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Design of Commercial Solar Updraft Tower Systems—Utilization of Solar Induced Convective Flows for Power Generation

A solar updraft tower power plant—sometimes also called "solar chimney" or just "solar tower"—is a solar thermal power plant utilizing a combination of solar air collector and central updraft tube to generate a solar induced convective flow which drives pressure staged turbines to generate electricity. The paper presents theory, practical experience, and economy of solar updraft towers: First a simplified theory of the solar tower is described. Then results from designing, building and operating a small scale prototype in Spain are presented. Eventually technical issues and basic economic data for future commercial solar tower systems like the one being planned for Australia are discussed. [DOI: 10.1115/1.1823493]

Introduction

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

The solar tower meets these conditions. Economic appraisals based on experience and knowledge gathered so far have shown that large scale solar towers (⩾100 MW) are capable of generating electricity at costs comparable to those of conventional power plants [1]. This is reason enough to further develop this form of solar energy utilization, up to large, economically viable units. In a future energy economy, solar towers could thus help assure the economic and environmentally benign provision of electricity in sunny regions.

The solar updraft tower's three essential elements—solar air collector, chimney/tower, and wind turbines—have been familiar for centuries. Their combination to generate electricity has already been described in 1931 [2]. Haaf [3,4] gives test results and a theoretical description of the solar tower prototype in Manzanares, Spain. Transferability of the results obtained in Manzanares is discussed by Schlaich et al. [5]. The same author provides an overview [6]. Kreetz [7] introduces the concept of water-filled bags under the collector roof for thermal storage. Gannon and v. Backström [8] present a thermodynamic cycle analysis of the solar tower, and also an analysis of turbine characteristics [9]. Ruprecht et al. [10] give results from fluid dynamic calculations and turbine design for a 200 MW solar tower. A thermal and technical analysis targeting computer-aided calculation is described by dos Santos Bernardes et al. [11].

For Australia, a 200 MW solar tower project is currently being developed (http://www.enviromission.com.au). Conditions in Australia are very favorable for this type of solar thermal power plant: Insolation levels are high (http://www.bom.gov.au), there are large suitably flat areas of land available, demand for electricity increases, and the government's Mandatory Renewable Energy Target (MRET), requires the sourcing of 9500 gigawatt hours of extra renewable electricity per year by 2010 through to 2020 (http://www.mretreview.gov.au).

In the paper an overview is given over solar updraft tower theory, practical experience with a prototype, and economies of large scale solar updraft tower power plants.

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Functional Principle

The solar tower's principle is shown in Fig. 1: Air is heated by solar radiation under a low circular transparent or translucent roof open at the periphery; the roof and the natural ground below it form a solar air collector. In the middle of the roof is a vertical tower with large air inlets at its base. The joint between the roof and the tower base is airtight. As hot air is lighter than cold air it rises up the tower. Suction from the tower then draws in more hot air from the collector, and cold air comes in from the outer perimeter. Continuous 24 hour operation can be achieved by placing tight water-filled tubes or bags under the roof. The water heats up during day-time and releases its heat at night. These tubes are filled only once; no further water is needed. Thus solar radiation causes a constant updraft in the tower. The energy contained in the updraft is converted into mechanical energy by pressure-staged turbines at the base of the tower, and into electrical energy by conventional generators [12].

Power Output. The fundamental dependencies and influence of the essential parameters on power output of a solar tower are presented here in a simplified form: Generally speaking, power output P of the solar tower can be calculated as the solar input $\dot{Q}_{\text{solar}}$ multiplied by the respective efficiencies of collector, tower and turbine(s):

$$P=\dot{Q}_{\text{solar}}\cdot\eta_{\text{coll}}\cdot\eta_{\text{tower}}\cdot\eta_{\text{turbine}}=\dot{Q}_{\text{solar}}\cdot\eta_{\text{plant}} \tag{1}$$

The solar energy input $\dot{Q}_{\text{solar}}$ into the system can be written as the product of global horizontal radiation G_h and collector area A_{coll}:

$$\dot{Q}_{\text{solar}}=G_h\cdot A_{\text{coll}} \tag{2}$$

The tower (chimney) converts the heat-flow produced by the collector into kinetic energy (convection current) and potential energy (pressure drop at the turbine). Thus the density difference of the air caused by the temperature rise in the collector works as

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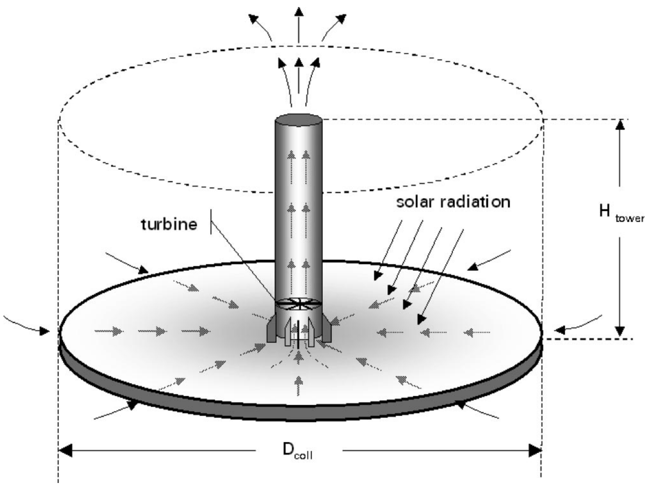

Fig. 1 Solar tower principle

a driving force. The lighter column of air in the tower is connected with the surrounding atmosphere at the base (inside the collector) and at the top of the tower, and thus acquires lift. A pressure difference Δp_{tot} is produced between tower base (collector outlet) and the ambient:

$$\Delta p_{\text{tot}}=g\cdot\int_0^{H\ \text{tower}}(\rho_a-\rho_{\text{tower}})\cdot dH \tag{3}$$

Thus Δp_{tot} increases with tower height.

The pressure difference Δp_{tot} can be subdivided into a static and a dynamic component, neglecting friction losses:

$$\Delta p_{\text{tot}}=\Delta p_s+\Delta p_d \tag{4}$$

The static pressure difference drops at the turbine; the dynamic component describes the kinetic energy of the airflow.

With the total pressure difference and the volume flow of the air at $\Delta p_s=0$ the power P_{tot} contained in the flow is now:

$$P_{\text{tot}}=\Delta p_{\text{tot}}\cdot v_{\text{tower,max}}\cdot A_{\text{coll}} \tag{5}$$

from which the efficiency of the tower can be established:

$$\eta_{\text{tower}}=\frac{P_{\text{tot}}}{\dot{Q}} \tag{6}$$

Actual subdivision of the pressure difference into a static and a dynamic component depends on the energy taken up by the turbine. Without turbine, a maximum flow speed of $v_{\text{tower,max}}$ is achieved and the whole pressure difference is used to accelerate the air and is thus converted into kinetic energy:

$$P_{\text{tot}}=\tfrac{1}{2}\dot{m}v^2_{\text{tower,max}} \tag{7}$$

Using the Boussinesq approximation [13], the speed reached by free convection currents can be expressed as

$$v_{\text{tower,max}}=\sqrt{2\cdot g\cdot H_{\text{tower}}\cdot\frac{\Delta T}{T_0}} \tag{8}$$

where ΔT is the temperature rise between ambient and collector outlet (=tower inflow).

Tower efficiency is given in Eq. (9) [6]:

$$\eta_{\text{tower}}=\frac{g\cdot H}{c_p\cdot T_0} \tag{9}$$

This simplified representation explains one of the basic characteristics of the solar tower, which is that the tower efficiency is

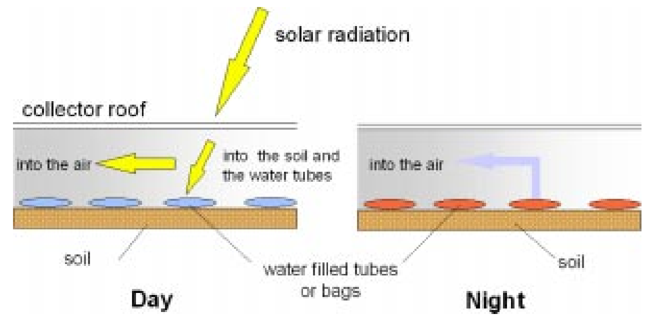

Fig. 2 Principle of thermal energy storage with water-filled tubes

fundamentally dependent only on its height. For heights of 1000 m the deviation from the exact solution, caused by the Boussinesq approximation, is negligible.

Using Eqs. (1), (2) and (9) we find that solar tower power output is proportional to collector area and tower height, i.e., proportional to the cylinder depicted in Fig. 1.

As electrical output of the solar tower is proportional to the volume included within the tower height and collector area, the same output may result from a large tower with a small collector area and vice versa. As soon as friction losses in the collector are included in a detailed simulation, the linear correlation between power output and the product "collector area times tower height" is not strictly valid any more. Still, it is a good rule of thumb as long as the collector diameter is not too large.

Collector. Hot air for the solar tower is produced by the greenhouse effect in a simple air collector consisting of a glass or plastic glazing stretched horizontally several meters above the ground. The height of the glazing increases adjacent to the tower base, so that the air is diverted to vertical movement with minimum friction loss. This glazing admits the solar radiation component and retains long-wave reradiation 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 tower.

Storage. If additional thermal storage capacity is desired, water filled black tubes are laid down side by side on the radiation absorbing soil under the collector [7]. The tubes are filled with water once and remain closed thereafter, so that no evaporation can take place (Fig. 2).

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 characteristics (Fig. 3).

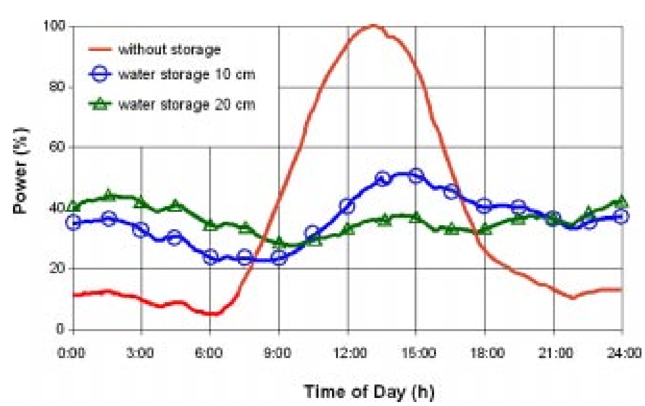

Fig. 3 Effect of heat storage underneath the collector roof using water-filled black tubes. Simulation results from [7].

At night, when the air in the collector starts to cool down, the water inside the tubes releases the heat that it stored during the day. Heat storage with water works more efficiently than with soil alone, since even at low water velocities—from natural convection in the tubes—the heat transfer between water tubes and water is much higher than that between ground surface and the soil layers underneath, and since the heat capacity of water is about five times higher than that of soil.

Tower Tube. The tower itself is the plant's actual thermal engine. It is a pressure tube with low friction loss (like a hydro power station pressure tube or pen stock) because of its favorable surface-volume ratio. The updraft velocity of the air is approximately proportional to the air temperature rise (ΔT) in the collector and to the tower height [cf. Eq. (8)]. In a multi-megawatt solar tower the collector raises the air temperature by about 30 to 35 K. This produces an updraft velocity in the tower of (only) about 15 m/s at nominal electric output, as most of the available pressure potential is used by the turbine(s) and therefore does not accelerate the air. It is thus possible to enter into an operating solar tower plant for maintenance without danger from high air velocities.

Turbines. Using turbines, mechanical output in the form of rotational energy can be derived from the air current in the tower. Turbines in a solar tower do not work with staged velocity like free-running wind energy converters, but as shrouded pressure-staged wind turbo generators, in which, similarly to a hydroelectric power station, static pressure is converted to rotational energy using cased turbines. The specific power output (power per area swept by the rotor) of shrouded pressure-staged turbines in the solar tower is roughly one order of magnitude higher than that of a velocity staged wind turbine. 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 pressure differential over 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.

To this end, 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 pressure drop 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 80 percent of the total pressure differential available. The optimum fraction depends on plant characteristics like friction pressure losses.

Prototype

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 (Fig. 4), with funds provided by the German Ministry of Research and Technology (BMFT) [4,5].

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 main dimensions and technical data for the facility are listed in Table 1.

The tower comprises a guyed tube of trapezoidal sheets, gauge 1.25 mm, corrugation 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 tower. A prestressed membrane of plastic-coated fabric, shaped to provide good flow characteristics, forms the transition between the roof and the tower. The tower is guyed at four levels, and in three directions, to foundations secured with rock anchors. The tower was erected at ground level, utilizing a specially developed incremental lifting method proposed by Brian Hunt of SBP: First, the top section of the tower was installed on a lifting ring on the ground, and then it was raised onto the supporting ring by means of hydraulic presses. Subsequently the other sections were assembled on the ground, connected to the already installed top tower section(s) and then the whole assembly was lifted. So the complete tower was built in 20 shots of 10 m each.

Fig. 4 Prototype of the solar tower prototype plant at Manzanares, Spain

The turbine is supported independently of the tower 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 (Fig. 5). Vertical wind velocity is 2.5 m/s on start-up and can attain a maximum of 12 m/s during turbine operation.

The collector roof of the solar tower not only has to have a transparent or translucent covering, it must also be durable and reasonably priced. A variety of types of plastic sheet, as well as glass, were selected in order to determine which was the best—and in the long term, most cost effective—material (Fig. 6). Glass resisted heavy storms for many years without harm and proved to be self-cleaning thanks to the occasional rain showers.

The plastic membranes are clamped to a frame and stressed down to the ground at the center by use of a plate with drain holes. The initial investment cost of plastic membranes is lower than that of glass; however, in Manzanares the membranes got brittle with time and thus tended to tear. Material (temperature and UV stability) and design improvements (e.g., membrane domes) achieved in the last years may help to overcome this particular disadvantage.

Completion of the construction phase in 1982 was followed by an experimental phase, the purpose of which was to demonstrate

Table 1 Main dimensions and technical data of the Manzanares prototype

Tower height	194.6 m
Tower radius	5.08 m
Mean collector radius	122.0 m
Mean roof height	1.85 m
Number of turbine blades	4
Turbine blade profile	FX W-151-A
Blade tip speed to air transport velocity ratio	10:1
Operation modes	stand-alone or grid connected mode
Typical collector air temp. increase	$\Delta T = 20$ K
Nominal output	50 kW
Collector covered with plastic membrane	40,000 m^2
Collector covered with glass	6,000 m^2

Fig. 5 Turbine of the prototype plant

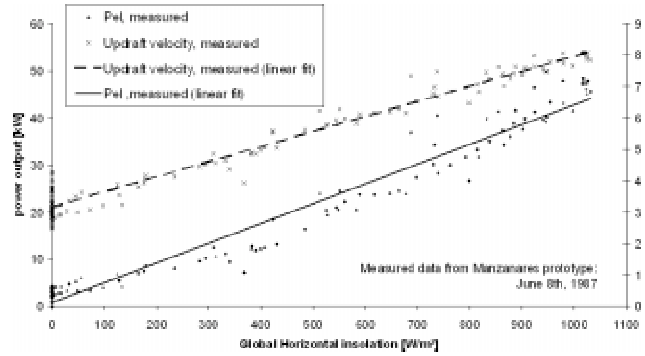

Fig. 8 Manzanares solar tower prototype input/output characteristics

the operating principle of a solar tower. The goals of this phase of the project were (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.

In Fig. 7 the main operational data, i.e., solar insolation, updraft velocity and electric power output, are shown for a typical day. Two things shall be pointed out: First, that power output during the day correlates closely with solar insolation for this small plant without additional storage. But, second, there is still an updraft during the night, which can be used to generate power during some hours of the night (Fig. 8).

With increasing collector size, i.e., generally speaking with increasing thermal inertia of the system, this effect increases, as will be seen later from the results of simulation runs for large scale plants (Fig. 10).

In order to arrive at a thorough understanding of the physical relationships and to evolve and identify points of approach for possible improvements, a computer simulation code was developed that describes the individual components, their performance, and their dynamic interaction. This program was verified on the basis of experimental measurement results from Manzanares. Today, it is a development tool that takes all known effects into account, and with the aid of which the thermodynamic behavior of large-scale plants under given meteorological conditions can be calculated in advance [3,14].

From mid-1986 to early 1989 the plant was run on a regular daily basis. As soon as the air velocity in the tower exceeded a set value, typically 2.5 m/s, the plant started up automatically and was automatically connected to the public grid. During this 32 month period, the plant ran, fully automatically, an average of 8.9 h per day. In 1987 there were 3067 h with a solar global horizontal irradiation of over 150 W/m^2 at the Manzanares site. Total operation time of the plant with net positive power to the grid was 3157 h, including 244 h of net positive power to the grid at night.

These results show that the system and its components are dependable and that the plant as a whole is capable of highly reliable operation. Thermodynamic inertia is a characteristic feature of the

Fig. 6 Glass roof of the prototype plant at Manzanares, Spain

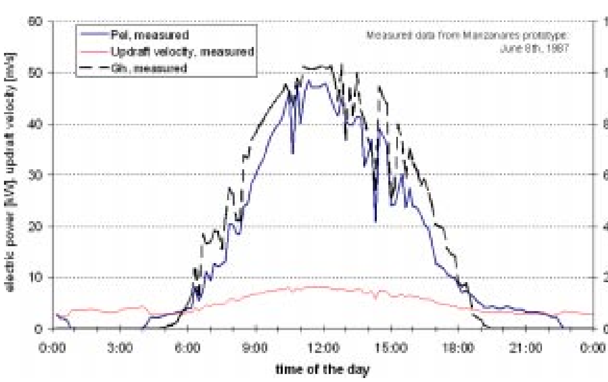

Fig. 7 Measurement from Manzanares: updraft velocity and power output for a typical day

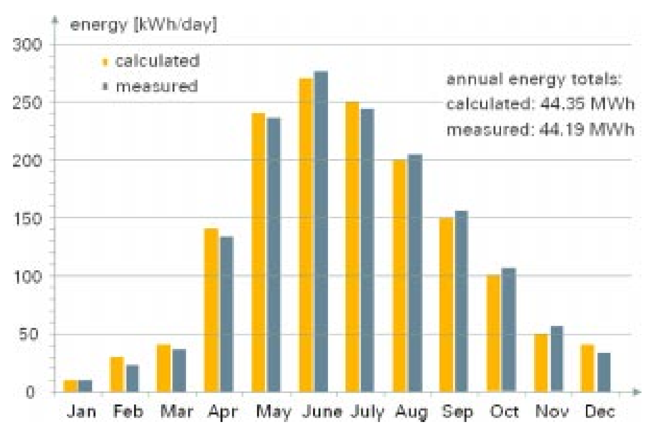

Fig. 9 Comparison of measured and calculated monthly energy outputs for the Manzanares plant

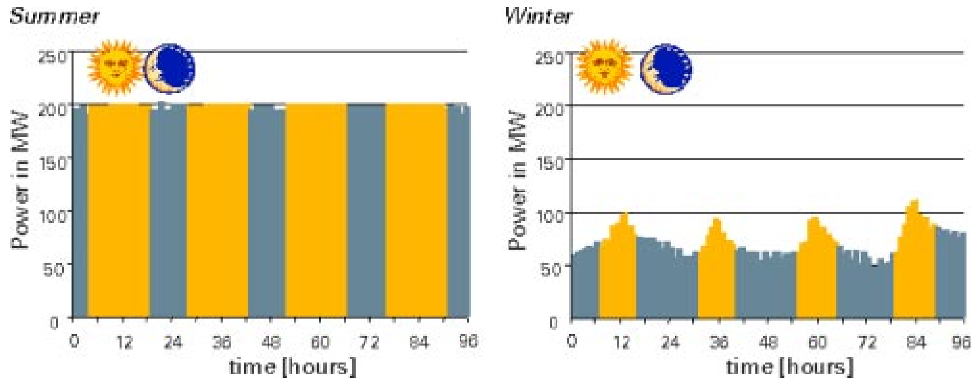

Fig. 10 Results of simulation runs (electric power output versus time of day) of a 200 MW solar tower with 25 percent of collector area covered by water-filled bags as additional thermal storage (weather data from [17])

system, continuous operation throughout the day is possible, and for large systems even abrupt fluctuations in energy supply are effectively cushioned.

Using the custom-made thermodynamic simulation code based on finite volumes that solves the equations for conservation of energy, momentum and mass, the theoretical performance of the plant was calculated and the results compared with the measurements obtained. The code includes simulation of collector performance based on standard collector theory [15], extended by an integration of thermal storage effects of the natural collector ground and—if required—additional thermal storage by water-filled bags into the model [7]. Fluid dynamics of collector, turbine and tower are calculated, taking into consideration friction in the respective system components. Calculation of pressure losses relies on standard calculation procedures [16], and where this is considered not to be applicable or sufficient, on experimental data including wind tunnel tests. Turbine behavior is modeled based on the CFD design calculations done by the Institute of Fluid Dynamics and Hydraulics Machinery of the University of Stuttgart [10].

Figure 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 thermodynamic processes in a solar tower are well understood and that models have attained a degree of maturity that accurately reproduces plant behavior under given meteorological conditions.

Commercial Solar Tower Power Plants

Scale-Up. Detailed investigations, supported by extensive wind tunnel experiments, show that thermodynamic calculations for collector, tower and turbine are very reliable for large plants as well [5]. Despite considerable area and volume differences between the Manzanares pilot plant and the projected 200 MW facility, the key thermodynamic factors are of similar size in both cases. Using the temperature rise and air velocity in the collector as examples, the measured temperature rise at Manzanares was up to 17 K, wind speed was up to 12 meters per second during turbine operation, while the corresponding average figures from simulation runs for a 200 MW facility are 18 K and 11 meters per second, respectively.

Therefore measurements taken from the experimental plant in Manzanares and solar tower thermodynamic behavior simulation codes are used to design large plants with an output of up to 200 MW. Results of such a simulation are shown in Fig. 10 [17]. Shown are four-day-periods for summer and winter. This plant with additional storage covering 25 percent of total collector area operates 24 h per day, at or close to nominal output in summer, and at significantly reduced output in winter.

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

Optimization. Electricity yielded by an updraft solar tower is in proportion to the intensity of global solar radiation, collector area and tower height. There is in fact no optimum physical size for such plants. Optimum dimensions can be calculated only by including specific component costs (collector, tower, turbines) for individual sites. And so plants of different optimum key dimensions will be built for different sites—but always at optimum cost: if collector area is cheap and concrete expensive, then the collector will be large and the tower relatively small, and if the collector is expensive, there will be a smaller collector and a tall tower.

General System Characteristics. Apart from working on a very simple principle, solar towers have a number of special features:

1. The collector can use all solar radiation, both direct and diffuse. This is crucial for tropical countries where the sky is frequently overcast.
2. Due to the soil under the collector working as a natural heat storage system, solar updraft towers can operate 24 h on pure solar energy, at reduced output at night time. If desired, additional water tubes or bags placed under the collector roof absorb part of the radiated energy during the day and release it into the collector at night. Thus solar towers can operate as base load power plants. As the plant's prime mover is the air temperature difference (causing an air density difference) between the air in the tower and ambient air, lower ambient temperatures at night help to keep the output at an almost constant level even when the temperature of natural and additional thermal storage also decreases without sunshine, as the temperature *difference* remains practically the same.
3. Solar towers are particularly reliable and not liable to break down, in comparison with other power plants. Turbines and generators—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 some other solar-thermal power station types), solar towers do not need cooling water. This is a key advantage in the many sunny countries that already have major problems with water supply.

5. The building materials needed for solar towers, mainly concrete and glass, are available everywhere in sufficient quantities. In fact, with the energy taken from the solar tower itself and the stone and sand available in the desert, they can be reproduced on site. Energy payback time is two to three years [18].
6. Solar towers can be built now, even in less industrially developed countries. The industry already available in most countries is entirely adequate for solar tower requirements. No investment in high-tech manufacturing plants is needed.
7. Even in poor countries it is possible to build a large plant without high foreign currency expenditure by using local resources and work-force; this creates large numbers of jobs while significantly reducing the required capital investment and thus the cost of generating electricity.

Nevertheless, solar towers also have features that make them less suitable for some sites:

A. They require large areas of flat land. This land should be available at low cost, which means that there should be no competing usage, like, e.g., intensive agriculture, for the land.

B. Solar towers are not adequate for earthquake prone areas, as in this case tower costs would increase drastically.

C. Zones with frequent sand storms should also be avoided, as either collector performance losses or collector operation and maintenance costs would be substantial there.

Technology. Structural design of large plants showed that a glass collector of the Manzanares design can be used for large plants without major modifications. This design represents a proven, robust and reasonably priced solution. The Manzanares experience also provided cost calculation data for the collector.

Towers 1000 m high are a challenge, but they can be built today. The CN tower in Toronto, Canada, is almost 600 m high and serious plans are being made for 2000 m skyscrapers in earthquake-ridden Japan. What is needed for a solar tower is a simple, large diameter hollow cylinder, not particularly slender, and subject to very few demands in comparison with inhabited buildings.

There are different ways of building this kind of tower: free-standing in reinforced concrete, guyed tubes with skin made of corrugated metal sheet, or also cable-net designs with cladding or membranes. The respective structural approaches are well known and have been used in cooling towers. No special development is needed.

With the support of international contractors especially experienced in building cooling towers and towers, manufacturing and erection procedures were developed for various tower types in concrete and steel and their costs were 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 than about one third of the earth's gravitational acceleration, then reinforced concrete tubes are the most suitable. Both conditions are fulfilled world-wide in most arid areas suitable for solar towers. Detailed statical/structural research showed that it is appropriate to stiffen the tower at several levels with cables arranged like spoked wheels within the tower, so that thinner walls can be used. This is maybe the only really new feature of solar towers compared to existing structures.

For mechanical design, it was possible to use a great deal of experience from hydro and wind power stations, cooling tower ventilation technology and the Manzanares solar tower's years of operation. Although one single vertical axis turbine arranged at the base of the tower might be seen as the straightforward solution, current designs and cost estimates are based on horizontal axis turbines arranged concentrically at the periphery of the tower, in order to realize redundancy, and also 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 and computer fluid dynamics.

Typical dimensions for selected solar towers without additional water heat storage are given in Table 2. The numbers are based on typical material and construction costs. Costs for unskilled labor are assumed to be 5 €/h.

Table 2 Typical dimensions and electricity output

Capacity	MW	5	30	100	200
Tower height	m	550	750	1000	1000
Tower diameter	m	45	70	110	120
Collector diameter	m	1250	2900	4300	7000
Electricity output[a]	GWh/a	14	99	320	680

[a]At a site with an annual global solar radiation of 2300 kWh/(m^2 a).

Table 3 Investment cost and LEC

Capacity	MW	5	30	100	200
Tower cost	Mio. €	19	49	156	170
Collector cost[a]	Mio. €	10	48	107	261
Turbine cost	Mio. €	8	32	75	133
Engineering, tests, misc.	Mio. €	5	16	40	42
Total	**Mio. €**	**42**	**145**	**378**	**606**
Annuity on investment	Mio. €/a	2.7	10.2	27.1	43.7
Annual operation and maintenance cost	Mio. €/a	0.2	0.6	1.7	2.8
Levelized electricity cost (LEC)[b]	€/**kWh**	**0.21**	**0.11**	**0.09**	**0.07**

[a]Cost for unskilled labor assumed to be 5 €/h.
[b]At an interest rate of 6 percent and a depreciation time of 30 years.

Economy. Based on specific costs, dimensions and electricity output from Table 2, investment costs were calculated. With the respective annual energy outputs from simulation runs, levelized electricity costs are calculated using an interest rate of 6 percent and a depreciation time of 30 years (Table 3).

From Table 3 it becomes obvious that LEC for a small 5 MW solar tower are relatively high, comparable, e.g., to a PV-System. With increasing plant size, a significant reduction of electricity generation cost is associated, leading to LEC of 0.07 €/kWh for a 200 MW plant in the given example at an interest rate of 6 percent.

A variation of the financial parameters interest rate and depreciation time is shown in Fig. 11. The upper boundary was calculated for a depreciation time of 20 years, the lower boundary for 40 years.

As expected, electricity generating costs of the capital intensive solar towers are dominated by interest rate. Depreciation time also has a significant influence. Assuming an interest rate of, e.g., 12% and a depreciation time of 20 years leads to LEC of 0.12€/kWh for the 200 MW system. When, e.g., by clever financial engineer-

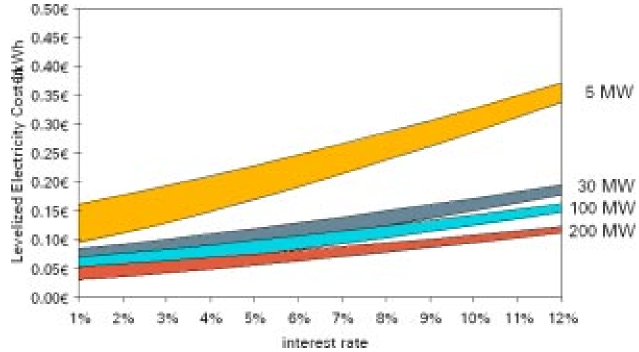

Fig. 11 Levelized electricity cost versus interest rate for selected typical solar tower systems

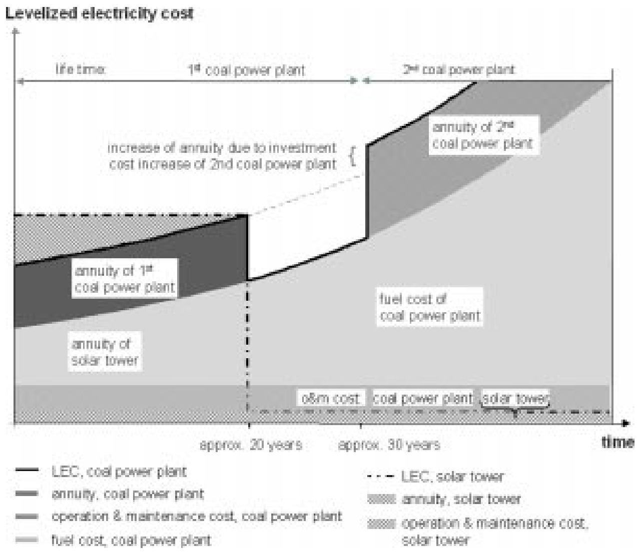

Fig. 12 Electricity generation costs for a solar tower and coal fired power plant

ing, an interest rate of 6 percent and a depreciation time of 40 years is achieved. LEC drop to 0.06 €/kWh, i.e., half the formerly calculated cost.

In Fig. 12 a schematic and more general comparison between power generation using a coal-fired plant and a solar tower is shown. In the selected example, electricity costs for the solar tower are higher than those for the coal-fired power plant in the first years of operation.

The gap between the two electricity costs closes with increasing fossil fuel costs. After 20 years, electricity generation costs are identical. Then both plants are paid for in this example; no more annuities have to be paid. From this point in time on the solar tower produces electricity at low cost, as only operation and maintenance costs have to be paid. In contrast to that, electricity generation costs of the coal fired plant are still comparatively high, as they are governed by fuel costs.

In our example, a new coal fired plant must be built after 30 years, whereas the solar tower is still operating in its original configuration. This reflects the difference in technical life time between the two systems. Thus the cost difference between coal fired plant and solar tower is further increased. In the case of the solar tower, loan redemption governs the cost of electricity, whereas in the case of fossil fuel power plants the variable fuel costs are the deciding factor.

In the example shown in Fig. 12 the interest rate and coal price escalation are deliberately chosen in such a way that calculated electricity costs are identical for both plants exactly after depreciation time. In reality, depending on actual cost and financing data, it may take longer until cost parity is reached, but this point might also be reached earlier.

In countries with very low wages, investment costs, and therefore mostly electricity generation costs of the solar tower, will be further reduced. This holds especially true as the collector, which alone amounts to roughly one half of the overall solar tower investment costs, is a low-tech component and can be built anywhere with unskilled labor.

Summary and Conclusions

The updraft solar tower works on a simple proven principle; its physics are well understood. As thermodynamic efficiency of the plant increases with tower height, such plants have to be large to become cost competitive. Large plants mean high investment costs, which are mostly due to labor costs. This in return creates jobs, and a high net domestic product for the country with increased tax income and reduced social costs (=human dignity, social harmony), and in addition no costly consumption of fossil fuels. The latter reduces dependence on imported oil and coal, which is especially beneficial for the developing countries, releasing means for their development.

There is no ecological harm and no consumption of resources, not even for the construction, as solar towers 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 towers can reproduce themselves. A truly sustainable source of energy!

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Nomenclature

Latin

A = area, m^2
G = global solar radiation, $W\,m^{-2}$
H = height, m
$\dot{P}$ = power, W
$\dot{Q}$ = heat flux, W
T = temperature, K
c_p = specific heat at constant pressure, $J\,kg^{-1}\,K^{-1}$
g = gravitational acceleration, 9.81, $m\,s^{-2}$
$\dot{m}$ = mass flow, $kg\,s^{-1}$
p = pressure, $N\,m^{-2}$
v = velocity, $m\,s^{-1}$

Greek

ρ = density, $kg\,m^{-3}$
η = efficiency, -

Prefix

Δ = change in value

Subscript

0 = at ground level
a = ambient
coll = collector
d = dynamic
h = horizontal
s = static
tot = total
max = maximum

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