Solar Thermal Electricity Generation

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Summary

This paper concentrates on solar thermal electricity generation and such promising technologies as trough collectors, tower plants, solar chimneys and Dish/Stirling systems. It is shown that the development, design and construction of such systems is a great challenge for civil engineering.

Technologies

When addressing solar electricity generation, it is common to distinguish between *small decentralised* and *large centralised* power generation. In the first case a unit has, say, an output of some 100 kW maximum and is therefore likely to be installed in remote areas away from the grid. Centralised generation means large-scale solar power plants feeding the grid with 10 to 500 MW per unit and capable of someday possibly replacing present large-scale fossil or nuclear electricity generation. However, bearing in mind the successful operation of hydroelectric power plants, this may be nothing less than a utopian goal.

According to the present state of the art, the following technologies for direct, active solar electricity generation are widely known and generally have been found to be feasible:

Centralised large-scale electricity generation

- Distributed collector systems (DCS) with parabolic trough collectors
- Central receiver systems (CRS) with heliostats
- Solar chimneys with flat glass collectors.

Decentralised small-scale electricity generation

- Dish/Stirling systems with parabolic concentrators (D/S)
- Photovoltaics (PV)

With the exception of PV, all these systems are solar thermal power plants. Both solar chimneys and photovoltaics are also able to utilise diffuse solar radiation, which suggests that solar chimneys are the only technology for large scale utilisation in the regions with substantial diffuse global radiation.

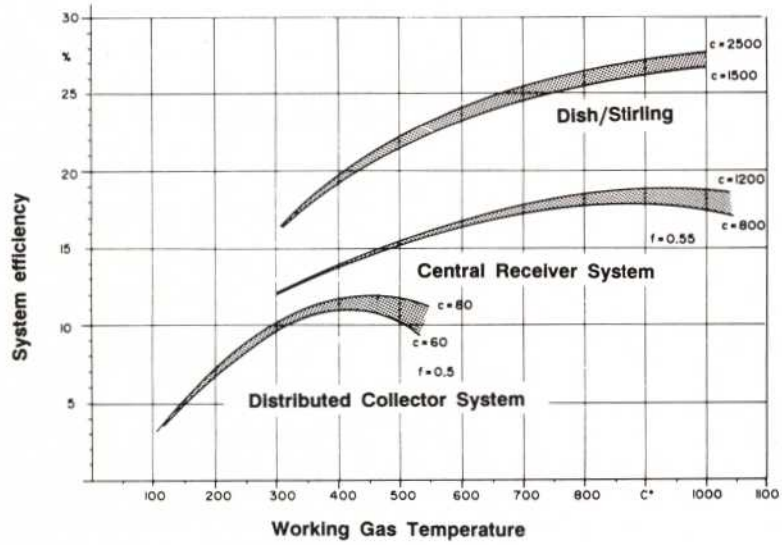

Fig. 1: Overall efficiency of concentrating systems

Obviously all these technologies only make economic sense if the annual solar irradiance is satisfactory, say, more than 1800 kWh/m²a. Installing PV plants in Central Europe with its 900 to 1100 kWh/m²a irradiance is manifestly futile, especially in view of the 2300 kWh/m²a available in nearby North Africa.

With distributed collector systems, central receiver systems and Dish/Stirling systems, the solar radiation is concentrated resulting in high temperatures which directly effect the efficiency of the system *(Fig. 1)*. Single curved troughs result, therefore, in lower efficiencies than systems using double curvatures.

Any concentrating system depends on direct solar irradiance. Diffuse radiation cannot be concentrated. This is very important to remember when deciding on a particular technology for a specific location.

Centralised Electricity Generation

Distributed Collector Systems

Line-focusing parabolic trough collectors, each 100 m long and 6 m wide, are made from hundreds of curved mirror segments. These troughs are suspended in such a way that they track the sun around one axis only. The structures supporting the curved mirror segments should be light, stiff and easy to manufacture. Future aperture widths of 9 m represent challenging structural design problems. The solar radiation bundles on a glass/metal tube are placed along the focal line of the trough. This tube transports a heat transfer medium, at present a synthetic oil but in future possibly just water-steam. This medium is collected and transferred to a conventional steam power plant consisting of heat exchangers, turbines, generators, and a cooling tower.

These trough collectors have meanwhile reached, through continuous improvements, a concentration factor of 82. Since 1984, six plants of 30 MW

output each and one with 80 MW have been successfully built in California, USA *(Fig. 2)*. In case of prolonged lack of solar radiation, a gas-burning capability may be added. This back-up capability avoids the need for costly thermal storage and guarantees continuous electricity supply, a requirement utilities certainly appreciate and pay for correspondingly.

An 80 MW solar electricity generating system plant was built in 1989 at Harper Lake in the Mojave Desert in California, where the sun shines 350 days a year. Its collectors amount to 464 000 m^2 and the heat-transferring thermo-oil is heated up to 393 °C. The yearly energy production is 249 000 MWh. The investment cost represents about $ 2500/kW.

Thanks to its use of a relatively simple technology and to skilful marketing, the decentralised trough collector plants were for some time rather successful and have demonstrated that large-scale solar energy utilisation must not remain merely a utopian dream if economies of scale can be achieved. However, recently the manufacturer ran into financial difficulties due to the withdrawal of subsidies and unfortunately the future of this system is uncertain.

Central Receiver Systems

Forming a huge faceted double-curved concentrator, a large number of heliostats is arranged on the ground around a tower. A central receiver is placed on top of this tower, between 50 and 150 m above ground. Solar radiation is reflected to the receiver, heating a heat transfer medium. The heat transfer medium may be air, water/steam, liquid sodium or melted salt and, correspondingly, the process temperatures vary from 550 to 1000 °C. Beyond that, as with the distributed collector systems, there is conventional thermal power plant technology: The heat transfer medium is carried by pipes to a power plant at the base of the tower and there drives a turbine coupled to a generator.

At present most concentrators consist of several individual mirrors which are mounted together on structures able to track the sun around two axes *(Fig. 3)*. Tracking is computer-controlled to guarantee precise focus. Up to now six such plants have been built in the United States, in Southern Europe and Japan, the largest being the 10 MW plant at Barstow, California, using steam as the heat transfer medium.

Fig. 2: The 150 MW DCS plant with trough collectors at Kramer Junction, California, USA

Further development is needed on system integration and cost reduction of the individual components. At present, the receiver plus heat transfer and short-term storage make up ¼ of total plant costs and the heliostats ⅓. It is expected that efficiency can be considerably improved and the whole system simplified by applying high-temperature air receivers.

Concerning the heliostats themselves, the accuracy and the robustness of the tracking devices need improvement and their costs must be reduced. The metal membrane technology described in more detail below is readily applicable to heliostats. Stretched metal membrane heliostats easily achieve the required improvements *(Fig. 4)*. In order to test both DCS and CRS, nine European countries are co-operating to install the Plataforma Solar test facility at Almeria, Spain *(Fig. 5)*.

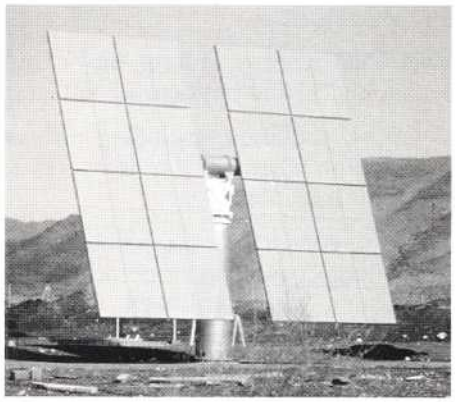

Fig. 3: A conventional facetted heliostat

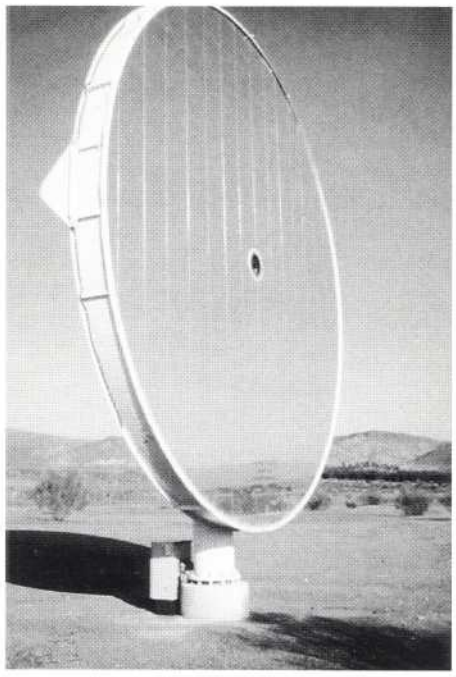

Fig. 4: A stretched metal membrane heliostat

Solar Chimneys

The solar chimney combines three well-known technologies – the greenhouse, the chimney, and the turbine – in a novel way *(Fig. 6)*. Incident solar radiation heats the air under a large transparent collector roof. The temperature difference causes a pressure drop over the height of the chimney resulting in an upwind which is converted into mechanical energy by turbines and then into electricity via conventional generators.

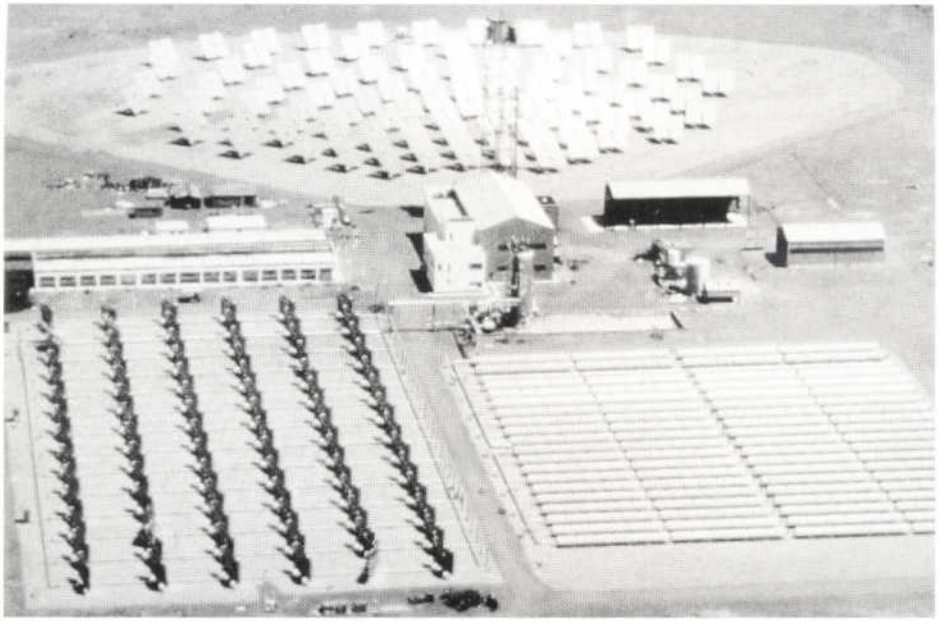

Fig. 5: The European Plataforma Solar at Almeria, Spain. Two 0.25 MW DCS in the foreground and a 0.5 MW CRS in the background

This solar energy system has many technological and physical advantages:

- Global radiation, including diffuse radiation when the sky is overcast, can be exploited.
- The natural storage medium – the ground – guarantees operation at a constant rate until well into the hours of darkness (and throughout the night with large-scale installations).
- There are no moving parts, nor are there parts that require intensive maintenance aside from the turbine and the generator. Not even water is required to cool mechanical parts.
- Its simple, low-cost design and materials (glass, concrete, steel) make solar chimney systems applicable to less industrialised countries. Labour represents a high proportion of the installation costs. This would stimulate the local labour market, while at the same time helping to keep overall costs down.

There is in fact no optimum physical size for solar chimneys. The same output may result from a large chimney with a small collector roof area and vice versa. This may be readily seen in *Fig. 7*, which combines the yearly energy production with the dimensions of a solar chimney. It also shows that a considerable increase in output results from using two layers of glass as against one for the collector. Thus, to decide the optimum dimensions of chimney height against collector radius, the specific construction costs of these items must be known. If glass is cheap but concrete expensive, a large collector and low chimney is preferable, and vice versa. Broadly, to achieve a maximum output of 30 resp. 100 MW at an irradiance of 1000 W/m^2, the roof must have a diameter of 1100 resp. 1800 m and the chimney a height of 750 resp. 950 m.

With this information the investment cost and the energy production costs may be analysed. The result, and comparison with other plants, is summarised in *Fig. 17*. Solar chimneys produce electricity at competitive prices if large units are built.

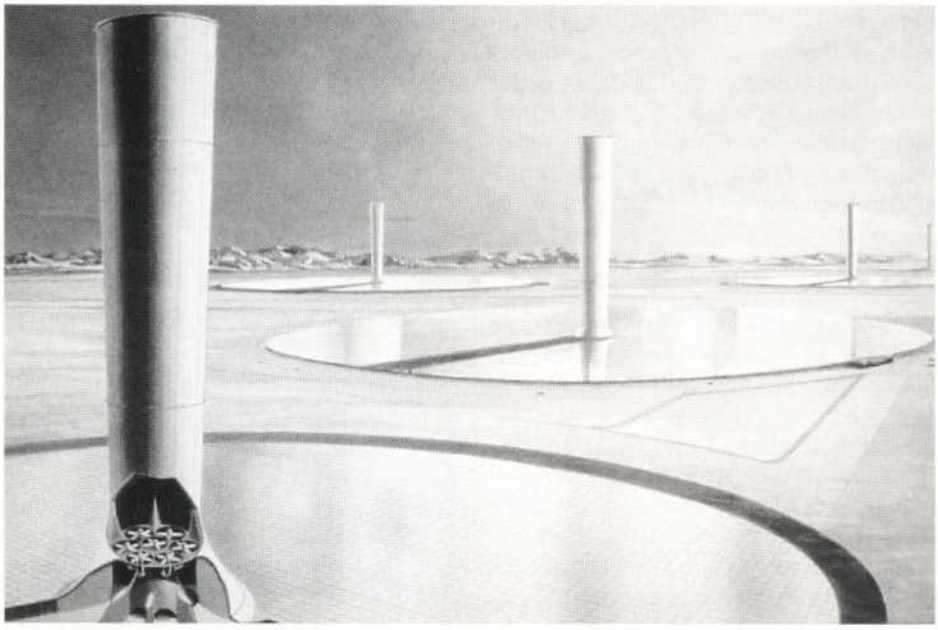

Fig. 6: Drawing of several large (100–200 MW) solar chimneys in a desert

Practical Experience with Solar Chimneys

Sponsored by the German Federal Ministry for Research and Technology, an experimental facility *(Fig. 8)* was developed and built in Manzanares, Spain, where the advantages of the solar chimney were confirmed by the plant's consistent performance and low operating and maintenance costs. Erection of the plant was completed in 1981 and, after a phase of improvements, continuous operation started in 1983 and continued until 1989. At this time, the chimney – designed as a temporary cable-stayed corrugated sheet tube without permanent corrosion protection – had to be dismantled.

This prototype's continuous operation throughout one typical year is shown in *Fig. 9*. For comparison, the measured hours of sunshine with an irradiance of more than 150 W/m^2 and the theoretically possible maximum number of hours of sunshine (sunrise to sunset) are also shown. In 1987 the plant was in operation for a total of 3197 hours, which corresponds to a mean daily operating time of 8.8 hours. As soon as the air velocity in the chimney exceeds 2.5 m/s, the plant starts operating and is automatically connected to the public grid.

These results show that all components are highly dependable and that

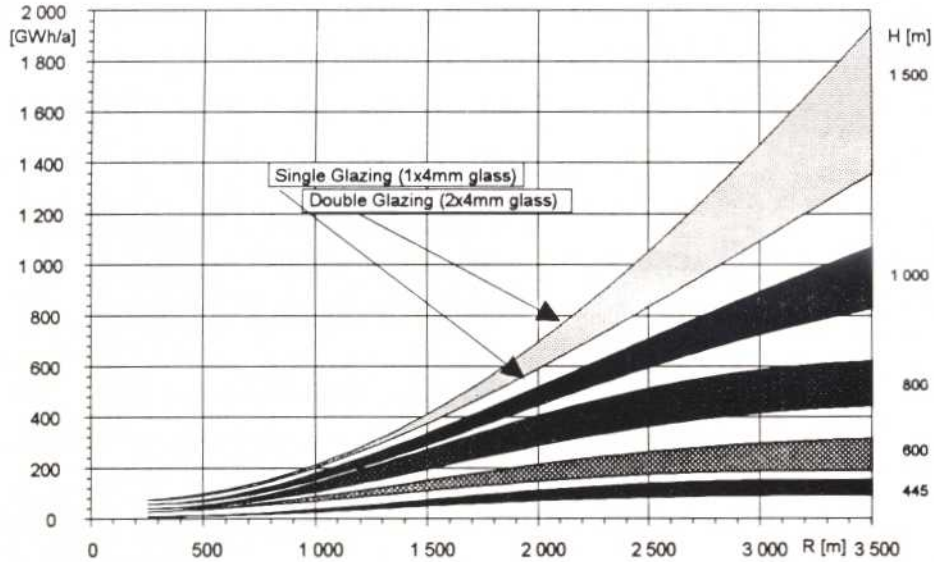

Fig. 7: Design data for large scale solar chimneys: yearly energy production (GWh/a) (assuming an insolation of 2300 kWh/m²/a) as a function of collector roof radius R (m) with a single or double layer of glass and of chimney height H (m)

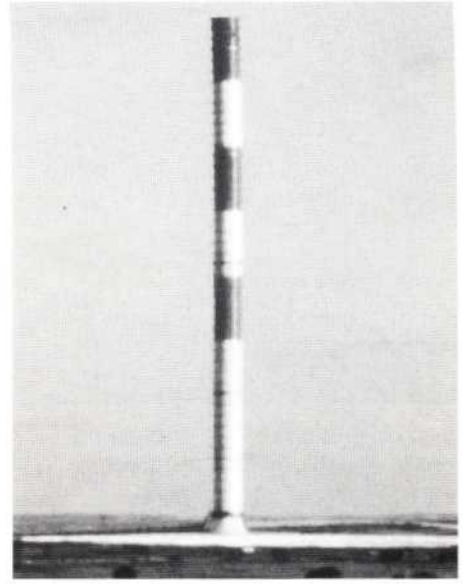

Fig. 8: Experimental solar chimney, Manzanares, Spain. Height of chimney: 200 m; radius 5 m; collector: 120/120 m; rotor diameter: 10 m; nominal speed 100 rpm

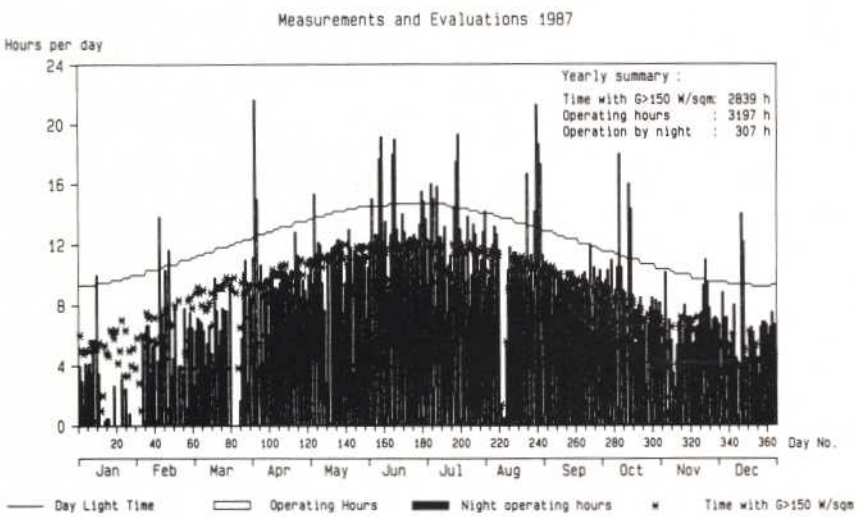

Fig. 9: Operating hours of the prototype, Manzanares, Spain, during 1987

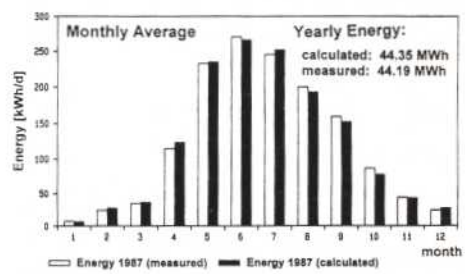

Fig. 10: Comparison of measured and calculated monthly output of the prototype, Manzanares, Spain

the plant as a whole is very reliable in operation. Thermodynamic inertia is a characteristic feature of the system. Even abrupt fluctuations in energy supply are effectively cushioned. The plant operated continuously even on cloudy days, albeit at reduced output.

Using a thermodynamic simulation program, the theoretical performance of the plant was calculated and the results compared with the measurements obtained, showing good agreement *(Fig. 10)*. Through this method the optical and thermodynamic processes in a solar chimney are well understood and analytical models have attained a degree of maturity that accurately reproduces plant behaviour under given meteorological conditions.

Decentralised Electricity Generation

The Construction of Solar Concentrators

Until recently, solar concentrators were made of individual facetted mirrors, but the development of stretched metal membrane technology now permits very large and precise concentrators *(Figs. 11 and 12)*. The concentrator surface is made of thin steel sheet to which mirror glass is bonded. The membrane is plastically deformed to the desired parabolic shape by air pressure and hydraulic load *(Figs. 13 and 14)*. When the concentrator is in operation, the shape of the membrane

Fig. 11: Two 17 m/50 kW Dish/Stirling systems in Riyadh, Saudi Arabia. Azimuthal tracking

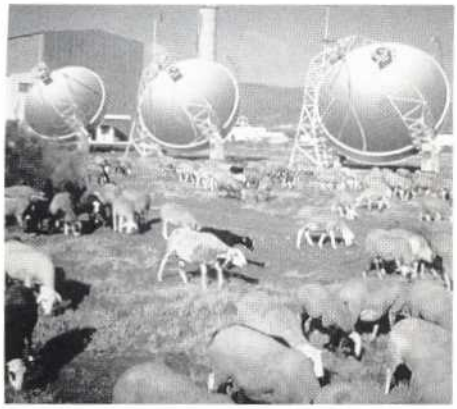

Fig. 12: Three 7.5 m/9 kW Dish/Stirling systems in Almeria, Spain. Polar tracking

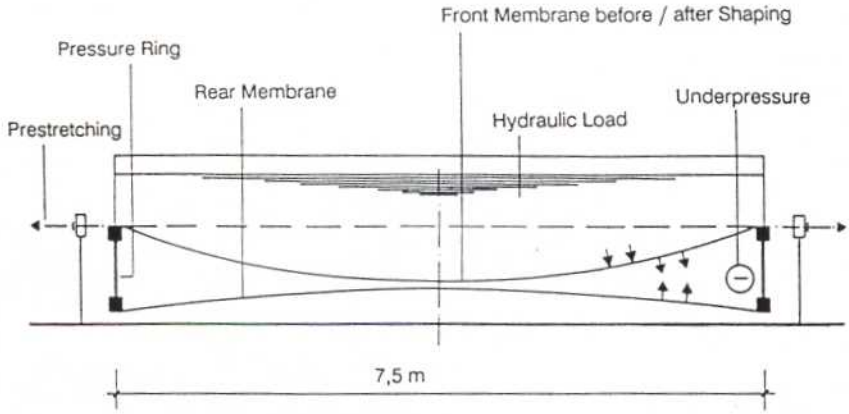

Fig. 13: Forming a stretched metal membrane concentrator by underpressure and hydraulic load

is kept constant by a partial vacuum in the interior of the concentrator, i.e., between the two concentrator membranes and the concentrator ring. In principle the same manufacturing method can also be applied to produce heliostats mentioned above in relation to central receiver systems. However, with heliostats a very long focal length is required and, therefore, the metal membrane after stretching must be deformed only within its elastic range *(Fig. 13)*.

Dish/Stirling Systems

In the Dish/Stirling system, a concave concentrator several meters in diameter is suspended in such a way that it can track the sun. At the focal point of the concentrator, an energy converter is suspended which converts the concentrated solar heat into electricity.

The concentrator is mounted on a supporting frame structure which tracks the sun. There are two different tracking modes – azimuthal and polar. For azimuthal tracking the concentrator follows the sun by rotating around two axes perpendicular to each other *(Fig. 11)*. In order to follow the sun continuously, both axes have to rotate permanently, with the speeds of both drives changing during the whole day. This requires electronic piloting and sophisticated step-motors. The distinctive feature of the polar tracking mode *(Figs. 12 and 15)* is that the two rotational axes are separated into diurnal (earth rotation) and seasonal tracking (orbit of the earth around the sun). The concentrator has to be rotated around the diurnal or polar axis at a constant speed of 15° per hour, corresponding to the rotation of the earth. The seasonal axis has to be adjusted only once a day. Obviously, polar tracking is superior for decentralised, remote application of dishes, whereas azimuthal tracking suits clusters of heliostats or dishes.

The energy conversion system consists of a Stirling engine with a receiver located at the focal point of the concentrator; the reflected solar rays heat the working gas (hydrogen) of the engine. A generator is coupled directly to the engine to produce electricity.

Since each unit is capable of fully independent operation, as many concentrators as desired can be operated in conjunction, according to requirements. They can be operated both in "grid connection" or "stand-alone" modes. By hybrid operation using fossil or, better still, biogas, storage devices such as batteries can be avoided.

Power plants with concentrators are capable of an overall efficiency (defined as the ratio of the electricity output to the solar irradiance over the concentrator surface) of up to 27%. This has never been achieved with other types of solar plants. As the membrane construction method used for the concentrator is relatively inexpensive, such systems make economical electricity generation a real possibility. The output depends on the accuracy of the beam path. The concentrator membrane satisfies this requirement with a relatively simple fabrication technology.

With carefully planned technology transfer such power plants could readily be fabricated in less developed countries. On the other hand, the de-

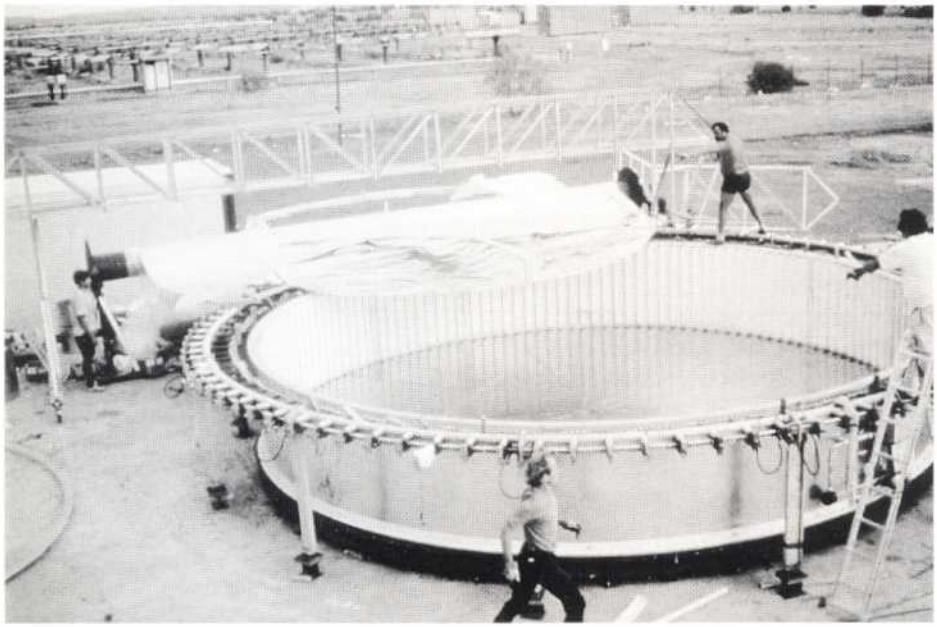

Fig. 14: Installing the concentrator ring for a 7.5 m stretched metal membrane concentrator and unrolling the front membrane

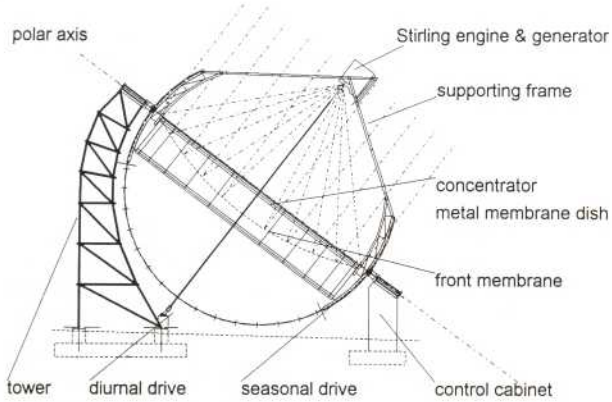

Fig. 15: Prototype drawing of a 7.5 m/9 kW Dish/Stirlingsystem with metal membrane concentrator and polar tracking

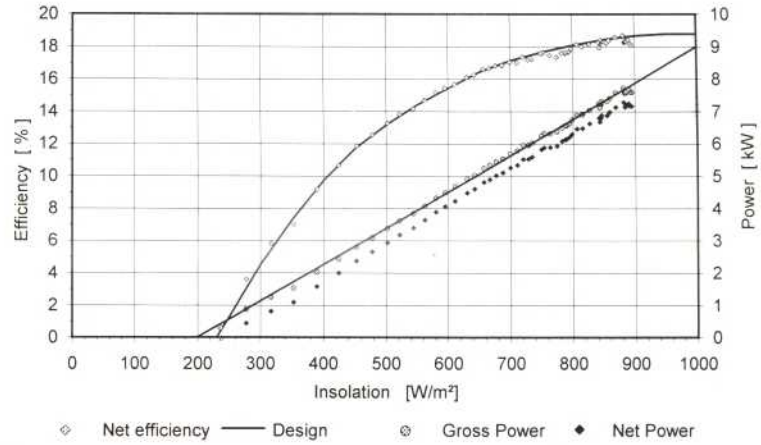

Fig. 16: Input/output characteristics and net efficiency of 7.5 m / 9 kW Dish/Stirling system in Almeria, Spain

sign has to consider the effects of extreme thermal expansion and special high-temperature-resistant materials have to be used for the receiver tubes in order to achieve long service life.

Practical Experience with Dish/Stirling Systems

In 1985, after constructing a test facility in Germany, two concentrators with 17 m diameters were installed in Saudi Arabia, co-sponsored by German Ministry of Research and Technology and the King Abdul Aziz City for Science and Technology in Riyadh *(Fig. 11)*. Their power output is 50 kW_e each. After the "usual" initial problems, especially with the Stirling engines, both are operating according to expectations.

With the experience gained from such projects, a further step of development was started in 1987 with the goal of developing a smaller and extremely robust plant using polar tracking for installation in remote regions and capable of operation by unskilled owners/users. With a 7.5 m diameter the power output is 9 kW_e. After testing a prototype in Stuttgart *(Fig. 15)*, three units were installed at the Plataforma Solar test facility at Almeria, Spain *(Fig. 12)*.

Due to the low thermal inertia of the system, power output is almost instantaneous *(Fig. 16)*. Thus, on cloudless days the very first hours of sunshine can be exploited, and daily operation time is almost as long as the daylight hours. Even on days with mixed weather conditions these systems demonstrate good efficiency due to the fast system response and the efficiency of the Stirling engine under partial load.

Since May 1992, all three units are operating from sunrise to sunset whenever weather permits. As of October 1993, the three systems have accumulated approximately 10 000 operating hours. It is expected that at the end of the present operating phase in December 1994, some 20 000 operating hours will have been accumulated, a world record for such systems.

Photovoltaics

Solar cells are photoelectric or photovoltaic (PV) cells which at normal temperatures transform solar light into electricity without any mechanical parts, an ideal method at a first glance. PV cells are also very durable and reliable and can be added in modules of any size and output. However, in spite of immense research efforts – e.g., in Germany one half of all money for renewable energy is spent on PV – and

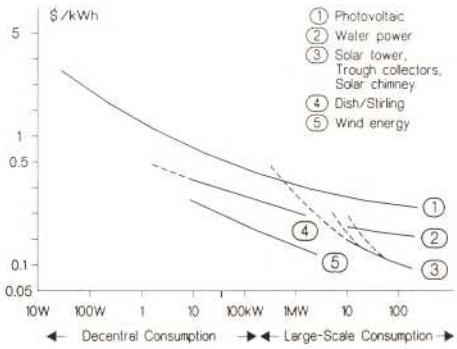

Fig. 17: Levelized Energy Costs (LEC) in US$/kWh of different renewable energy power plants

considerable progress, the cost of PV electricity is still by far higher than that of any other technology. It must be expected that this will remain so for a long time.

For very decentralised mini-scale energy production and consumption, PV already has achieved wide application.

In any case, PV does not present much of a challenge for structural engineering since the frames supporting PV cells from a structural point of view are rather simple.

Cost Comparison

Fig. 17 summarises the results of a detailed cost study commissioned by the German government. It shows that for decentralised small-scale application wind energy converters and Dish/Stirling systems have a chance to become economically competitive, whereas for large-scale use solar chimneys, distributed collector systems and central receiver systems can produce electricity in the cost range around 0.1 $/kWh, close to profitability and comparable to hydroelectric power. Therefore, further work to improve these technologies is worthwhile and civil engineers should participate in these efforts.

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This article is dedicated to Prof. Jörg Schneider on the occasion of his 60th birthday.