is assumed that solar cost projections from DOE, JPL, Sandia Laboratories, et. al. are known from the literature. All follow more or less the mass production cost reduction schemes and arrive at low collector cost and power conversion unit prices for large series to mass production of heliostats or dishes in the year 1990 - 2020.

Instead of basing our calculations on competing systems with large power grid structures today involving difficult economic assessment parameters such as tax rebates, etc., we see the market penetration at the present time and the near future in the application of LPDS and HIRST type plants in the isolated load market, as stated under 1.2 in this paper. Developing countries have different energy consumption schemes from the industrialized countries and their fossil fuel import costs cannot be compared to the cost in industrialized countries.

Solar energy power plants of the LPDS type can be placed as stand-alone systems in remote areas and also form a local grid structure when arrays of LPDS are employed.

The *demonstration* LPDS plant and HIRST should both be placed in an area with high technology access and not in a third-world country; it is with these first LPDS plants that experience for future and series production power plant units can be gained, essential for cost-effective system development.

LPDS Demonstration Plant Cost Figures

Cost figures given below are based on actual offers of hardware (year 2000 value figures) and in cases where this has not been able to achieve within the contract period, reliable cost estimates have been given. *It has to be kept in mind, that these prices are for one-only hardware units and no scaling for larger production numbers has been included.*

Comparison of the installed kWh price to existing plants of the same net power range show a favorable cost advantage for the LPDS; when taking into account the increased electric power production of 27% throughout one solar year for the same site (compared to a heliostat tower system due to cosine losses and higher thermal inertia), the price for one kWh is very attractive for solar energy. LPDS design points are not for any specific day in the year but are based on insolation values and are reached every day throughout the year (calculations are derived from the HELIOS program and checked against by our own comparison program SHINE for LPDS versus heliostat tower system given the same insolation conditions and site parameters).

The areas of development are clearly defined:

(1) reduction in collector cost with performance trade-off studies from experience with the demonstration LPDS and HIRST,
(2) thermodynamic improvement of receiver assembly to improve electric power production,
(3) higher efficiencies with higher process temperatures,
(4) simplify handling and reduce maintenance and operation requirements towards automated stand-alone systems,

(5) enable developing country to manufacture part of system itself (dish).

LPDS Demonstration Power Plant Cost Breakdown for 500 kW_{el}:

All cost figures are in EURO

1. Collector with driving system and panels	2'000'000
2. Receiver	200'000
3. Turboset and hot gas duct with adaptation	450'000
4. Instrumentation and Control	360'000
5. Layout, programming, simulation	320'000
6. Site infrastructure	400'000
7. Plant testing and commissioning	350'000
8. Miscellaneous	200'000
Total Demonstration LPDS Plant Cost	4'280'000

Cost per installed kW is 8'560 Euro.

Projections for Series Production

Bearing in mind the difficulties for future cost projections of solar hardware and its comparison to conventional mass production electric power generation units, an attempt is nevertheless made to show the direction in which cost improvement can be made for LPDS solar power plants and the effect this has on cost for the installed kW and consequently for the price of one kWh.

LPDS Series Production Cost Estimate (Cost in Euro)

1. Collector total cost	1'500'000
2. Receiver unit	150'000
3. Turbo machinery	300'000
4. Control instrumentation	150'000
5. Site infrastructure	200'000
6. Installation, training	200'000
LPDS series production unit	2'500'000

The above prices are site dependent and a further cost reduction can be seen in case the dish hardware can be manufactured in the developing country itself with a very positive influence on the local economy. Site infrastructure is another cost item that can be reduced substantially for a topographically well-suited site.

COST COMPARISON MODEL "COST"

A computer simulation model for comparing electric power production costs in the isolated load market between a LPDS solar power plant and a local diesel generator has been established - COST.

The program is completely operator selectable for all parameters under the heading "PARAMETERS" in order to allow different philosophies to be adopted. The program outputs values of plant cost items such as maintenance costs, total running cost and cost per kWh for three specific values of diesel fuel cost per liter at a specific site. It first lists the associated parameters for the diesel plant under (A) and then conducts a comparison between the LPDS for different unit costs, labeled Unit 1, Unit 10, Unit 100, and Unit 1000, allocating series production cost reductions for units 100 and mass production unit 1000.

A breakeven point is given when the cost per kWh for the diesel power plant and the LPDS are equal; this breakeven point is printed out for the respective comparison unit.

Running arrays of these cost comparisons shows that the most breakeven point related influencing figure is the period for depreciation of the plant, much above other parameters such as diesel cost increase per annum or maintenance and interest costs.

The model has been kept simple on purpose and does not pretend to be highly sophisticated and taking into account many special features that are present in industrialized countries for plant depreciation; the isolated load market itself is usually a very simple financial structure.

The highlights from the provided output are given below; the output itself is for 220 kW_{el} . Scaling to 500 kW only improves the LPDS picture.

For three fuel costs:	US$ 0.40 / 0.80 / 1.10 per liter Diesel fuel
Fuel price increase per annum	9 %
Capital Cost	5 % net
Depreciation period	10 years
LPDS unit costs (in millions US$)	14.0 (including 50% grant),
US$ (million)	8.0, 7.5, 7.0

The associated break even points are between 9.9 and 6.7 years depending on LPDS unit number and diesel fuel price per liter representing acceptable figures for the markets in question.

CONCLUSION

A solar thermal power plant, the Large Parabolic Dish System (LPDS) has been presented with two units described in detail: the 15 m HIRST - High Intensity Radiation Solar Test facility primarily for process heat generation in the temperature spectrum 900 – 200^{o} Celsius until industrial grade prime movers of such small size become available; its main goals will be to demonstrate the economy and technical feasibility of very high process heat production and conduct further studies into even higher process temperatures with ceramic materials for receivers and associated power plant components. Its application is feasible today for producing process heat in developing countries at a competitive price.

The LPDS demonstration power plant is laid out for 500 kW_{el} using a 56 m diameter parabolic dish structure as collector; high efficiencies for optical and thermodynamic components yield high electric plant efficiency. Components for the LPDS have been described and tradeoff parameters listed.

The LPDS as a power plant using solar energy and fossil fuel firing in hybrid mode is a competitive solution for power stations in the isolated load market in stand-alone or array configurations. The wide use of process heat and usable waste heat from the gas turbine make the LPDS a desirable choice for remote site installations.

Costs for the demonstration power plant are listed with projections for series production; developments for improvement of cost structure to the benefit of the local industry are given.

When compared with existing power generation systems in the isolated load market, the LPDS can achieve acceptable payback times today and break even in those markets with the diesel power plant between 9.5 and 6.5 years of operation.

The development potential of the LPDS lies in high process temperature and its high conversion efficiency due to high quality components. Cost reductions for the large dish collector have been proposed by sheltered placement from high wind loads.

The cycle is simple, using air as a working medium and employing a standard industrial gas turbine as a prime mover for low maintenance and service requirements. Due to the high operating temperature of 800^{o} C, waste heat from the cycle at app. 160^{o} C can be employed for process heat applications, raising the total plant use to levels of 80 to 90% of the primary energy input (solar and/or fossil).

Tables, Figures, References

Tables

Figures

References:

(1) Bammert, K. "Long Term Experience With Coal Fired Heaters in German Closed-Cycle Air Turbine Plants", Atomkernenergie/Kerntechnik Vol 38, No 4 (1981).

(2) "Proceedings Fourth Parabolic Dish Solar Thermal Power, Program Review", Nov 30 - Dec 2, 1982, Pasadena Calif. USA, Jet Propulsion Laboratory (JPL), California Institute of Technology.

(3) United Stirling of Sweden "The Stirling Engine Solar Parabolic Dish System", Oct. 1982.

(4) Hunt "A New Solar Thermal Receiver Utilizing Small Particles", Lawrence Berkeley Laboratory, University of California, Berkeley, May 1979.

(5) L. Jaffe, P. Poon "Secondary and Compound Concentrators for Parabolic Dish Solar Thermal Power Systems", JPL Pasadena USA.

(6) Weltraumbild-Atlas Deutschland Österreich Schweiz, Edited by J. Bodechtel, L. Beckel, H. Haefner, Westermann Germany 1978.

(7) "TBC Key Design Requirements" - JPL Private Communication.

(8) Offer from: KHD Deutz Gas Turbine Generating Set - ICRA, May 1983.

(9) Deuster G., "Long-Term Operating Experiences with Oberhausen Closed-Cycle Gas-Turbine Plant" ASME Paper No 70-GT-73.

(10) JPL "Optical Analysis" - Private Communication 1981.

(11) Hunt, A. "Performance Analysis of a Windowed High Temperature Gas Receiver using a Suspension of Ultrafine Carbon Particles as the Absorber" Lawrence Berkeley Laboratories, Berkeley CA, USA, April 1980.

(12) Bammert, K. and Seifert, P. "Design Parameters for tube cavity receivers in solar power plants" Atomkernenergie/ Kerntechnik Bd. 39, Nr.3 (1981).

(13) Bammert, K. "The thermal load of tubes in radiation heaters" Forschung Ingenieurwesen (1982) Nr.5.

(14) Bammert, K., Hegazy, A., Seifert, P. "The solar flux distribution in cavity receivers with parabolic dish collector" Atomkernenergie/Kerntechnik Bd. 40, Nr.3 (1982).

(15) Bammert, K., Sutsch, A., Simon,M. "Large Parabolic Dish Collectors with Gas Turbines" Atomkernenergie/Kerntechnik Bd.38 (1981)

(16) Sutsch, A. "Advantages of Large Parabolic Dish Systems For Solar Power Generation" Solar World Forum, Brighton England, 1981.

Not listed in text :

JPL "Advanced Concentrator Subsystem" - Private Communication ICRA 1981

JPL "Advanced Receivers" - Private Communication ICRA 1981

JPL "Tracking and Control Analysis" - Private Communication ICRA 1981

Owen, W. "The JPL Flux Mapper", JPL Pasadena 1982

Hughes, R. "Effects of Tracking Errors on the Performance of point focusing Solar Collectors" JPL Pasadena 1979

Jaffe, L. "Dish Concentrators for Solar Thermal Energy: Status and Technology Development" JPL, Pasadena 1981.

Lucas, J., Roschke, E. "Solar Thermal Power Systems Point-Focusing Ditributed Receiver (PFDR) Technology: A Project Description" JPL Pasadena, 1978.

Revere, W. et al. "Configuration Selection Study for Isolated Loads Using Parabolic Dish Modules" JPL Pasadena 1981.

More literature has been provided with a previous contract from the EU on the subject matter. Please consult the author for further information.