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Solar Chimneys
The Principle — The Pilot Plant — Prospects for the Future

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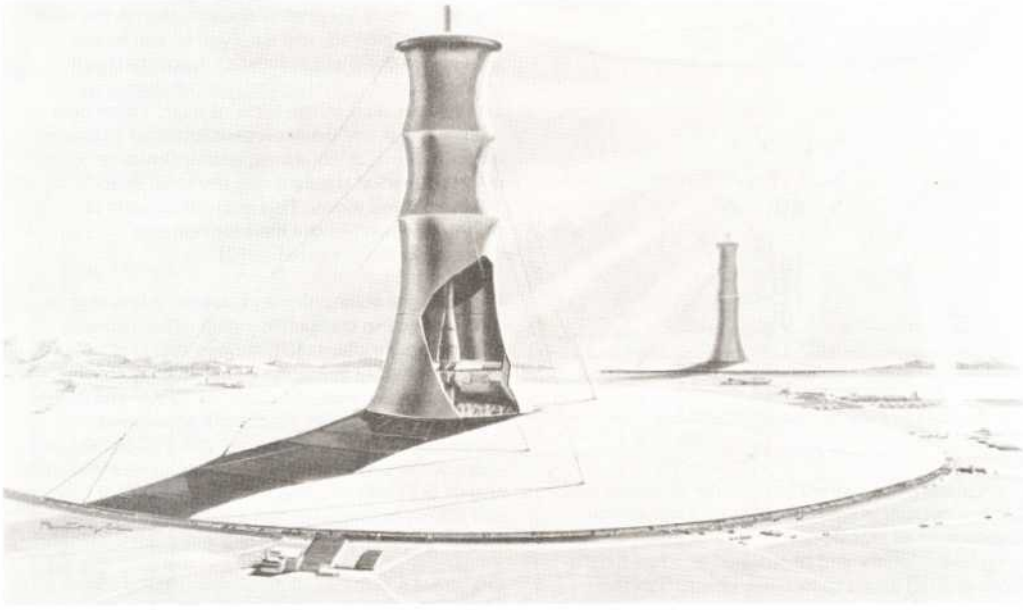

Fig. 1: Drawing of a 100 MW_{el} solar chimney

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1. The principle

1.1 The basic concept

Solar chimneys convert solar radiation into electrical energy by combining in a novel way the principles of the greenhouse, the chimney and the wind-turbine generator (Figs 1+2) [1], [2]. In fact, even the idea of such a combination is not totally new [3], but only with the increasing costs of conventional energy on the one hand and the proven fact that huge chimneys are feasible [4], [5] on the other, has it appeared reasonable to pursue it.

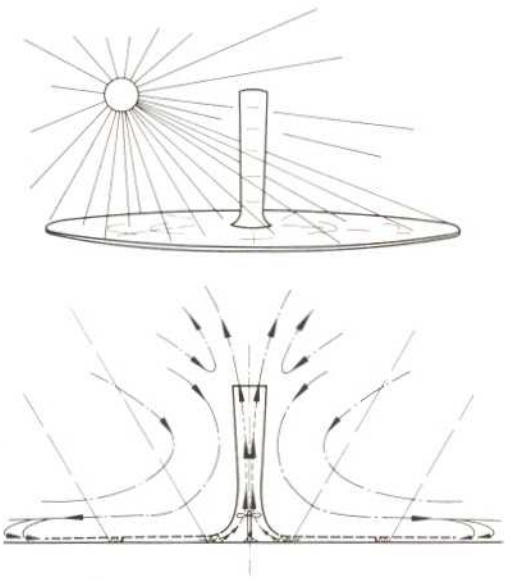


Fig. 2: The principle of solar chimneys

The "greenhouse" serves as the solar collector and covers a circular area. It consists of a horizontal canopy roof of translucent plastic or glass, open along its periphery and positioned at a low height above ground level; to increase absorption the ground is simply blackened. At the centre of the canopy roof is the chimney cylinder, around the base of which the roof is closely fitted. The opening of the base of the chimney is underneath the roof so that the air mass under the roof is sucked up through the chimney cylinder. Air thus enters the space underneath the roof at its periphery and flows towards the chimney, its temperature being raised by the action of the sun as it does so. This presupposes, of course, that the roof material is of a type which will create the necessary greenhouse effect, i.e., short-wave solar radiation must be able to pass through the roof and warm the blackened ground surface below, but the long-wave thermal radiation must not be allowed to escape (see Figs. 3 and 4); fortunately most translucent materials have this property to a certain extent. The warmed air creates an updraft in the chimney strong enough to turn a turbine placed there for generating electricity. The wind turbine is placed in the lower part of the chimney with its axis oriented vertically and is coupled directly to the generator.

The greater the difference in the temperature of the warm air mass underneath the roof and that of the outside air, and the higher the chimney, the higher is the velocity of the updraft in the chimney. The actual output of electricity depends upon the air flow quantity, and therefore also on the diameter of the chimney or turbine. The air temperature and air flow quantity involved are determined by the dimensions of the plant itself, i.e. the diameter and height of the circular roof, the optical and thermal characteristics of the roof material employed, and the type of soil in the area where the plant is located. Important soil characteristics are its capacity to absorb and store energy in the form of heat. These parameters and many others were subject to extensive investigations, calculations, and optimizing efforts aimed at determining the most cost-effective dimensions. This analysis process is briefly reviewed in the next section and thoroughly documented in [2].

Basically the solar chimneys possess a low degree of efficiency in comparison with other types of solar power plants [6], though this is offset by low collector costs. As the efficiency increases sharply with the absolute size of the plant, only plants with peak electricity generating capacities of 10 MW, or better still 100 to 500 MW, make sense (see Figs. 6+7). A peak generating capacity of 500 MW requires a chimney 1,000 m high and 300 m in diameter and a collector roof 10,000 m in diameter.

One great advantage of solar chimneys is their natural thermal storage capacity, which costs nothing. During the day, roughly one-third of the total radiance is reflected by the roof, one-third directly transferred into the working air and one-third absorbed by the soil. At night the soil releases its heat. Solar chimneys can therefore operate throughout the night and, depending upon their size and the soil characteristics at the site, still deliver 20% of their peak generating capacity on the following morning.

1.2 Physical and cost estimates

Energy balances, plant dimensions and power output

The first step in designing and optimizing a solar chimney is to determine the individual energy balances in the collector, which depend on its radius. Figure 4 shows the heat transmission for two different radii with single and double layer translucent films, respectively. Figure 5 shows the 24-hour course of ground temperatures for soil with good conductivity at various depths, derived from detailed model calculations. This curve reflects the above-mentioned storage effect.

The individual heat transmission values add up radially to the total enthalpy increase at the entrance to the chimney cylinder. The resulting increase in temperature ΔT generates the operating pressure and hence the updraft with the velocity v:

$$\Delta T = \eta_c \cdot \frac{J \cdot \pi \cdot R_c^2}{C_p \cdot \dot{m}} \qquad (1)$$

$$v = \sqrt{2 \cdot \frac{\Delta p}{\rho_i}} = \sqrt{2g \cdot H_T \cdot \frac{\Delta T}{T_a}} \qquad (2)$$

Both are connected through the air mass flow rate

$$\dot{m} = \rho_i \cdot v \cdot \pi \cdot R_T^2 \qquad (3)$$

where: J: global radiance
R_c: radius of collector
H_T: height of chimney tube
R_T: radius of chimney tube (const)
η_c (T,$\dot{m}$): collector efficiency
C_p: specific heat capacity of the air
ρ_i: air density in the chimney cylinder
T_a: ambient temperature at ground level
Δp: generated pressure difference

Of course these equations involve major simplifications which forbid their use in actual design. Nevertheless they enable the basic interrelationship to be grasped immediately. The output given by $\dot{m}$ or v respectively ΔT increases when the collector area and the chimney height are increased.

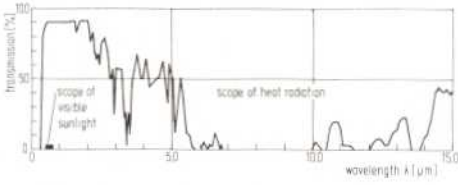


Fig. 3: The canopy roof: transmission spectrum of a polyester membrane, 125 µm thick

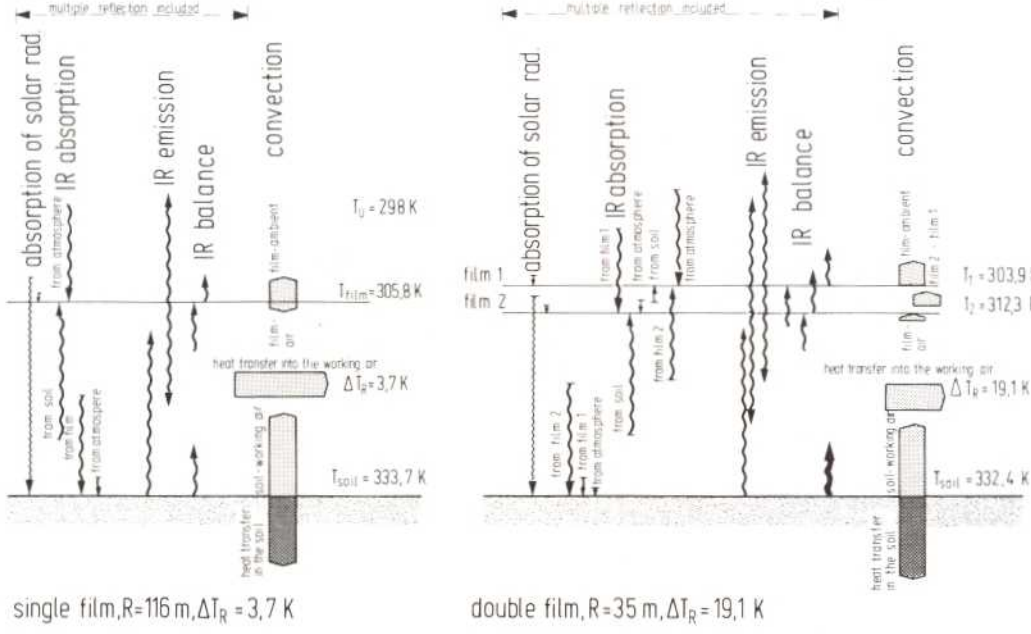


Fig. 4: Vertical section through the canopy roof. Energy balances at two radii (examples)

There is, however, an upper limit to ΔT, above which there is no point in increasing the size of the collector, since beyond it the losses due to radiation, convection and friction become excessive. Depending on the many parameters of the soil and the canopy, this limit may be reached around $\Delta T_1 = 15K$.

Taking at $\Delta T \approx \Delta T_1$ the proportion between the power output N and the upwind velocity approximately as $N \sim v^3$, we read from (2) that the tower height governs N according to $N \sim H_T^{3/2}$.

The electrical output of a wind turbine is

$$N_{el} = \eta_T \cdot \Delta p_T \cdot \dot{V} \qquad (4)$$

where: η_T: efficiency of the turbine, the gearing and the generator
Δp_T: pressure drop at the turbine which can be taken for this type of turbine as $^2/_3\ \Delta p$ with Δp from equ. (2)
$\dot{V} = v \cdot A = v \cdot \pi \cdot R_T^2$: volumetric flow rate.

The combination of equ. (1), (2) and (3) in (4) with the inclusion of a further efficiency factor η_f for all frictional losses under the canopy roof and in the chimney, finally yields

$$N_{el} = \eta_c \cdot \eta_f \cdot \eta_T \cdot {}^2/_3 g \cdot H_T \cdot \pi \cdot R_c^2 \cdot J \cdot \frac{1}{C_p \cdot T_a} \qquad (5)$$

The plot in Fig.6 is based on this equation, i.e. it shows how N_{el} depends on the main parameters H_T and R_c. Concerning η_c and η_f it is based on a detailed and far more complex simulation analysis which includes, among other parameters, the height of the roof and the radius R_T of the chimney tube. R_T is kept constant, i.e. the chimney is a cylindrical tube without diffusor. Since R_T is a major design factor, it is also included in Fig. 6.

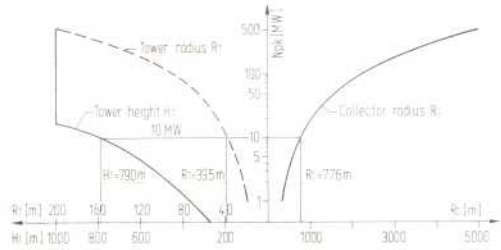


Fig. 6: Major design parameters of solar chimneys versus electrical output
N_{pk}: peak electrical output
H_T, R_T: height and radius of chimney tube
R_c: radius of collector roof

Cost estimates

Taking the above data and typical current prices as a basis, the specific installation costs were computed as shown in Fig. 7. It may be seen that with increasing plant dimensions the specific costs decrease; this is not because a cost reduction factor has been applied, but because the real physical efficiency increases.

From an economic point of view, however, it is the average power generating costs which count. They are expected to be around 0.25 DM/kWh (0.1 $/kWh). It would be beyond the scope of this paper to define and discuss all parameters such as local radiance, wind and soil conditions, maintenance, durability and repair, amortization period, interest and inflation rates etc., which had to be considered when computing them.

The recovery time for the primary energies required for the production of a solar chimney itself, a characteristic value in the comparison of solar energy installations, is expected to be around 5 years.

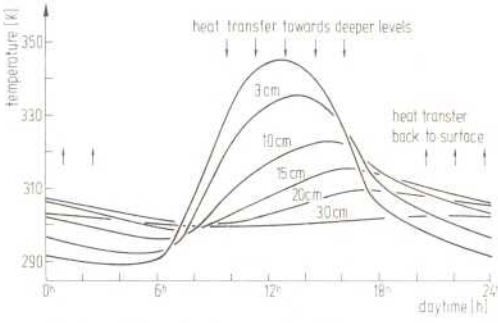


Fig. 5: Model calculation of soil temperature profiles (limestone) near the perimeter of the canopy

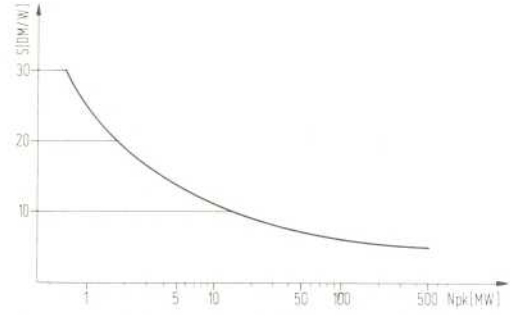


Fig. 7: Total specific installation costs of solar chimneys based on 1982 prices in West Germany

2. The pilot plant

2.1 Design data

Studies and preliminary calculations of this kind induced the German Federal Ministry for Research and Technology (BMFT) and its Project Management, Department for Energy Research, KFA Jülich, to provide the funds for the construction of a prototype. A site was selected in the arid region of La Mancha near Manzanares, 170 km south of Madrid, Spain.

The chimney is about 200 m high and has a diameter of 10 m. The solar collector roof is 250 m in diameter and approximately 2 m above the ground (see Figs. 8÷10). Its main data are given in Table 1. These are, of course, not optimum dimensions. As can be seen from Figs. 6 and 7, the facility is much too small overall to achieve a reasonable degree of efficiency but is nevertheless just large enough to provide realistic physical data. The relative dimensions of its various parts are also not optimal. For example, for the diameter of the collector, its roof should be located only approximately 50 cm above the ground in order to achieve the best air current velocity for heating the air underneath the roof. However, this would have led to an unrealistic roof design for later large-scale facilities.

The relationship between the tower dimensions and the radius of the collector was designed to ensure $\Delta T \geqslant 20°$, even for unfavourable climatic conditions. This relatively high ΔT has the advantage of greater accuracy for measuring purposes as well as for verifying the principle, though it also brings the disadvantage of a relatively low collector efficiency $\eta_C = 0.32$.

Chimney tube height	$H_T =$	194.6 m
Chimney tube radius	$R_T =$	5.08 m
Mean collector radius	$R_C =$	122.0 m
Average canopy roof height		1.85 m
No. of turbine blades		4
Blade radius		5.0 m
Operating modes		
a) stand-alone operation with variable speed (optimum utilization of upwind energy)		
b) grid connection mode		
Turbine speed in grid connection mode		100 rpm
Gear ratio		1 : 10
Design irradiation	$J =$	1000 W/m²
Design fresh-air temperature	$T_a =$	302 K
Temperature increase*	$\Delta T =$	20 K
Collector efficiency*	$\eta_C =$	0.32
Turbine efficiency	$\eta_T =$	0.83
Friction loss factor	$\eta_f =$	0.9
Upwind velocity under load conditions		9 m/s
Upwind velocity on release		15 m/s
Power output*	$N_{el} =$	50 kW

*mean for model assumptions at design point

Table 1: Data and design values of the pilot plant

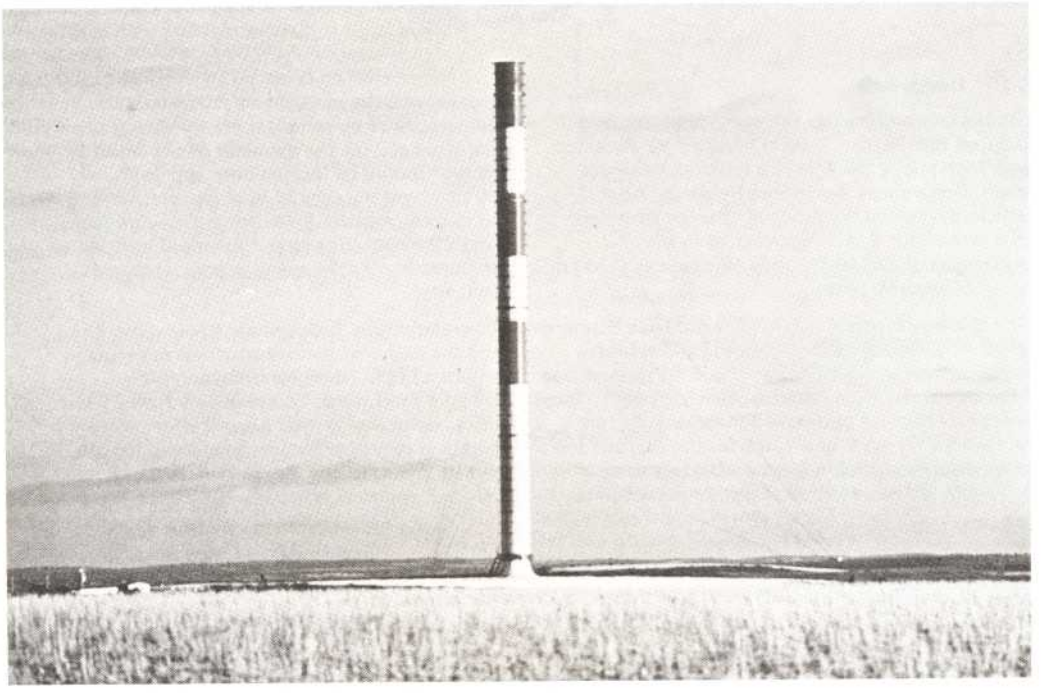


Fig. 8: The solar chimney pilot plant at Manzanares/Spain

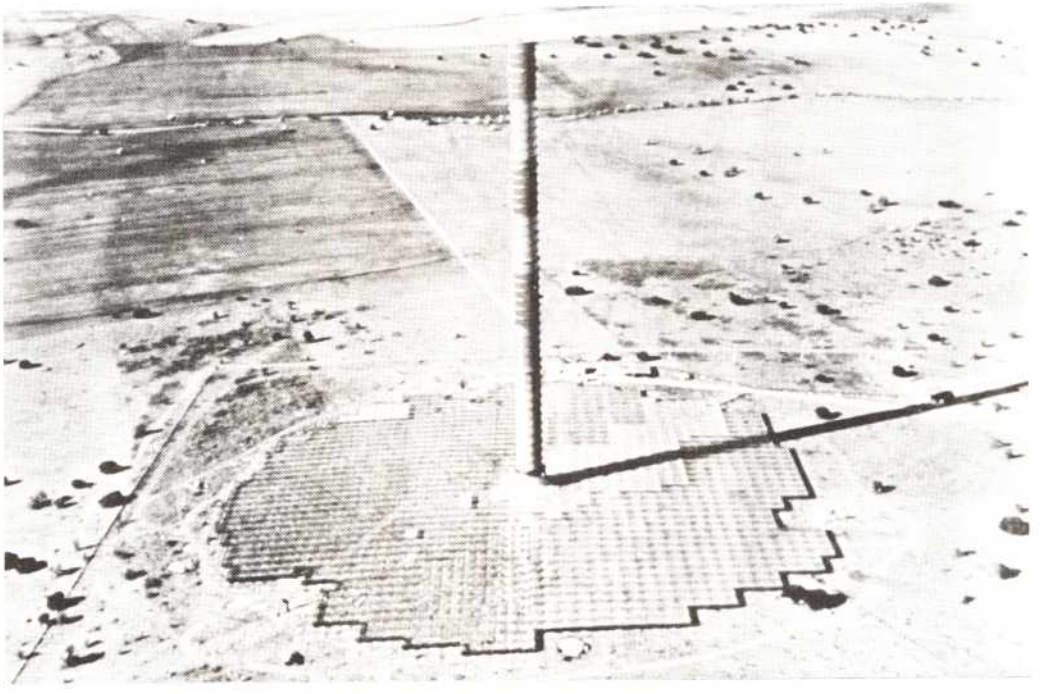


Fig. 9: Aerial view of the pilot plant

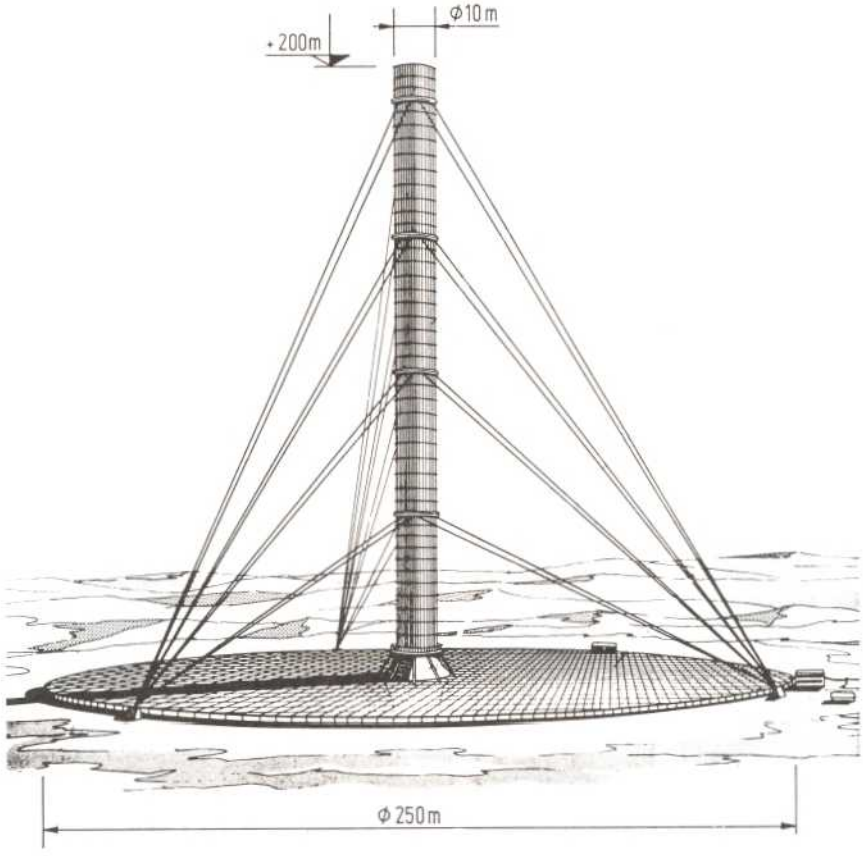


Fig. 10: Main dimensions of the pilot plant

2.2 The chimney

The huge tubes as needed for large solar chimney power plants may be concrete, cable net or membrane structures [4], [5]. The choice depends on individual and local requirements which, as regards the structure, may include soil and seismic conditions, and as regards physical conditions, may include geometrical parameters ($^{H_T}/_{R_T}$).

For the pilot plant a very slender tube with $^{H_T}/_{R_T} = {}^{200}/_{5}$ was to be built, in a remote arid area with no infrastructure. It has to be dismantled and the site completely cleared after a few years' measurements. Therefore, a lightweight structure was chosen, a stayed tube of corrugated sheet steel 1.25 mm thick with a valley depth of 155 mm. The sheets are overlapped and bolted vertically every 8 m and stiffened every 4 m by external ring-shaped truss beams (Figs. 11 and 12). The chimney is supported 8 m above the ground by a ring-shaped beam on 8 small-diameter tubes so that the warm air can flow into it with as little turbulence as possible.
A polymer-coated fabric cape forms a smooth transition between the collector roof and the chimney at its base (Figs. 13, 14, 20).
The chimney is guyed vertically at four levels and in three different directions to foundation blocks along the periphery of the collector roof (Fig. 10).

The construction method used is worthy of note. The chimney cylinder was erected from the ground upward, by means of an incremental lifting procedure specially developed for the purpose, using a lifting ring and hydraulic jacks, the cylinder growing from below by 8 m per lift, the stays being slackened simultaneously. This permitted complete prefabrication on the ground and erection with a minimum number of skilled labourers (Figs. 14+15). Construction of the foundations started in November 1980 and the chimney was completed in September 1981.

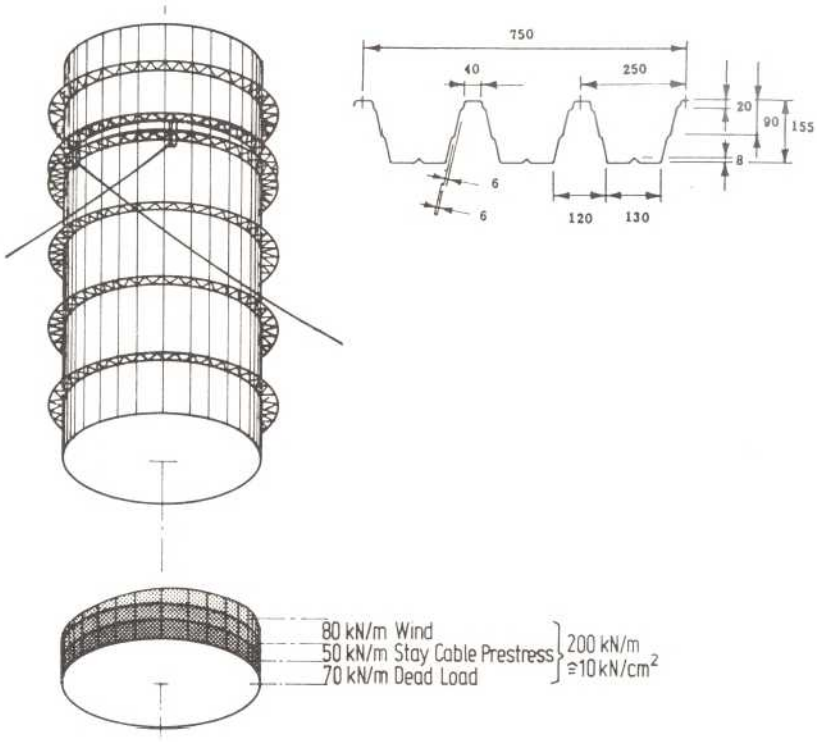


Fig. 11: The chimney tube: dimensions of the corrugated sheet and axial forces

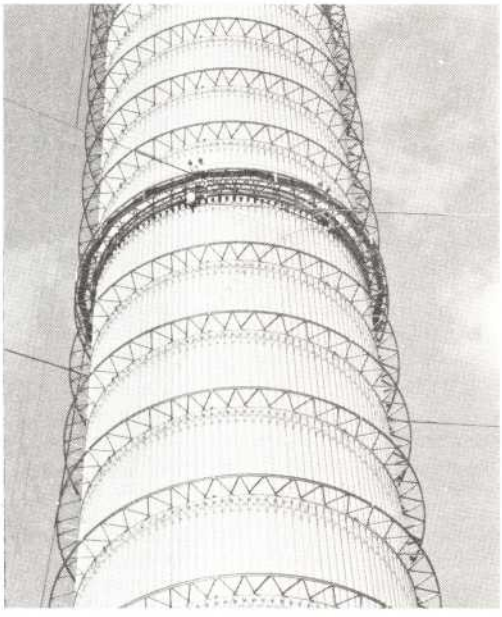


Fig. 12: The corrugated sheet tube and its external stiffeners

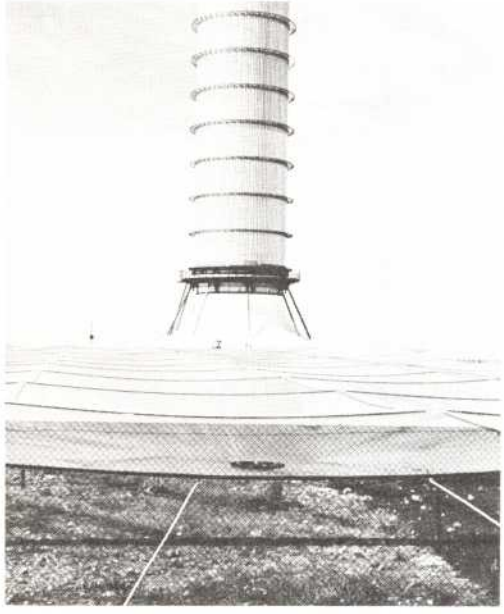


Fig. 13: The fabric cape forming a smooth transition between the roof and the tube (see also Fig. 21)

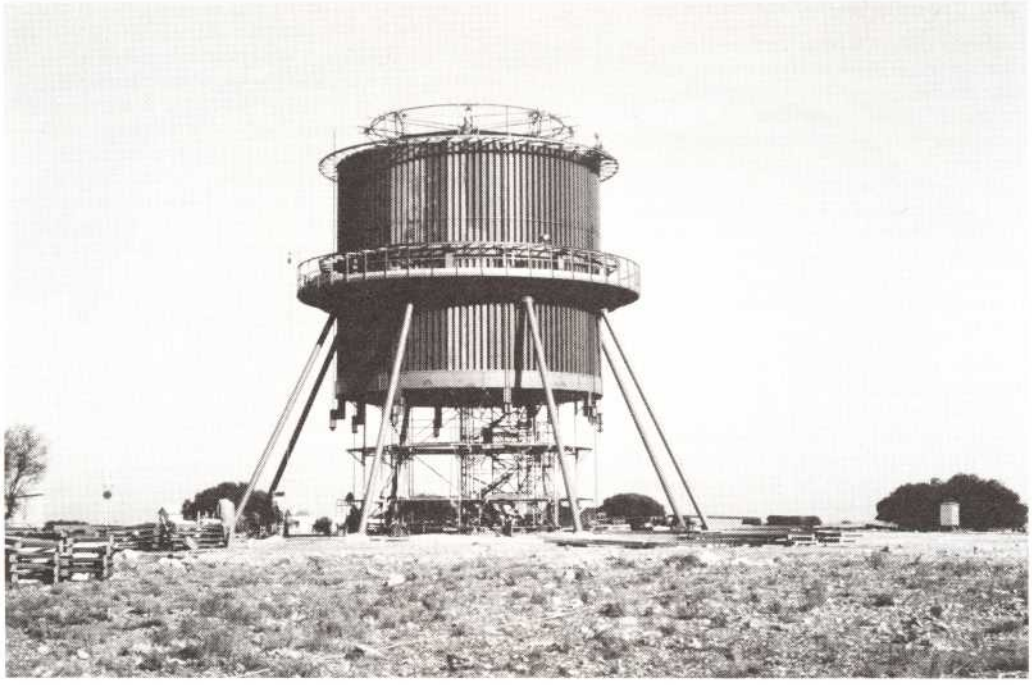


Fig. 14: The erection of the chimney by incremental lifting

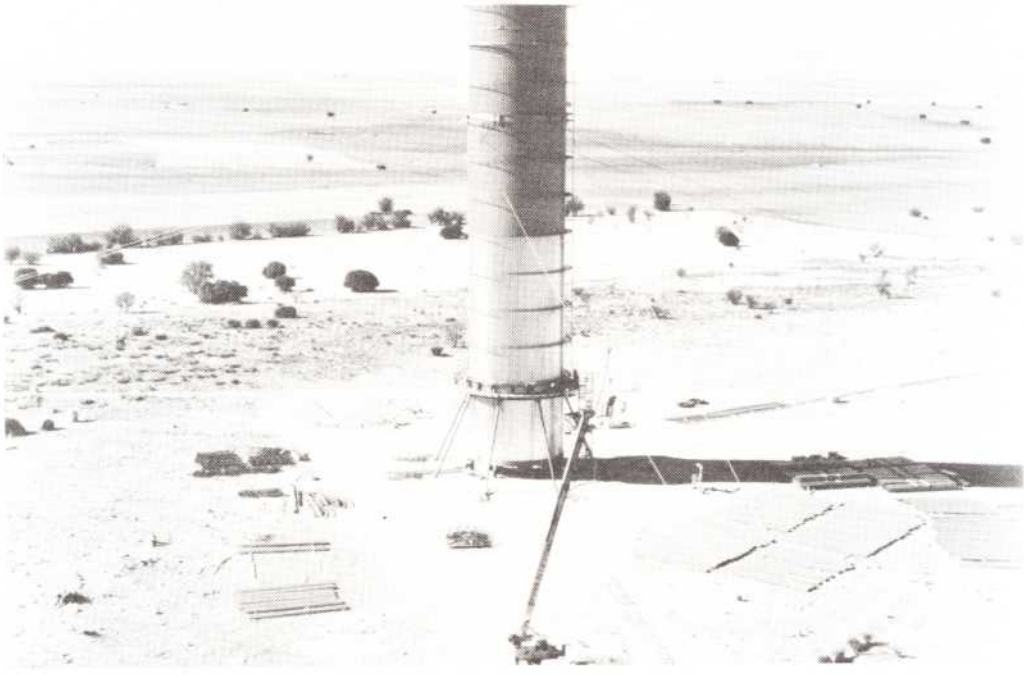


Fig. 15: The erection of the chimney by incremental lifting

2.3 The collector roof and the turbine

From the technical point of view the future of solar chimneys depends in particular upon whether it is possible to develop an inexpensive, long-lasting, thermally efficient collector roof. For the pilot plant, therefore, possibly the cheapest and – with respect to structural detail, dynamic safety and durability – the most difficult material, i.e. plastic film, was chosen. Four different types of plastic film were employed at Manzanares for purposes of comparison. They have 94% transmission in visible light range and approximately 14% in the long wavelength range of thermal radiation (see Fig. 3).

The roof was composed of rectangular, originally flat, panels measuring 6 X 6 m or 4 X 6 m which were clamped along their peripheries in metal frames and supported on tube columns. The panels were stabilized against wind by means of plastic discs placed in the centre of each panel and anchored in the ground. The discs doubled as drainage points for the roof (Figs. 16÷18).

The entire film canopy was erected by an unskilled workforce trained on site. This possibility of employing local labour is of particular importance for the introduction of solar technology in Third World countries.

Between the time of the trial construction of the roof in 1981, its completion at the beginning of 1982 and today, there have been several extremely violent storms with wind velocities as high as 160 km/h, causing severe damage in the surrounding area. The design proved to be basically sound. In places where trailing eddy currents from the chimney produced high suction forces a number of panels were torn to shreds. Fibre-reinforced polymers are therefore now being used for the panels. These are, however, more expensive and less translucent. It is crucial to the project that the right material be found for the panels. For this reason glass is also being tested now; it is more expensive but durable.

After the first measurements were taken with the natural earth surface as it was, it was blackened with bitumen to increase its thermal absorption capacity (Figs. 17+19).

Another problem of the collector roof is that it may lose its translucence because of dust. There is no doubt that collector roofs in desert regions would have to be cleaned from time to time. Washing and vacuuming devices have been considered for this purpose. The structural details selected for Manzanares have the advantage that the funnel-shaped polymer panels are automatically cleaned when it rains. As a result, the roof in Manzanares remained completely clean in spite of severe dust storms. Furthermore, investigations have shown that a certain amount of dust on the panels is not detrimental. It does reduce light transmission but reduces the heat losses even more.

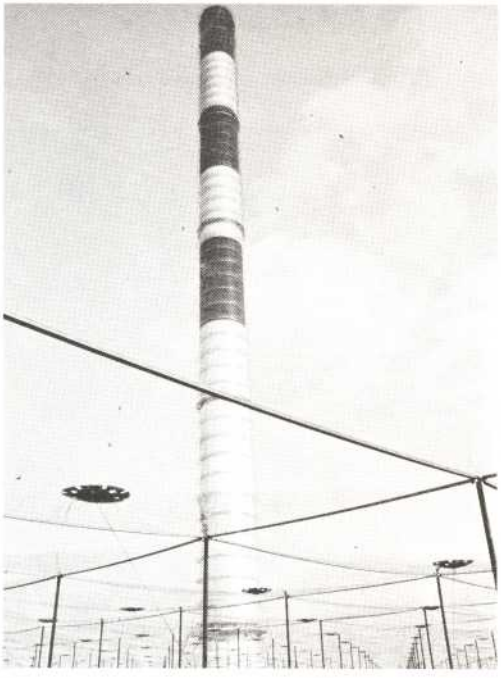


Fig. 16: The translucent collector roof at Manzanares seen from underneath. The earth is not yet blackened

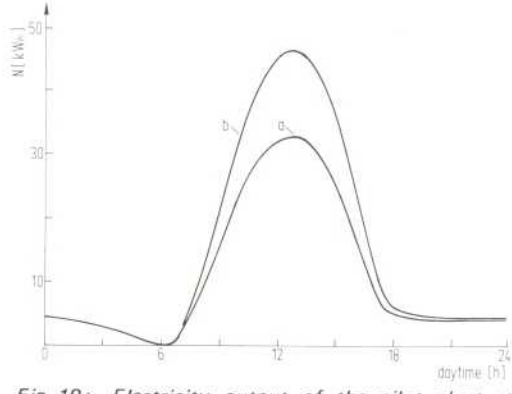


Fig. 19: Electricity output of the pilot plant at Manzanares for varying soil thermal absorption capacity
a) light natural earth
b) blackened earth

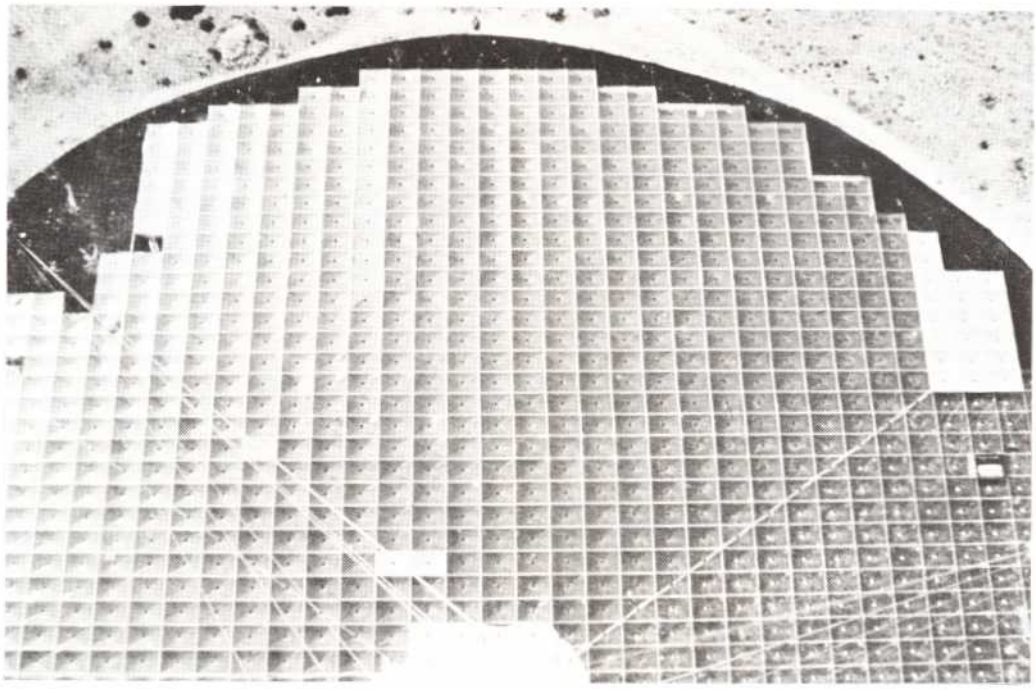


Fig. 17: The translucent collector roof seen from the chimney with the blackened earth visible at the perimeter

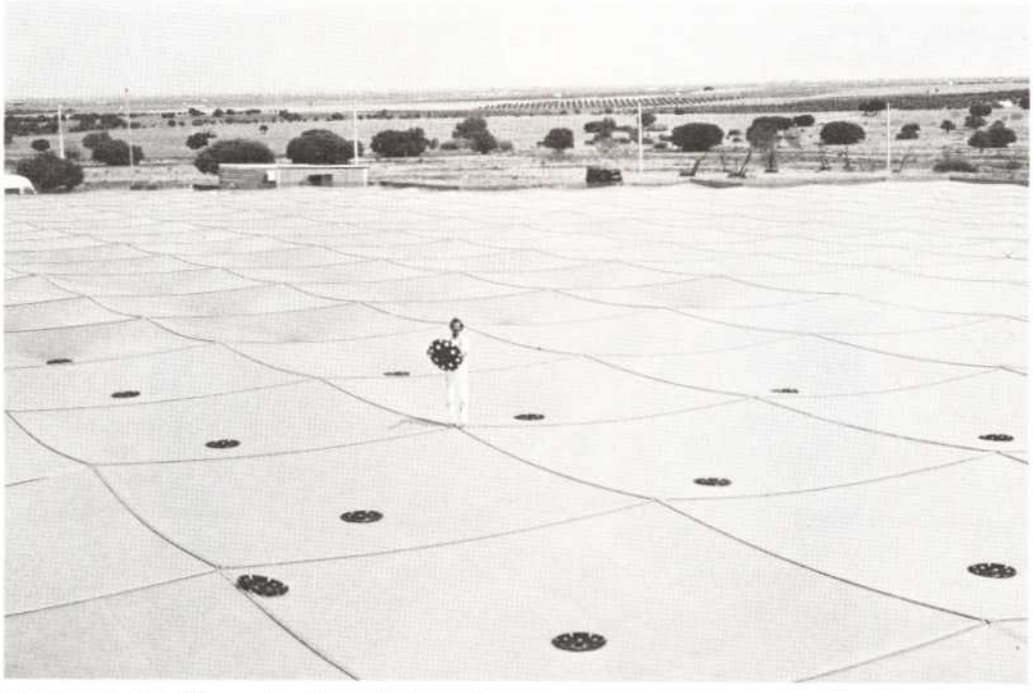


Fig. 18: The 6 m/6 m panels of the collector roof

2.4 The wind turbine

The wind turbine is located at the base of chimney, just above the transition from the cape to the tube; it is supported independently of the chimney on a steel-frame platform 9 m above the ground (see Figs. 20÷22). It has four types FXW-151-A blades whose angles can be adjusted during operation in order to maintain a constant speed or to attain the optimum one. It can be run at a maximum of 170 rpm and can be switched from a 100 kW A.C. generator to a 40 kW one for maximum night-time electricity generation. The electricity generated is fed directly into the grid. The turbine requires a vertical start-up wind velocity of 3 m/s and can handle velocities of up 20 m/s. The air flow can be controlled and shut off by regulating inlet valves, which are nothing more than doors located at the transition between the collector roof and the chimney. The facility can be operated either manually or fully automatically. Automatic operation includes start-up, accommodation to grid requirements and the setting of the blade angles for optimum operation.

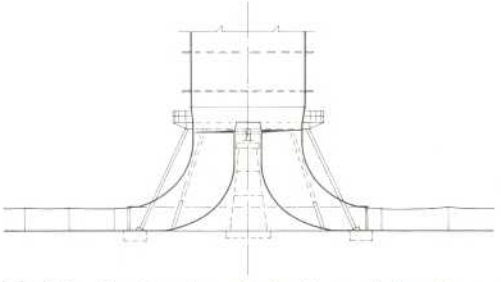


Fig. 20: Section through the base of the chimney

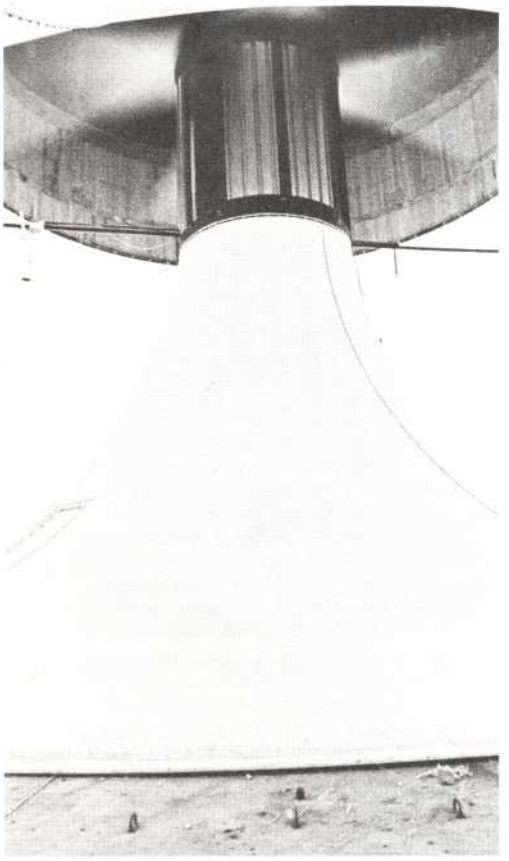


Fig. 21: The funnel providing a smooth transition from the collector's horizontal airflow into the chimney's updraft

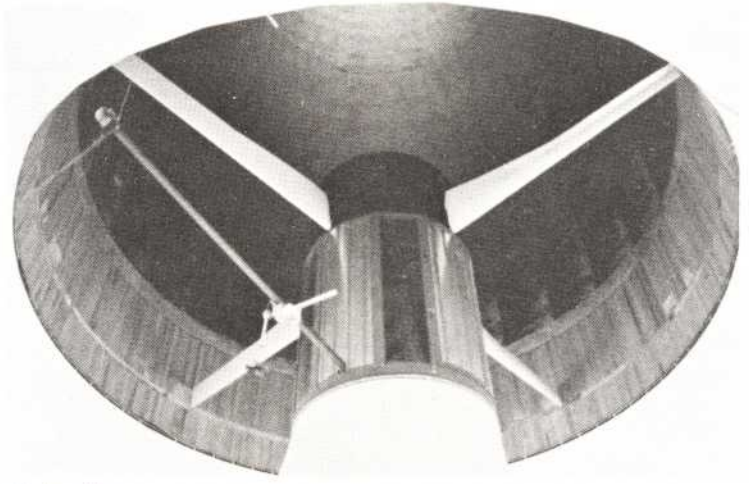


Fig. 22: The wind turbine

2.5 Some results

Extensive measurements have been carried out since fall 1982, and in particular in summer 1983. They include climatic data, solar and sky radiation, film transmission values, temperatures above and below the roof, up to 100 cm below ground level and in the chimney, pressure distribution and losses due to friction in the air flow and finally everything connected with the turbine and its output. Preliminary results are available but they still have to be evaluated and further verified before publication and final assessment (Fig. 23).

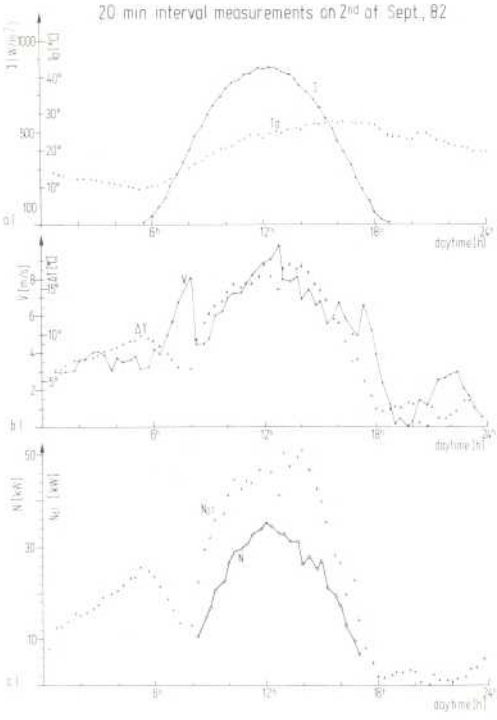


Fig. 23: Momentary measurements at 20-minute intervals on 2nd September 1982 (earth surface not yet blackened):
a) global radiation I and fresh-air temperature T_a
b) temperature difference at bottom ΔT and upwind velocity V
c) terminal output N and potential output $N_{\Delta T}$, the latter calculated from the measured increase in temperature

Even now it may be said that this pilot plant has been a successful undertaking. The simple principle and the reliability were confirmed at this very first attempt.
Since it was put into operation on 7.6.1982 the turbine has only been shut down when there has been a risk of thunderstorms, because of the danger to the control electronics from voltage peaks in the inadequately safeguarded grid. The plant is operated by a single assistant trained on site.

The extent of agreement between the physical model and the measurements is satisfactory (Fig. 24). It may be expected that the predictions made in section 1 with respect to the geometry and the output (Fig. 6) and with respect to the costs (Fig. 7) will be confirmed! With these positive results in hands, detailed design work on larger solar chimneys has already started.

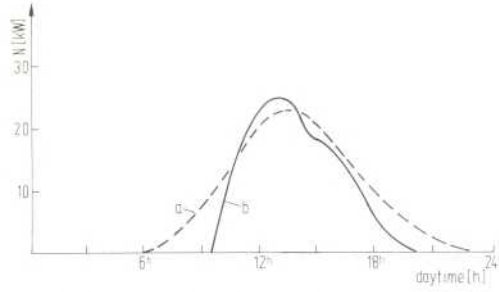


Fig. 24: Comparison of model calculation and measured power output. The climatic data obtained on site were used for the simulation model.
a) power output model calculation
b) power output measured on 12th July, 1982

3. Prospects for the future

From a technical point of view it is already possible today to build solar chimneys of large size and generating capacity. Chimneys with heights of as much as 1,000 m give rise to no special problems. They can be built either free-standing or stayed, depending upon their height-to-diameter ratio, of reinforced concrete or in the form of a cable net or membrane structure (see Fig 1).

Even the wind turbines for the solar chimneys are no technical problem. As they are vertical-axis machines, they are from the very start much easier to master than classic wind-mills with their horizontal axes. Mounted on simple support structures placed directly on the ground, these wind turbines are statically and dynamically independent of the chimney. It is also possible to support the blades of a large-diameter turbine at their outer edges, e.g. by means of electromagnetic pads. Further one may mount in large-diameter chimneys not one turbine but 6 or 7 with a radius of $^{R}T/_{3}$ each without any great loss of generating capacity.

Thus, there remains only the aforementioned question of the most appropriate sheeting for the collector roof, a question more of an economic nature than a technical one.

At present it is simply too early to make a well-founded statement about the economic prospects of using renewable sources in general [6] nor of solar chimneys in particular. Neither the naiveté of the environmentalists nor the occasional arrogance of the "Megawatt Clan" is sufficiently capable of handling the greatest challenge in the history of mankind, which is to find the solutions to the problems of energy and population growth, which are linked through the standard of living, or in other words through energy consumption. We owe it to the Third World with its crying need for energy even today, to develop energy sources that they can afford. Solar energy should not be excluded from such considerations as long as its success or failure has not been clearly proven.

Solar chimneys represent one possibility. They permit large-scale electricity generation with simple technology where unproductive arid or desert land is available free. An added advantage is their thermal storage capacity at no extra cost. Since it may be expected, as described above, that the data collected at Manzanares support the calculations, it will have been demonstrated that solar chimneys are able to generate electricity at costs that are competitive and even lower than most known solar power plants today. Other solar energy plants may of course have other advantages, for example that they are competitive for a decentralized power supply in remote areas. Therefore, our office is also working on other types of solar energy plants in addition to solar chimneys, including in particular those with concentrators or heliostats, based on metal membrane structures, for high-temperature energy production; i.e. solar farms and solar towers (7), (8), (Fig. 25).

It is also too early to ascertain which kind of renewable energy source is worth pursuing further. In view of the seriousness of the energy problem, as indicated above, we should even refuse to admit this question, but rather demand that as many different types as possible to be developed. The research funds flowing in this direction are in any case ridiculous if we compare them with other government expenses, not to mention the military budgets. We should fight for more!!.

If this paper has shown that also civil engineers can and should join scientists and engineers of other faculties to solve the energy problem, it has served its purpose.

(Jörg Schlaich, Stuttgart)

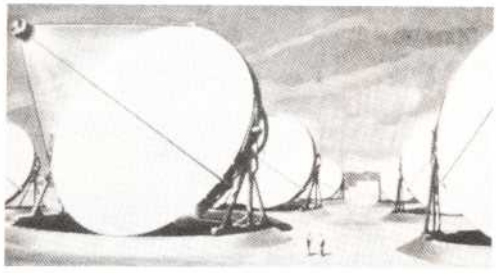
The solar chimney pilot plant in Manzanares/Spain:

Sponsor: The Federal Minister for Research and Technology (BMFT), Bonn, and his Project Management, Department for Energy Research, KFA Jülich/Fed. Rep. of Germany.

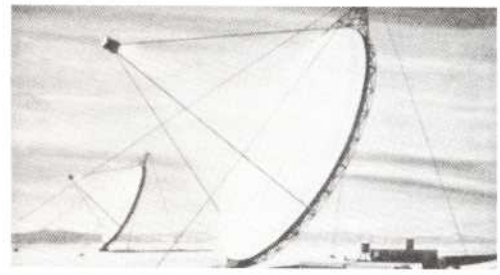
Grantee, project management, design, supervision, measurements:
Schlaich+Partner, Civil Consulting Engineers, Stuttgart
J. Schlaich and R. Bergermann
Structural staff: G. Mayr, K. Friedrich
Physical staff: W. Haaf, H. Lautenschlager

Spanish partner: Unión Electrica, Madrid

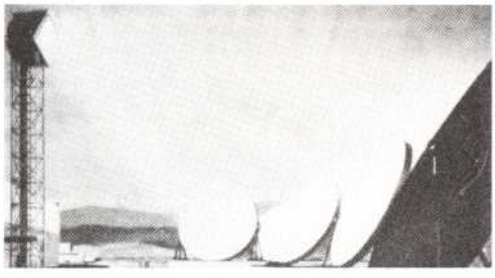
Major participating institutes and contractors:
Institut für Aero- und Gasdynamik, Universität Stuttgart
Euroconsult S.A., Madrid
Promoción de Infraestructuras S.A., Madrid
Maurer Söhne, München
Balcke-Dürr AG, Ratingen
Institut für Meteorologie der Universität Mainz



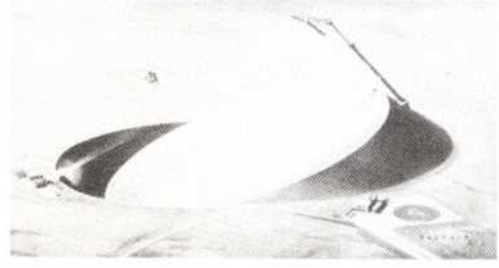
Solar Farm.
For production of electric power via steam, photovoltaic, Stirling engine or gas turbine.
A farm consists of several mirrors with diameters between 10 and 17 meters, each producing 12-34 kW electrical power.



Large Mirrors.
Mirrors which are biaxially adjustable to the sun with diameters of say 50 meters and thermal power of ~1800 kW or electrical 300 kW.



Solar Tower.
For production of electrical power via steam.
Several mirrors with long and permanently adjustable focus and with diameters of 10 to 17 meters and 70 to 200 kW thermal power form a heliostat field. They are adjusted to one common receiver.



Fixed membrane mirrors of say 80 meters diameter with thermal power of 4500 kW or electrical 750 kW.

Fig. 25: Metal membrane solar concentrators (projects)

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