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Solar Chimneys

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GLOSSARY

Greenhouse: Large collector roof under which air is heated by solar radiation.

Solar Chimney: Solar radiation heats air under a large roof. This air rises in a tower and runs a turbine that generates electricity.

Solar energy utilization: Conversion of the electromagnetic radiation from the sun into usable energy as there is heat or electricity.

In a future energy economy, solar chimneys will be able to produce electricity from solar radiation at economically viable prices. The results obtained at the experimental facility in Manzanares, Spain, have demonstrated that fully automatic operation with a high level of technical availability is already feasible. Economic appraisals have shown that the solar chimney is potentially economically viable, and that plants designed for an output of around 200 MW would be capable of producing electricity at less than \$0.07 per kW hr.

I. INTRODUCTION

Current energy production from coal and oil is damaging to the environment and non-renewable. Many developing countries cannot afford these energy sources, and nuclear power stations are an unacceptable risk in many locations. Inadequate energy supplies can lead to high energy costs as well as to poverty, which commonly results in population explosions.

Sensible technology for the use of solar power must be simple and reliable, accessible to the technologically less developed countries that are sunny and often have limited raw materials resources, should not need cooling water or produce waste heat and should be based on environmentally sound production from renewable materials.

The solar chimney meets these conditions and makes it possible to take the crucial step toward a global solar energy economy. Economic appraisals based on experience and knowledge gathered so far have shown that even solar chimneys rated at 100 and 200 MW are capable of generating energy at costs comparable to those of conventional power plants. This is reason enough to develop this form of solar energy utilization further, up to large, economically viable units, because in a future energy economy, solar chimneys could thus help assure economic and environmentally appropriate utilization of energy in sunny regions.

II. THE USE OF THREE "OLD" TECHNOLOGIES

Man learned to make active use of solar energy at a very early stage: greenhouses helped to grow food, chimney suction ventilated and cooled buildings and windmills ground corn and pumped water.

The solar chimney's three essential elements - glass roof collector, chimney, and wind turbines - have thus been familiar from time immemorial.

A solar-thermal chimney simply combines them in a new way (Fig. 1.).

Air is heated by solar radiation under a low circular glass roof open at the periphery; this and the natural ground below it form a hot air collector. In the middle of the roof is a vertical chimney with large air inlets at its base. The joint between the roof and the chimney base is airtight. As hot air is lighter than cold air it rises up the chimney. Suction from the chimney then draws in more hot air from the collector, and cold air comes in from the outer pe-

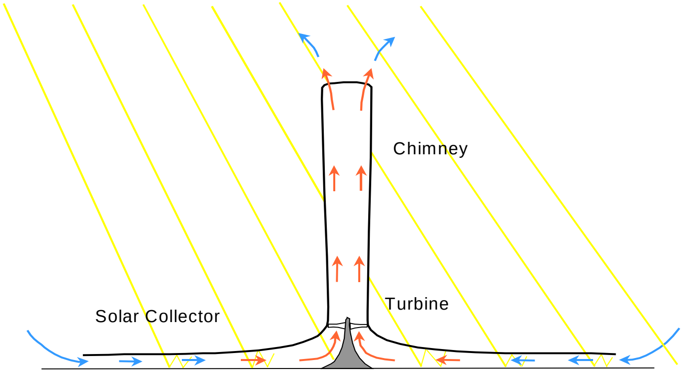

Fig. 1. Principle of the solar chimney: glass roof collector, chimney tube , wind turbines.

rimeter. Continuous 24 hours-operation is guaranteed by placing tight water-filled tubes under the roof. The water heats up during daytime and emits its heat at night. These tubes are filled only once, no further water is needed. Thus solar radiation causes a constant updraught in the chimney. The energy this contains is converted into mechanical energy by pressure-staged wind turbines at the base of the chimney, and into electrical energy by conventional generators.

A. The collector

Hot air for the solar chimney is produced by the greenhouse effect in a simple air collector consisting only of a glass or plastic film covering stretched horizontally two to six meters above the ground. The height of the covering increases adjacent to the chimney base, so that the air is diverted to vertical movement with minimum friction loss. This covering admits the short-wave solar radiation component and retains long-wave radiation from the heated ground. Thus the ground under the roof heats up and transfers its heat to the air flowing radially above it from the outside to the chimney.

B. The energy storage

Water filled black tubes are laid down side by side on the black sheeted or sprayed soil under the glass roof collector. They are filled with water once and remain closed thereafter, so that no evaporation can take place. The volume of water in the tubes is selected to correspond to a water layer with a depth of 5 to 20 cm depending on the desired power output (Fig.2.).

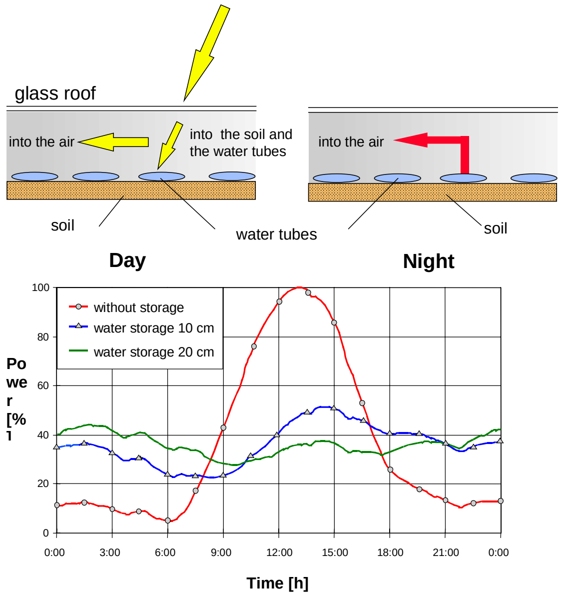

Fig. 2. Principle of heat storage underneath the roof using water-filled black tubes.

Since the heat transfer between black tubes and water is much larger than that between the black sheet and the soil, even at low water flow speed in the tubes, and since the heat capacity of water (4.2 kJ/kg) is much higher than that of soil (0.75 – 0.85 kJ/kg) the water inside the tubes stores a part of the solar heat and released it during the night, when the air in the collector cools down. This enables the plant to run for 24h per day on pure solar.

C. The chimney

The chimney itself is the plant's actual thermal engine. It is a pressure tube with low friction loss (like a hydroelectric pressure tube or pen stock) because of its optimal surface-volume ratio. The updraft of the air heated in the collector is approximately proportional to the air temperature rise (ΔT) in the collector and the volume, (i.e. the height and the diameter) of the chimney. In a large solar chimney the collector raises the temperature of the air by about 30 to 35° K. This produces an updraught velocity in the chimney of about 15m/s at full load. It is thus possible to enter into an operating solar chimney plant for maintenance without difficulty.

D. The turbines

Using turbines, mechanical output in the form of rotational energy can be derived from the air current in the chimney. Turbines in a solar chimney do not work with staged velocity like a free-running wind energy converter, but as a cased pressure-staged wind turbo generator, in which, similarly to a hydroelectric power station, static pressure is converted to rotational energy using a cased turbine - in this application installed in a pipe. The energy yield of a cased pressure-staged turbine of this kind is about eight times greater than that of a velocity staged open-air turbine of the same diameter. Air speed before and after the turbine is about the same. The output achieved is proportional to the product of volume flow per time unit and the fall in pressure at the turbine. With a view to maximum energy yield the aim of the turbine control system is to maximize this product under all operating conditions.

Blade pitch is adjusted during operation to regulate power output according to the altering airspeed and airflow. If the flat sides of the blades are perpendicular to the airflow, the turbine does not turn. If the blades are parallel to the air flow and allow the air to flow through undisturbed there is no drop in pressure at the turbine and no electricity is generated. Between these two extremes there is an optimum blade setting: the output is maximized if the pressure drop at the turbine is about two thirds of the total pressure differential available.

E. Optimization

A single solar chimney with a suitably large glazed roof area and a high chimney can be designed to generate 100 to 200 MW continuously 24 h a day. Thus even a small number of solar chimneys can replace a large nuclear power station.

Electricity yielded by a solar chimney is in proportion to the intensity of global solar radiation, collector area and chimney height.

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 (Fig. 3.). Optimum dimensions can be calculated only by including specific component costs (collector, chimney, turbines) for individual sites. And so plants of different sizes are built from site to site - but always at optimum cost: if glass is cheap and concrete expensive then the collector will be large with a high proportion of double glazing and a relatively low chimney, and if glass is expensive there will be a smaller, largely single-glazed collector and a tall chimney.

Broadly, to achieve a maximum output of (30) 200 MW at an irradiance of 1.000 W/m^2, the roof must have a diameter of (2.200) 4.000 m if the chimney has a height of (750) 1.500 m. If black water-filled tubes are placed on the soil underneath the roof for a continuous 200 MW full load 24 hours electricity production the diameter of the roof must be increased to 7.200 m. Now this solar chimney from a solar radiation of 2.300 kWh/m^{2}a extracts about 1.500 GWh/a, in fact a power plant!

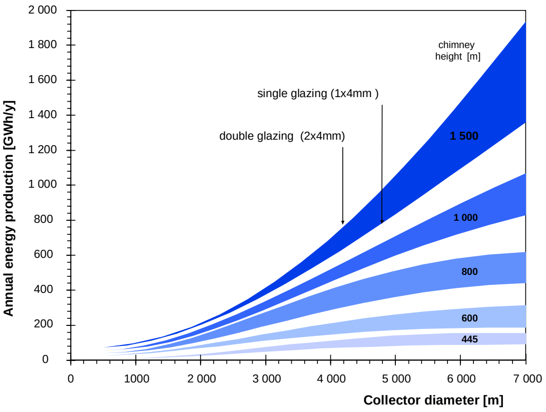

Fig. 3. Annual energy production by a Solar Chimney (at 2300kwh/m^2/a global insolation) dependent on collector diameter and chimney height.

F. Advantage

Solar chimneys operate simply and have a number of other advantages:

1. The collector can use all solar radiation, both direct and diffused. This is crucial for tropical countries where the sky is frequently overcast.

2. Due to the heat storage system the solar chimney will operate 24 h on pure solar energy. The water tubes laying under the glass roof absorbs part of the radiated energy during the day and releases it into the collector at night. Thus solar chimneys produce electricity at night as well.

3. Solar chimneys are particularly reliable and not liable to break down, in comparison with other solar generating plants. Turbines, transmission and generator - subject to a steady flow of air - are the plant's only moving parts. This simple and robust structure guarantees operation that needs little maintenance and of course no combustible fuel.

4. Unlike conventional power stations (and also other solar-thermal power station types), solar chimneys do not need cooling water. This is a key advantage in the many sunny countries that already have major problems with drinking water.

5. The building materials needed for solar chimneys, mainly concrete and glass, are available everywhere in sufficient quantities. In fact, with the energy taken from the solar chimney itself and the stone and sand available in the desert, they can be reproduced on site.

6. Solar chimneys can be built now, even in less industrially developed countries. The industry already available in most countries is entirely adequate for their requirements. No investment in high-tech manufacturing plant is needed.

7. Even in poor countries it is possible to build a large plant without high foreign currency expenditure by using their own resources and work-force; this creates large numbers of jobs and dramatically reduces the capital investment requirement and the cost of generating electricity.

G. A 'hydroelectric power station for the desert

Solar chimneys are technically very similar to hydroelectric power stations – so far the only really successful large scale renewable energy source: the collector roof is the equivalent of the reservoir, and the chimney of the pen stock. Both power generation systems work with pressure-staged turbines, and both achieve low power production costs because of their extremely long life-span and low running costs. The collector roof and reservoir areas required are also comparable in size for the same electrical output. But the collector roof can be built in arid deserts and removed without any difficulty, whereas useful (often even populated) land is submerged under reservoirs.

Solar chimneys work on dry air and can be operated without the corrosion and cavitation typically caused by water. They will soon be just as successful as hydroelectric power stations.

Solar chimneys can convert only a small proportion of the solar heat collected into electricity, and thus have a "poor efficiency level". But they make up for this disadvantage by their cheap, robust construction, and low maintenance costs.

Solar chimneys need large collector areas. As economically viable operation of solar electricity production plants is confined to regions with high solar radiation, this is not a fundamental disadvantage, as such regions usually have enormous deserts and unutilized areas. And so "land use" is not a particularly significant factor, although of course deserts are also complex biotopes that have to be protected.

Fig. 4. Prototype of the solar chimney at Manzanares.

IV. THE PROTOTYPE IN MANZANARES

Detailed theoretical preliminary research and a wide range of wind tunnel experiments led to the establishment of an experimental plant with a peak output of 50 kW on a site made available by the Spanish utility Union Electrica Fenosa in Manzanares (about 150 km south of Madrid) in 1981/82, with funds provided by the German Ministry of Research and Technology (BMFT) (Fig.4.).

The aim of this research project was to verify, through field measurements, the performance projected from calculations based on theory, and to examine the influence of individual components on the plant's output and efficiency under realistic engineering and meteorological conditions.

The principle dimensions and technical data for the facility are:

Chimney height: HT = 194.6 m
Chimney radius: RT = 5.08 m
Mean collector radius: RC = 122.0 m
Mean roof height: HC = 1.85 m
Number of turbine blades: 4
Blade: length 5 m, profile FX W-151-A tip-to-wind speed ratio: 1 : 10
Transmission ratio: 1 : 10
Operation: stand-alone or grid connection mode
Heating in collector: $\Delta T = 20°$ C
Nominal output: 50 kW
Roof covered with plastic: 40,000 m²
Roof covered with glass: 6000 m²

The chimney comprises a guyed tube of trapezoidal sheets, gauge 1.25 mm, knuckle depth 150 mm. The tube stands on a supporting ring 10 m above ground level; this ring is carried by 8 thin tubular columns, so that the warm air can flow in practically unhindered at the base of the chimney. A pre-stressed membrane of plastic-coated fabric, with good flow characteristics, forms the transition between the roof and the chimney.

The chimney is guyed at four levels, and in three directions, to foundations secured with rock anchors. The chimney was erected at ground level, utilizing a specially developed incremental lifting method. First, the top section of the chimney was installed on a lifting ring on the ground, and then it was raised onto the supporting ring by means of hydraulic presses.

The turbine is supported independently of the chimney on a steel framework 9 m above ground level. It has four blades, which are adjustable according to the face velocity of the air in order to achieve an optimal pressure drop across the turbine blades. Vertical wind velocity is 2.5 m/sec on start-up and can attain a maximum of 15 m/sec (Fig. 5.).

The collector roof of the solar chimney not only has to have a translucent covering, it must also be durable and reasonable priced. A variety of types of plastic sheet, as well as glass, were selected in order to establish which was the best – and in the long term, cheapest – material (Figs. 6 and 7).

Fig. 5. The turbine of the prototype plant in Manzanares.

Completion of the construction phase in 1982 was followed by an experimental phase, the purpose of which was to demonstrate the operating principle of a solar chimney. The goals of this phase of the project are (1) to obtain data on the efficiency of the technology developed, (2) to demonstrate fully automatic, power-plant-like operation with a high degree of reliability, and (3) to record and analyze operational behavior and physical relationships on the basis of long-term measurements.

Fig. 6. Glass roof of the prototype plant at Manzanares, Spain. It resisted heavy storms for many years without harm and proved to self-cleaning thanks to the occasional rain showers.

In order to arrive at a thorough understanding of the physical relationships and to evolve and identify points of approach for possible improvements, a simulation program was developed that describes the individual components, their performance, and their dynamic interaction. This program was verified on the basis of experimental measurement results, and its accuracy was checked. Today, it is a development tool that takes all effects known so far into account, and with the aid of which, the thermodynamic behavior of large-scale plants under given meteorological conditions can be calculated in advance.

Figure 8 shows the hours of daily service for a full operating year. To permit a comparison, the measured hours of sunshine with over 150 W/m² irradiation and the theoretically possible maximum number of hours of sunshine (from sunrise to sunset) are also shown. The analysis revealed that, for example, in 1987 the plant was in operation for a total of 3197 hr, which corresponds to a mean daily operating time of 8.8 hr. 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.

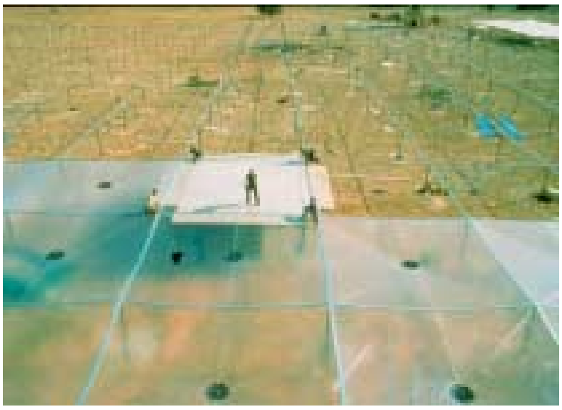

Fig. 7. Plastic membrane roof used in part of the prototype plant at Manzanares, Spain. It was installed there for comparison with the glass roof. It was cheaper than glass; however, plastic gets brittle with time and thus tends to tear. The membranes are clamped to a frame and stressed down to earth at the center by use of a plate with drain holes.

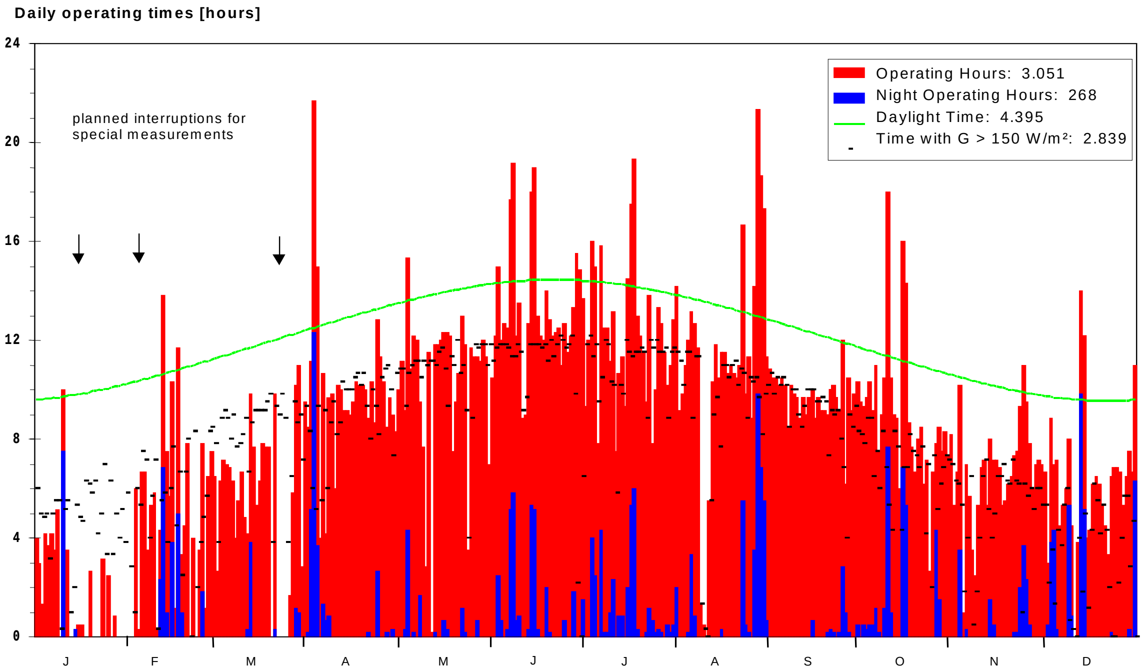

Fig. 8. Plant operating hours for 1987 at the solar chimney in Manzanares, Spain.

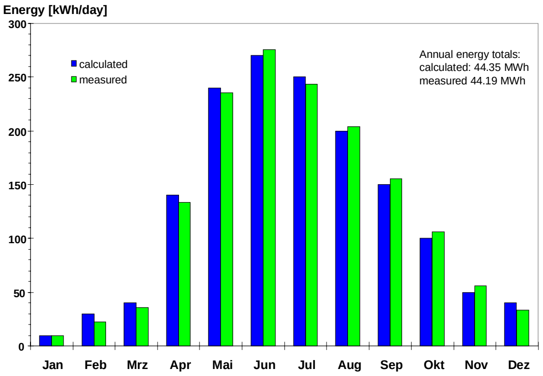

Fig. 9. Comparison of measured and calculated monthly energy outputs for the Manzanares plant.

These results show that the components are highly dependable and that the plant as a whole is capable of highly reliable operation. The advantages of the system are these: single global radiation is exploited and the thermodynamic inertia is a characteristic feature of the system, continuous operation throughout the day is possible, and even abrupt fluctuations in energy supply are effectively cushioned. As can be seen from the figure, 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. Fig. 9 shows a comparison between the measured and calculated average monthly energy outputs, showing that there is good agreement between the theoretical and measured values. 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 behavior under given meteorological conditions.

V. DESIGNING LARGE SOLAR CHIMNEYS

Measurements taken from the experimental plant in Manzanares and solar chimney thermodynamic behavior simulation programs were used to design large plants with outputs of 200 MW and more (Fig.10). Detailed investigations, supported by extensive wind tunnel experiments, showed that thermodynamic calculations for collector, tower and turbine were very reliable for large plants as well. Despite considerable area and volume differences between the Manzanares pilot plant and a projected 100 MW facility, the key thermodynamic factors are of similar size in both cases. Using the temperature rise and wind speed in

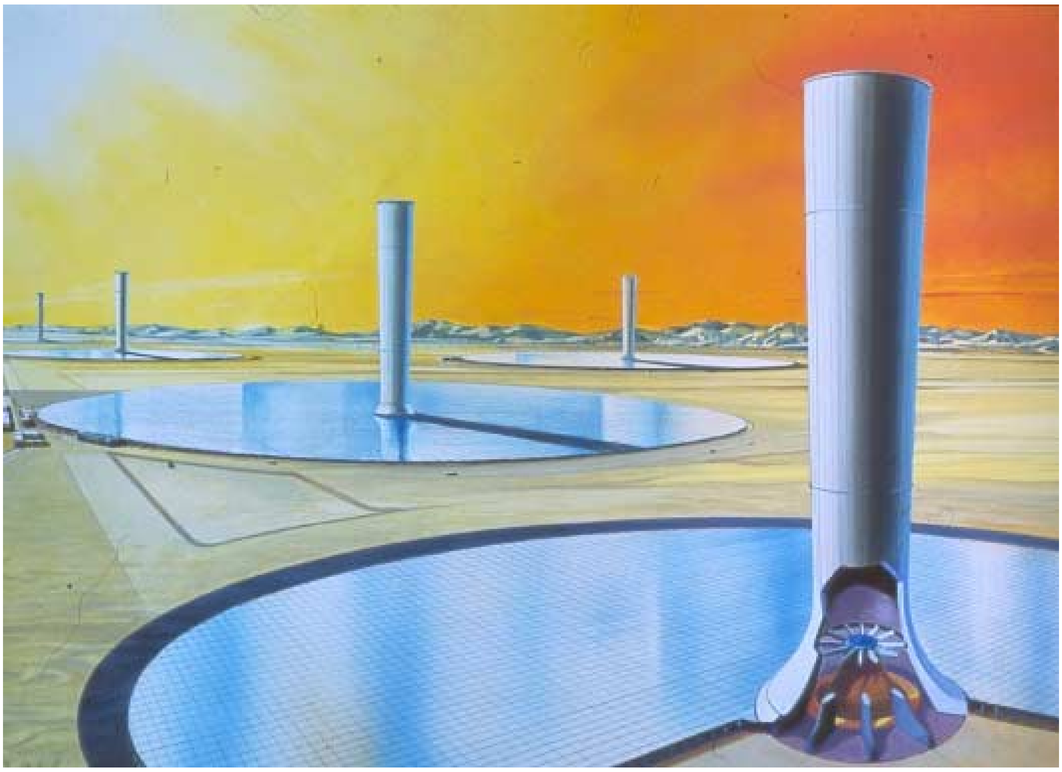

Fig. 10. Artist view of the essential components of a solar chimney: the collector, a flat glass roof (the chimney, a vertical tube supported on radial piers, and the wind turbines at the chimney base).

the collector as examples, the measured temperature rise at Manzanares was up to 17°K and the wind speed up to 12 meters per second, while the corresponding calculated figures for a 100 MW facility are 35°K and 16 meters per second.

In this way the overall performance of the plant, by day and by season, given the prescribed climate and plant geometry, considering all physical phenomena including single and double glazing of the collector, heat storage system , condensation effects and losses in collector, tower and turbine, can be calculated to an accuracy of ± 5%.

Structural design of large plants showed that the glazed collector can be used for large plants without major modifications. This was successfully demonstrated in the Manzanares experimental plant, and thus represents a proven, robust and reasonably priced solution. The Manzanares experience also provided cost calculation data for the collector.

Chimneys 1,000 m high can be built without difficulty. The television tower in Toronto, Canada is almost 600 m high and serious plans are being made for 2,000 meter skyscrapers in earthquake-ridden Japan. But all that is needed for a solar chimney is a simple, large diameter hollow cylinder, not particularly slender, and subject to very few demands in comparison with inhabited buildings.

There are many different ways of building this kind of chimney. They are best built freestanding, in reinforced concrete. But guyed tubes, their skin made of corrugated metal sheet, as well as cable-net designs with cladding or membranes are also possible. All the structural approaches are well known and have been used in cooling towers. No special development is needed.

Reliable statical and dynamic calculation and construction for a chimney about 1,000 meters high (slenderness ratio = height : diameter < 10) is possible without difficulty today. With the support of a German and an Indian contractor especially experienced in building cooling towers and chimneys, manufacturing and erection procedures were developed for various types in concrete and steel and their costs compared. The type selected is dependent on the site. If sufficient concrete aggregate materials are available in the area and anticipated seismic acceleration is less

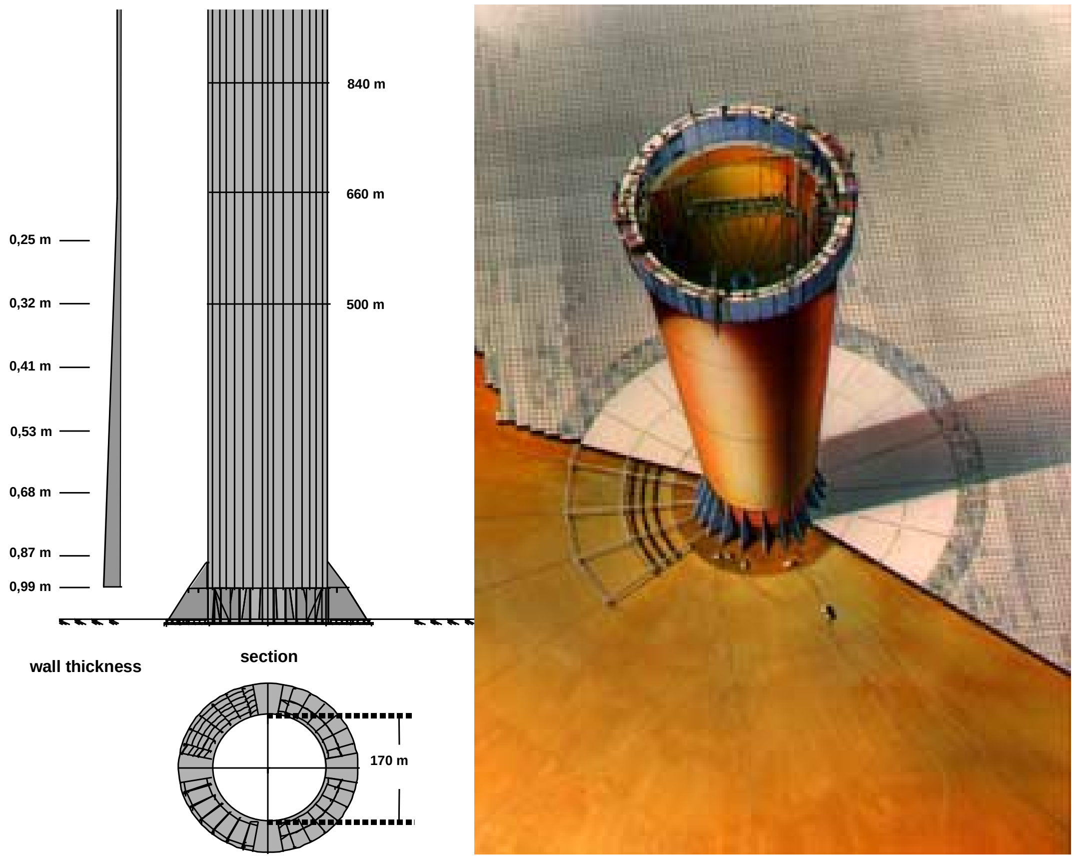

Fig. 11. Wall thickness of a chimney tube 1,000 m high and 170 m in diameter and artist view of a 1,000 m chimney tube under construction.

than 9/3, then reinforced concrete tubes are the most suitable. Both conditions are fulfilled world-wide in most arid areas suitable for solar chimneys. Detailed statical/structural research showed that it is appropriate to stiffen the chimney at about three levels with cables arranged like spokes within the chimney, so that thinner walls can be used. Detailed research by the Indian contractor showed that it is possible to build such tall concrete chimneys in India, and that construction would be particularly reasonable in terms of cost.

For mechanical design, it was possible to use a great deal of experience with wind power stations, cooling tower ventilation technology and the Manzanares solar chimney's years of operation. Although one single vertical axis turbines arranged at the base of the tower are seen as the correct solution, the cost estimate was based on horizontal axis turbines arranged concentrically at the periphery of the tower, in order to be able to utilize turbines of existing sizes - particularly with regard to rotor diameter. Aerodynamic design for entrance area and turbines was achieved by means of wind tunnel airflow experiments.

As already shown, there is no physical optimum for solar chimney cost calculations, even when meteorological and site conditions are precisely known. Tower and collector dimensions for a required electrical energy output can be determined only when their specific manufacturing and erection costs are known for a given site.

VI. ENERGY PRODUCTION COSTS

With the support of construction companies, the glass industry and turbine manufacturers a rather exact cost estimate for a 200 MW solar chimney could be compiled. Together with a big utility "Energie in Baden-Württemberg" the energy production costs were determine and compared to coal- and combined cycle power plants based on equal and common methods (Tab.1).

Purely under commercial aspects with a gross interest rate of about 11 % and a construction period of 4 years during which the investment costs increase already by 30 % (!) electricity from solar chimneys is merely 20 % more expensive than that from coal.

In case of the solar chimney the interest on the fix investment governs the price of electricity, whereas in the case of fossil fuel power plants the variable fuel costs are the deciding factor.

By just reducing the interest rate to 8 % electricity from solar chimneys would become competitive today. In low-wage countries the costs will reduce further especially those of the glass roof collector which alone amounts to 50 % of the overall costs (Fig.12.).

On the other hand there are a number of advantages:

No ecological harm and no consumption of resources, not even for the construction. Solar chimneys predominantly consist of concrete and glass which are made from sand and stone plus self-generated energy. Consequently in desert areas – with inexhaustible sand and stone solar chimneys can reproduce themselves. A truly sustainable source of energy!

Proportion of	Solar Chimney Pf/kWh	Coal Pf/kWh	2 x C.C. Pf/kWh
Investment	11,32	3,89	2,12
Fuel	0,00	3,87	6,57
Personnel	0,10	0,78	0,31
Repair	0,52	0,92	0,83
Insurance	0,01	0,27	0,12
Other running costs	0,00	1,16	0,03
Tax	2,10	0,69	0,37
Total	**14,05**	**11,58**	**10,35**

Commissioning in 2001
Power: 400 MW
Running hours: 7445 h/a
Yearly energy: 2978 GWh

Own investment 1/3 at 13,5%
External investment 2/3 at 8%
Total interest rate: 10,67%
Tax rate: 30%

Table 1. Comparison between the energy production costs of 2 x 200 MW solar chimneys and 400 MW coal and combined cycle power plants according to the present business managerial calculations.

The (high) investment costs are almost exclusively due to labor costs. This creates jobs, and a high net product for the country with increased tax income and reduced social costs (= human dignity, social harmony), and in addition no costly imports of coal, oil, gas which is especially beneficial for the developing countries releasing means for their development.

We have no choice but to do something for the energy consent, the environment and above all for the billions of underprivileged people in the Third World. But we should not offer them hand-outs, a multiple of which we deceitfully regain by imposing a high interest rate on their debt. Instead we should opt for global job sharing. If we buy solar energy from Third World countries, they can afford our products. A global energy market with large scale solar energy generation supplementing substantially hydropower, fossil and nuclear fuels is not utopian dream!

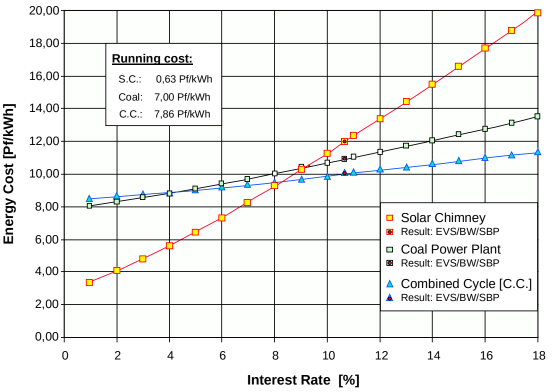

Fig. 12. Energy production costs from solar chimneys, coal and combined cycle power plants depending on the interest rate.

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Figure Legends

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