Solar thermal electricity generation

Solar Thermal Electricity Generation

Production d'électricité par chaleur solaire

Die solar-thermische Elektrizitätserzeugung

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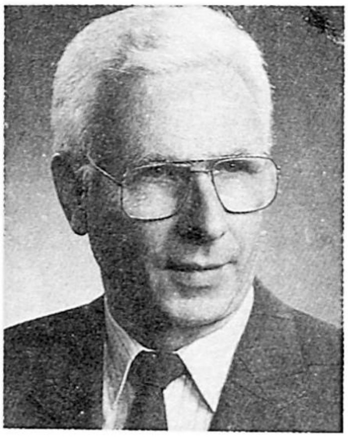

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SUMMARY

Seven technologies are today considered to be able to share a future renewable energy electricity production. These are, in addition to water power plants, wind generators and photovoltaic cell arrays, four systems which directly utilize the sun's heat: the atmospheric power tower, also called solar chimney, and three systems using solar concentrators. After discussing the technological state of the art of these thermal systems, especially in view of Third World requirements, a more general discussion of the necessity of more research and development in the field of solar energy utilization follows.

RÉSUMÉ

Il existe aujourd'hui sept technologies considérées comme capable d'apporter une amélioration sérieuse à la production d'énergie électrique solaire. Hormis les centrales hydroélectriques, les éoliennes, et les cellules photovoltaïques, il s'agit de quatre systèmes qui exploitent la chaleur des rayonnements solaires: les cheminées d'énergie solaire ainsi que trois procédés à miroirs convergeants. L'avancement technologique de ces systèmes thermiques est décrit ici, pour aboutir d'une facçon plus générale sur la nécessité d'un accroissement de l'utilisation de l'énergie solaire, compte tenu, en particular, de la situation dans le Tiers Monde.

ZUSAMMENFASSUNG

Es gibt heute sieben Technologien, denen die Chance eingeräumt wird, einen ernsthaften Beitrag zur solaren Elektrizitätserzeugung leisten zu können. Dies sind neben den Wasser- und Windkraftanlagen und der Photovoltaik vier Systeme, die die Wärme der Sonnenstrahlung nutzen: die Aufwindkraftwerke und drei Systeme mit konzentrierenden Spiegeln. Der technische Stand dieser thermischen Systeme wird hier beschrieben, um dann noch allgemeiner die Notwendigkeit der verstärkten Sonnenenergienutzung, insbesondere im Hinblick auf die Situation in der Dritten Welt, zu erläutern.

1. STATE OF THE ART OF SOLAR THERMAL ELECTRICITY GENERATION

1.1 Atmospheric power towers or solar chimneys

In the solar chimney three well-known physical principles - the greenhouse effect, the chimney, and the turbine - are combined in a novel way (Fig. 1).

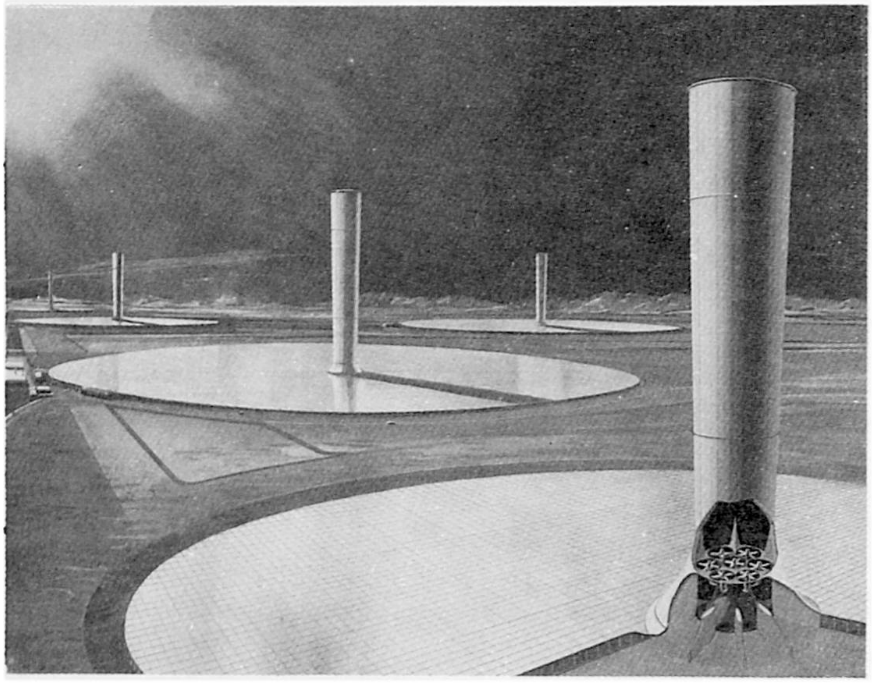


Fig. 1 Drawing of several large solar chimneys in the desert

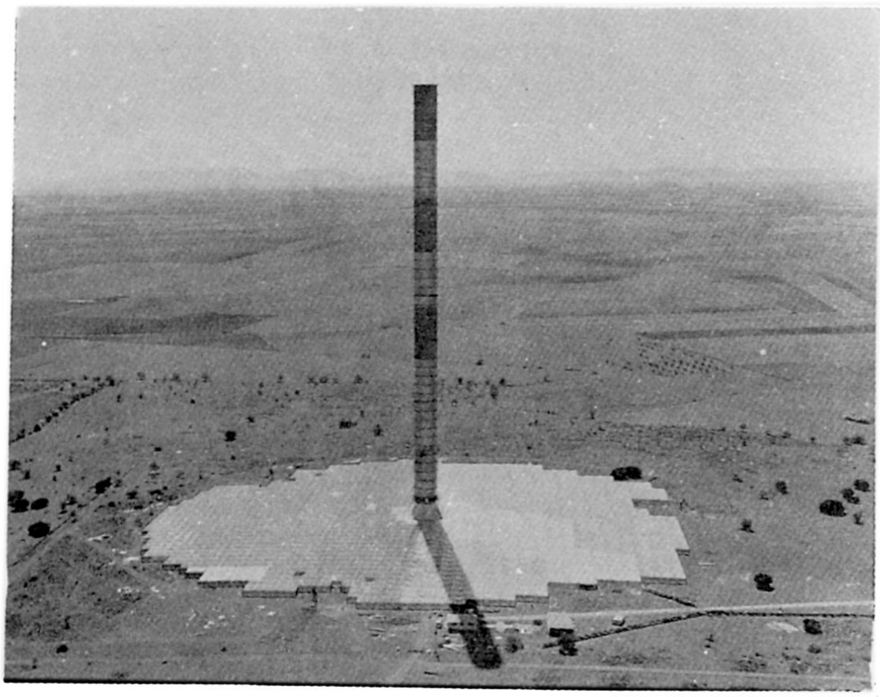


Fig. 2 Aerial photograph of the experimental facility at Manzanares, Spain (height of chimney 200 m; chimney radius 5 m; collector 120/120 m; rotor diameter 10 m; nominal speed 100 rpm)

Incident solar radiation heats the air under a large 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 a turbine and then into electricity via a conventional generator. This solar energy system has many technological and physical advantages:

1. It makes use of global radiation, including diffuse radiation when the sky is overcast.
2. 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).
3. Aside from the turbine and generator, there are no moving parts or parts that require intensive maintenance. No water is required to cool mechanical parts.
4. It features a simple, low-cost design utilizing know-how and materials that are also available in Third World countries (glass, concrete, steel). A high proportion of the costs is accounted for by work that is simple. This would benefit the local labour market while at the same time helping to keep overall costs down.

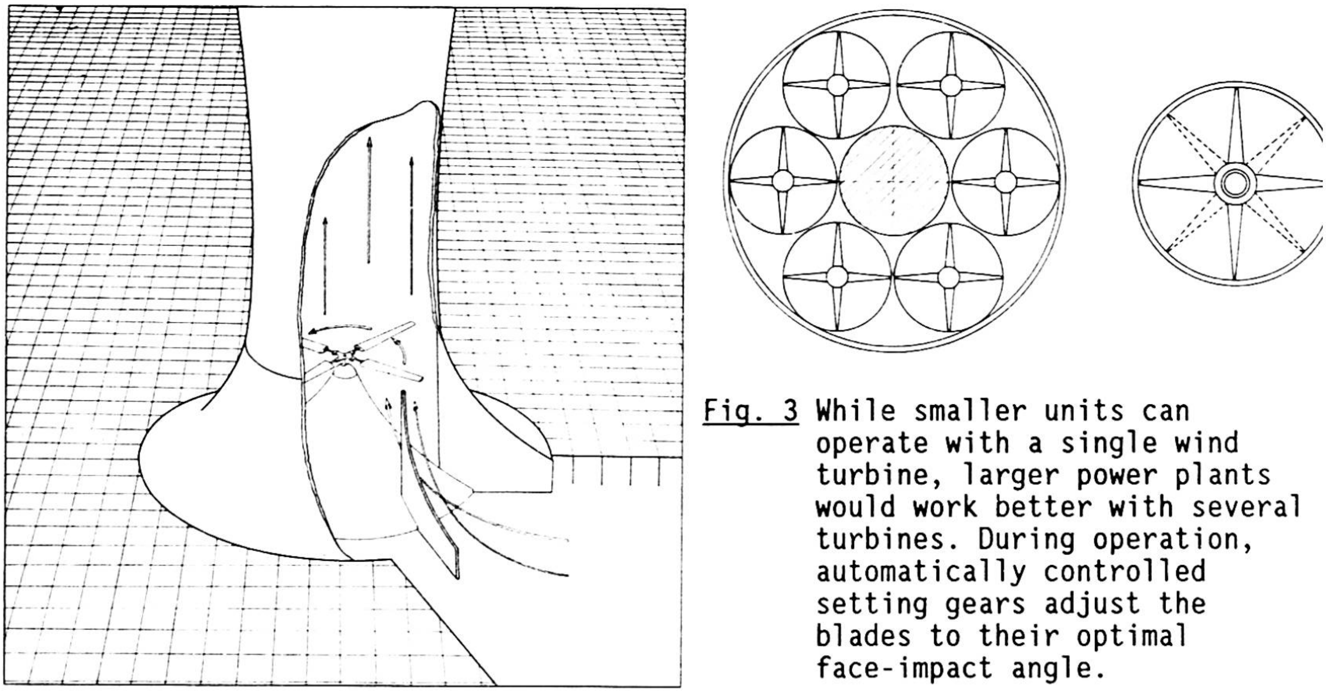


Fig. 3 While smaller units can operate with a single wind turbine, larger power plants would work better with several turbines. During operation, automatically controlled setting gears adjust the blades to their optimal face-impact angle.

With assistance from the German Federal Ministry for Research and Technology, an experimental facility was developed and built in Manzanares, Spain (Fig. 2), where these advantages were documented by a high degree of availability of the plant and low operating and maintenance costs.

Fig. 4 shows the hours of daily service for a full operating year. To permit a comparison, the measured hours of sunshine with over 150 W/m^2 irradiation and the theoretically possible maximum number of hours of sunshine (from sunrise to sundown) are also shown. The analysis revealed that, for example, 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/sec, the plant starts up automatically and is automatically connected to the public grid.

These results show that the components are highly dependable and that the plant as a whole is capable of highly reliable operation. The 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 that there is good agreement. Overall, it may be said that the optical and thermodynamical processes in a solar chimney are well understood and that models have attained a degree of maturity that accurately reproduces plant behaviour under given meteorological conditions.

Extrapolation of these results to larger plants produces the results summarized in Fig. 5. It shows the energy costs as a function of the size of the plant, expressed by the 24 hr-average power output. The height of the chimney (first figure) and the approximate diameter of the collecor roof are given along the curves. Further parameters are the climate of location, where Almeria, Spain, with approx. 2100 kW hr/yr and Barstow, California, with approx. 2600 kW hr/yr are compared, because of these two places all meteorological data are available. With the same plant specifications, for example, a chimney height of

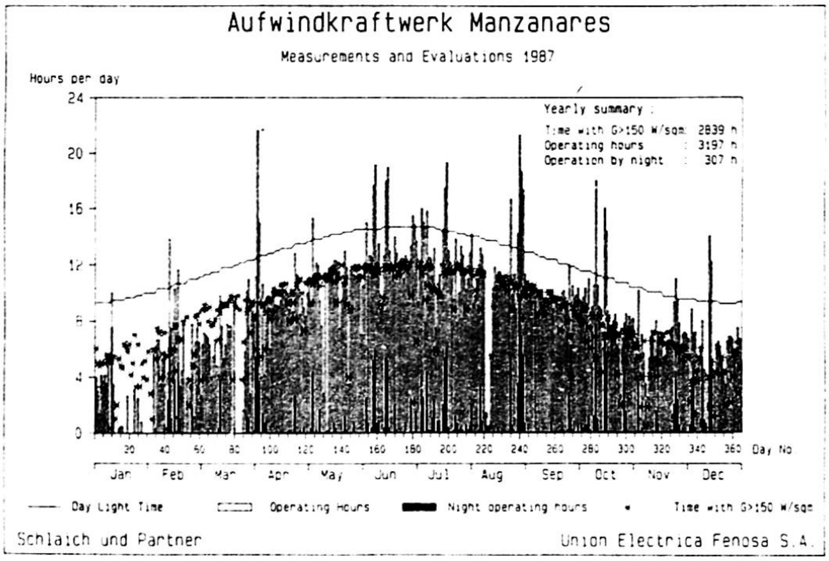


Fig. 4 Plant operating hours for 1987 of the solar chimney in Manzanares, Spain

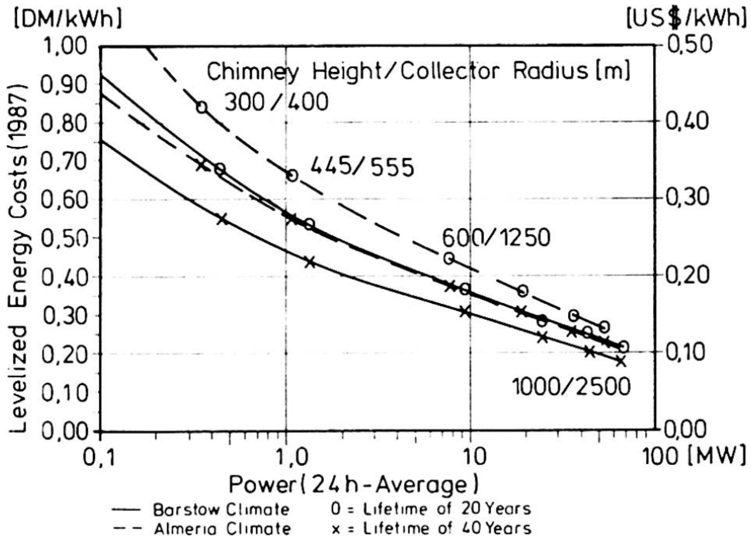


Fig. 5 Solar chimneys's electricity generating costs in relation to mean installed power

445 m and collector radius of 555 m, it would generate approximately 7.1 kW hr/yr under Almeria conditions, and 11.6 kW hr/yr, that is approximately 38 % more, in a climate such as that in Barstow, California. The calculations were based on a chimney life of 20 years; purely theoretically, therefore, the roof and machinery could be replaced in the twenty-first year. The specific electricity generating costs were calculated by the real present value method (with a real discount rate of 4% and a depreciation period of 20 or 40 years).

The economy of the power plant is dictated by the investment necessary to construct the plant and operating costs; these comprise personnel costs, maintenance and repair costs, and the cost of the necessary fuel. The calculations show that this power station technology, based on a renewable form of energy, satisfies every precondition for continuing development: technically feasible potential combined with power generating costs that, conservatively estimated, will be below $ 0.10/kW hr.

1.2 Distributed collector systems (DCS) with trough concentrators

The individual collectors are parabolic troughs, each 100 metres long and 6 metres wide, which are made from hundreds of curved mirror segments. These troughs are suspended in such a way that they track the sun, however around one axis only. The solar radiation bundles on a glass/metal tube 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, turbine generator, and a cooling tower.

These collectors have meanwhile reached, following from continuous improvements, a concentration factor of 82. Starting 1984 up to now six plants of 30 MW output each and one with 80 MW have been successfully built in California. In case of scarce of solar radiation gas firing may be added. This permits to avoid the costly thermal storage and guarantees continuous electricity supply, a requirement utilities certainly appreciate and pay for correspondingly.

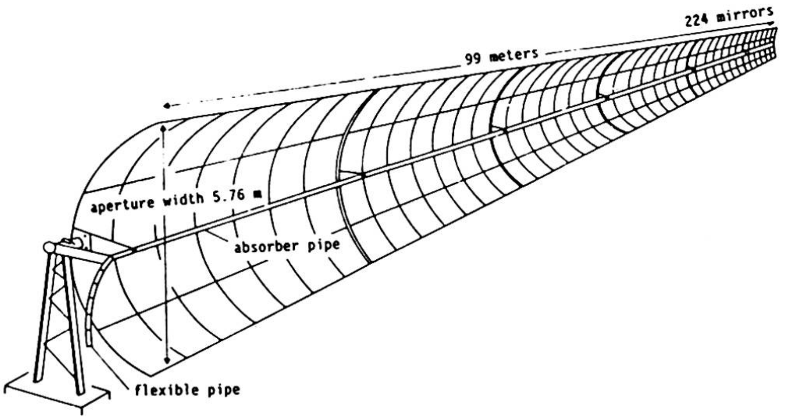


Fig. 6 Sketch of the LS-3-Collectors as built by Luz International Ltd. and Flachglas-Solartechnik GmbH

The 80 MW SEGS-plant (SEGS stands for Solar Electricity Generating System) was built in 1989 at Harper Lake in the Mojave desert 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 MW hr. The investment costs are about 2500.-- \$/kW and the energy production costs are given to be 0.08 \$/kW hr.

Thanks to a relatively simple technology and a skillful marketing the DCS trough collector plants are rather successful and have demonstrated that a large-scale solar energy utilization must not mean an utopia and that economy can be reached through mass production. In regions with a high direct solar radiation these plants have a promising future.

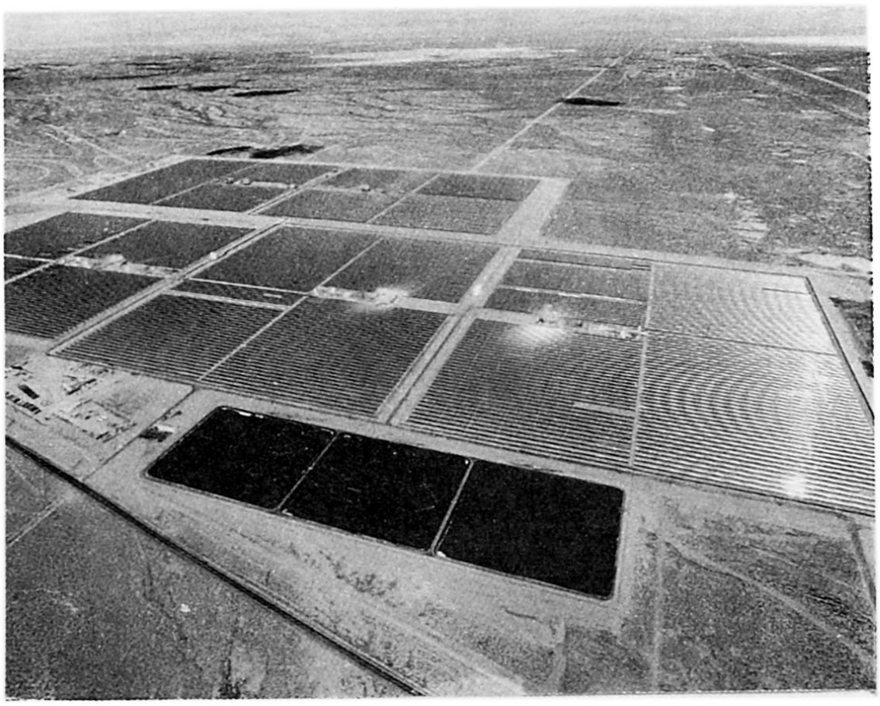


Fig. 7 The DCS plant at Kramer junction, USA (5 x 30 MW)

1.3 Central receiver systems (CRS), solar tower plants

The central receiver is placed on a tower, between 50 and 150 metres above ground. On ground around this tower the field of heliostats is arranged, heliostats in this case being the name for the concentrators or mirrors. The solar radiation is reflected by these heliostats to the receiver heating up a heat transfer medium there. Beyond that, as with the DCS, there is conventional thermal power plant technology: The medium is brought by pipes to a power plant at the base of the tower and drives there a turbine coupled with a generator.

The heat transfer medium may be air, water steam, liquid natrium or melted salt, and correspondingly the process temperatures vary from 550° to 1000° C. Each heliostat consists of several individual mirrors which are all together mounted on a structure able to track the sun around two axes. The tracking is computer controlled to guarantee a precise focusation. Up to now six such plants were built in the United States, in Southern Europe and Japan, the largest being the 10 MW plant at Barstow, California (Fig. 8) using steam as heat transfer medium.

Further development is to be concentrated on system integration and cost reduction of the individual components. The receiver plus heat transfer and short-time storage make up 1/4, the heliostats 1/3 of the total plant costs. It is expected that the efficiency can be considerably improved and the whole system simplified by applying high-temperature air receivers.

Concerning the heliostats, the accuracy and the robustness of the tracking device need improvements and the costs must be reduced. The metal membrane concentrators, as shown in section 1.4 are very well adaptable to heliostats, too, and would easily fulfill these requirements.

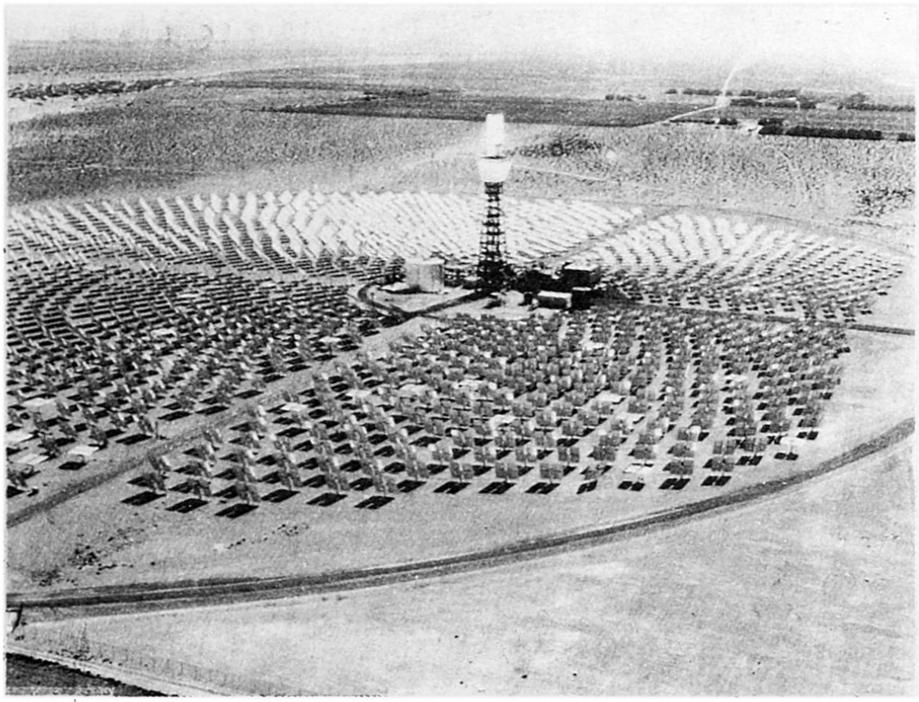


Fig. 8 The CRS plant Solar One at Barstow, California (10 MW)

1.4 Dish (metal membrane)/Stirling decentral electricity plants

As a means of generating electricity from solar energy, high-temperature energy conversion with concentrating systems has a very promising future.

A large hollow reflector is suspended in such a way that it can track the sun. The reflector has an energy converter, which converts the concentrated solar heat into electricity, suspended at its focal point.

The new and special feature of the power plant described here is the construction method, which makes a very large and precise concentrator possible. The concentrator is a hollow membrane of thin sheet steel to which mirror glass is bonded. The membrane is plastically deformed to the desired parabolic shape by air pressure. When the concentrator is in operation the shape of the membrane is kept constant by a partial vacuum in the interior of the concentrator, i.e. between the reflector membrane, the rear membrane and the reflector ring (Fig. 12).

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

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 mode or "stand-alone" mode. Storage devices (batteries, pumped storage etc.) may be provided or a hybrid conversion in combination with gas.

Power plants with reflector membranes are capable of an overall efficiency (defined as the ratio of the output usable electricity to the solar irradiation over the reflector surface) of up to 27 %. This has never been achieved with other types of solar plants. As the membrane construction method used for the reflector is relatively inexpensive they also make economic electricity generation a real possibility. The output of the energy converter depends on the accuracy of the beam path. The reflector membrane satisfies this requirement, though only a simple technology is needed for its fabrication. With carefully planned technology transfer such power plants could therefore also be fabricated in the low-income countries of the Third World.

In 1985, after constructing a test facility in Germany, two concentrators with 17 m diameter were installed in Saudi Arabia (co-sponsored by the King Abdul Aziz City for Science and Technology in Riyadh), (Fig. 9). Their power output is 50 kWe each. After the "usual" initial problems, especially with the Stirling engines, both are now continously operating according to expectations.

With the experience such gained, a further step of development was started in 1987 with the goal to develop a smaller size and extremely robust plant for installation at remote farms or other remote places and for operation by its unskilled owner. With a 7.5 m diameter the power output is 9 kWe.

This concentrator is polar mounted with one axis parallel to the earth's center of rotation. Thus, tracking of the sun may occur at an almost constant speed of 15 degrees/hr which can be achieved without electronic aid but only by means of a clock. Along the second axis the necessary adjustment is prescribed by the ecliptic of the earth; due to its very small daily changes it can be operated discontinuously and manually.

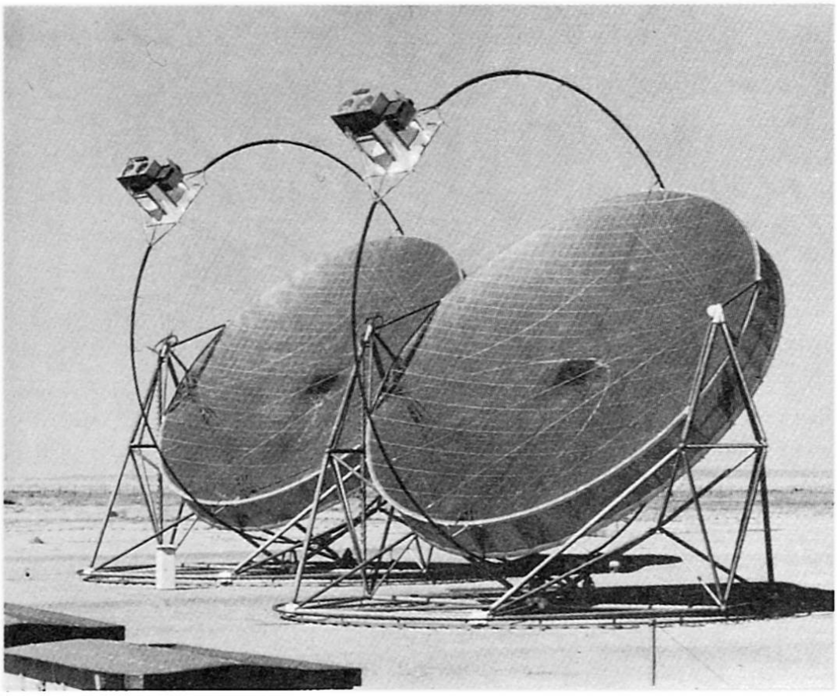


Fig. 9 Two 50 kWe concentrators in Riyadh

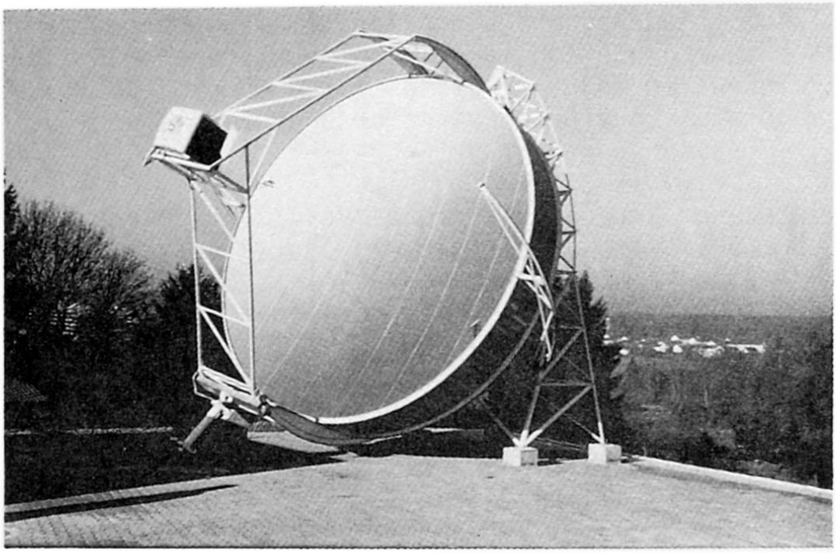
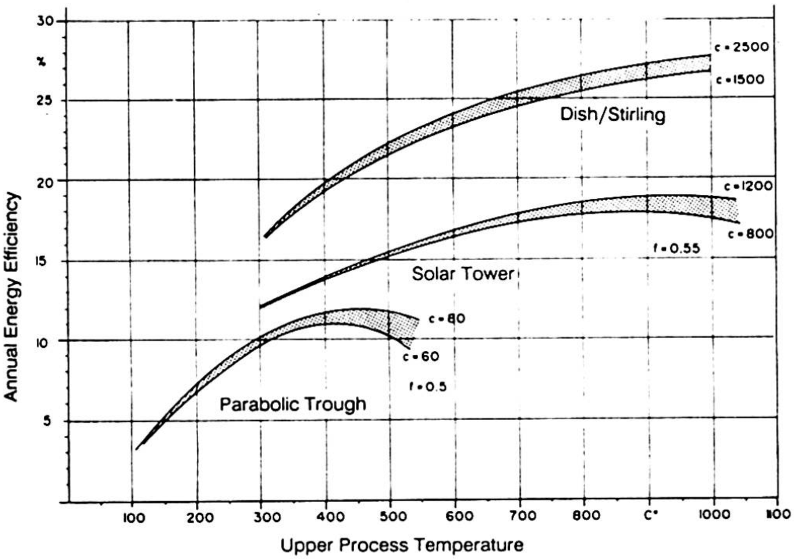


Fig. 10 9 kWe concentrator in Stuttgart

A test facility of that sort is now operating in Stuttgart. The quality of its concentrator is extremely good since a concentration factor of at least 10,000 was measured (Fig. 10). Thus the main aim of future development must be to build Stirling engines in series. It is also intended to reach a 24 hours operation of such plants by combining it with a biogas installation. Finally it should be mentioned that such metal membrane concentrators are also capable to make extremely precise and economical heliostats for the so-called solar towers (sect. 1.3).

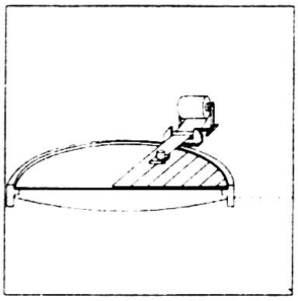


(sect. 1.4)

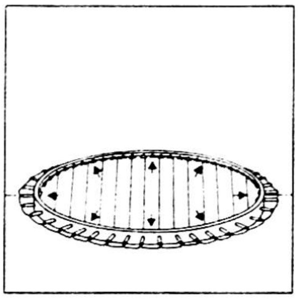
(sect. 1.3)

(sect. 1.2)

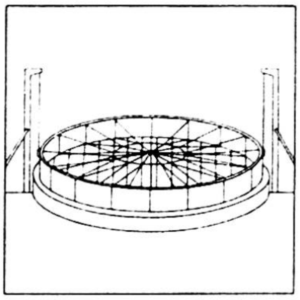
Fig. 11 Overall efficiency of concentrating systems



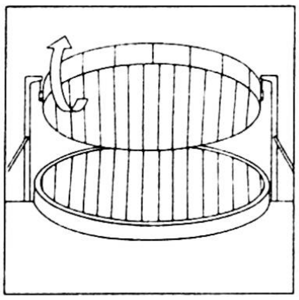
The membranes are made of individual sheet-metal strips welded together in the same plane with a welding device specially developed for thin sheet metal, which insures a gastight seam.



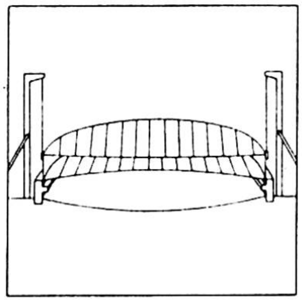
They are fixed to a ring and stretched radially until flat.



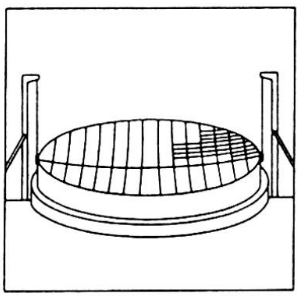
After fixing the rear membrane to the ring the concentrator is turned over.



The front membrane is then deformed to a paraboloid by applying air pressure between the membrane and the ground and subsequently fixed to the ring.



Now the air can be extracted from the concentrator housing thus created; with a partial vacuum between them the membrane surfaces will also withstand high wind loads.



Finally, thin glass mirrors are bonded onto the front membrane.

Fig. 12 Fabrication of the concentrator housing

1.5 Summary and cost comparison

Especially the solar chimney (sect. 1.1) and the trough-DCS-systems (sect. 1.2) are feasibile for large-scale solar electricity production, whereas the CRS-tower plants need further verification first. Since the solar chimney's investment respectively construction costs depend on labour predominantly, it becomes superior to any other system in places where labour is cheap.

For the decentral application the dish/Stirling-system should be further developed because they have a chance to serve the same purpose in sunny places as the wind converters in windy regions, where the latter are already today economical.

The graph in Fig. 13 compares all seven technologies at suitable locations with respect to their electricity production costs. Without hesitating it can be said that already today solar electricity can be produced for less than $ 0.1/kW hr. This is economical if one considers that this price does not depend on fuel and comprises all environmental costs.

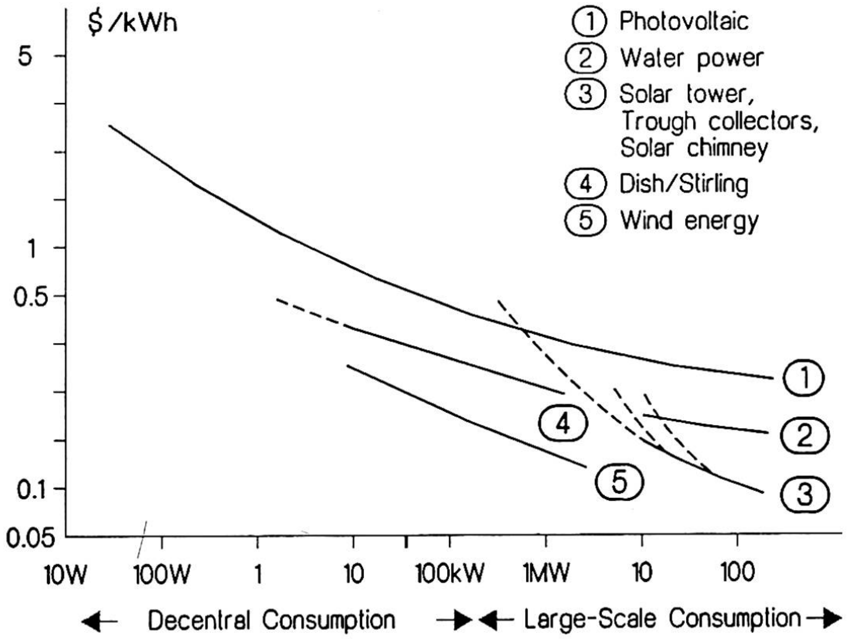


Fig. 13 Electricity production costs of the relevant renewable energy technologies

2. WHY AND WHERE SOLAR ENERGY UTILIZATION?

We are facing the greatest materials problem in the history of mankind, that of keeping this earth habitable and viable. The threats are
- a population explosion accompanied by poverty and undignified living conditions in large parts of the world
- the reckless exploitation and imminent exhaustion of our natural resources
- as a consequence of the above, the destruction of our natural environment.

Do we have to fear that our political leaders will not foresee this global threat and further that they will not have a clear concept of the consequences? Should not only those deserve our trust and our votes who commit themselves to the people and their interest; who purposefully and consistently pursue the "north-south dialog" and who work to develop a concept for a new global responsibility?

It would be presumptuous to try to present such a concept here. The social, cultural, economic and political implications in the creation of a new global responsibility are far too complex and intricate. A prudent agenda would have to include manifold solutions tailored specifically to each society or segments of society, from measures to combat illiteracy and promote the emancipation of women, to moving away from the traditional forms of national sovereignty and obsolete nation-state thinking.

However, beyond any doubt, the emphatic devlopment of renewable energy sources would be a tangible and promising beginning, creating jobs here and relieving the drain on natural resources and harm to the environment. All we need is to react sharply and move promptly before it is too late!

Obviously the threat to our planet grows progressively with the number of people it houses. Slowing down population growth can help reduce degradation of the earth's environment and relieve some of the plight of the people. Of course, predictions about the future development of the world's population differ greatly. However, all agree that the population increase in the developing world will be significantly reduced in the next century as a result of factors similar to those we have experienced in industrialised societies, and will finally come to a standstill once a population of some 10 to 12 billion has been reached. Wishful thinking? In fact, a high birth rate is directly correlated to a low standard of living and the latter, respectively the productivity of a country, is directly proportional to the energy consumption (Fig. 14).

By no means should we encourage the Third World countries into a development that is as energy greedy as ours or rationalise such development solely by the relationship between energy consumption, living standard, and number of children. Yet, it would be self-deception to promote an end to the population explosion in the foreseeable future without also planning to raise those people's standard of living and, at the same time, providing the required increase in output of energy. If it is already difficult to predict the future world's population increase, it is even more difficult to predict the future energy demand and its regional distribution.

Table 1 represents a speculation of the author and permits the reader to put in his own figures. The left side registers the present situation: 26% of the world's population consume 76% of the energy! The per capita consumption in the developing countries is only a fraction of what is wasted in the rich countries. On the right side of the table it is first assumed that the world's population of today approx. 5 billion (in fact already 5.5) will double (as last time) within 35 years and amount to 10 billion with a regional distribution, i.e. more in the D- and less in the I-countries. It is further assumed that the D-countries will receive a certain increase in energy per capita, enough to increase their standard of living "sufficiently" and that the I-countries are able and willing to compensate that increase completely by savings such that the average per capita consumption remains the same as today, i.e. 2.0 kW per capita, an extremely optimistic assumption! So the duplication of the population from 5 to 10 billion results in a duplication of the consumption from 10 to 20 Terawattyears/year only! But even then - and that is the problem! - the developing countries increase their consumption from 2.41 TW (today) to 13.1 TW (in 35 years), i.e. almost by a factor of 6! Then the D-countries, though their per capita consumption is still much less than that of the I-countries, will provide 84% of the world's population and require 66% of the total energy production.

How to satisfy this giant future energy demand at least necessary to break out of this vicious circle of population explosion, poverty, and environmental destruction? It got to be an energy source that is inexhaustible, environmentally sound, available everywhere, and that everyone can afford. Since neither fossil fuel nor nuclear energy can presently fulfil these needs on a global basis, only the direct use of the sun in the earth's desert areas offers a realistic source for the expected energy demand. This is why it is a paramount obligation also to structural engineers to participate in the development of solar energy power plants. It is beyond that up to each citizen of this world to propagate the idea of an increased solar energy utilization and to urge his political representatives to give financial priority for R+D in this field.

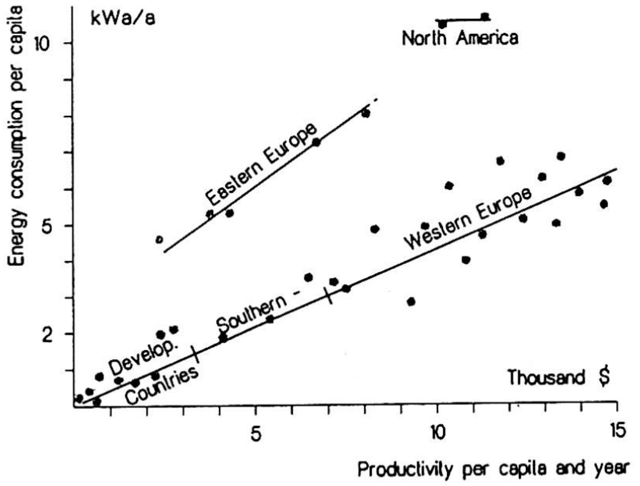


Fig. 14 Energy consumption per capita as a function of regional productivity

		Today					After about 35 years						
		Population		Consumption			Population			Consumption			
		Mill.	Σ/%	kW/cap.	TW	Σ/%	Mill.	Factor	Σ/%	kW/cap.	Factor	TW	Σ/%
Ind. countries (I)	North America	260		11.20	2.91		313	1.20		8.18		2.56	
	Other western ind. countries	620	1310/26	4.20	2.60	7.59/76	750	1.20	1643/16	3.07	0.73	2.30	6.9/34
	Soviet Union, Eastern Europe	430		4.80	2.08		580	1.35		3.50		2.03	
Developing countries (D)	Latin America	400		1.60	0.64		1130	2.80		2.00	1.25	2.26	
	Middle East, North Africa	190	3690/74	1.20	0.23	2.41/24	460	2.40	8360/84	2.00	1.67	0.92	13.1/66
	China, Asian soc. countries	1000		0.64	0.64		1600	1.60		2.00	3.13	3.20	
	South Asia, Africa	2100		0.43	0.90		5170	2.46		1.30	3.02	6.72	
		5 Bil		ϕ 2.0	10 TW		10 Bil			ϕ 2.0		20 TW	

Table 1 Scenario of the regional increase of energy consumption