SOLAR UPDRAFT POWER PLANT TECHNOLOGY: BASIC CONCEPTS AND STRUCTURAL DESIGN

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Summary

Renewable and sustainable energy sources are nowadays considered to be a key element for sustainable development of the worldwide economy. The Solar Updraft Power Plant technology addresses a very challenging, not yet exploited, idea of combining both kinds of renewable energy: wind and solar.

The working principle is simple: a Solar Updraft Power Plant (SUPP) consists of a collector area to heat the air due to the wide-banded ultra-violet solar radiation, the high-rise solar chimney to updraft the heated air to the atmosphere, and in between the power conversion unit, where a system of coupled turbines and generators transforms the stream of heated air into electric power. However, a good efficiency of the power plant can only be reached with extra-large dimensions of the tower and/or the collector area. Therefore, the potentials of an unrivalled economical energy production can be achieved only through the highest degree of optimization of the structural behavior, the thermodynamic efficiency and the construction costs.

From the structural viewpoint, one of the major objectives is to construct the solar tower as thin as possible. This can be achieved by using high-strength concrete and/or by installing stiffening rings along the chimney height and on top. They can be realized in several ways, e.g. with classical RC-beams, with composite steel-concrete or with spoked wheels. The stiffening rings improve the structural behavior of the tower by avoiding ovalling deformations of the cross section.

Such very high-rise and extremely thin shell structures are mainly affected by the wind action, which thus decides the feasibility of this new technology. The modeling of the wind action and the stochastic analysis of the structural response need to be up-graded, since the tower height and the loading models are far beyond the current experience.

1. Solar Updraft Power Technology: Introduction and Working Principles

Renewable and sustainable energy sources are nowadays considered to be a key element for sustainable development of the worldwide economy. The Solar Updraft Power Plant technology (Figure 1) addresses a very challenging, not yet exploited, idea of combining both kinds of renewable energy: wind and solar. The basic idea is the conversion of solar radiation into electric power.

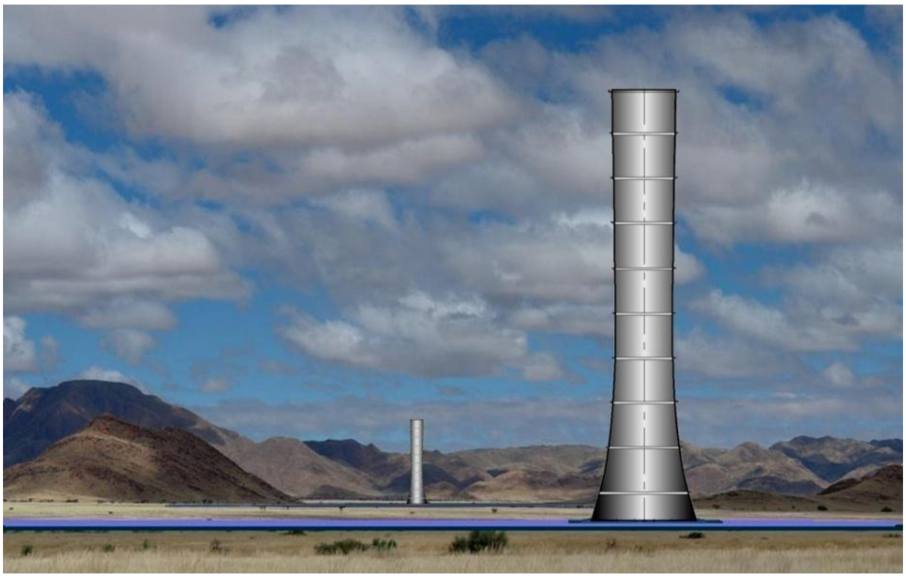


Figure 1. Solar Updraft Power Plants

The working principle is simple (see Figure 2): a solar updraft power plant (SUPP) consists of the collector area, the turbine(s) with coupled generator(s) as power conversion unit, and the solar chimney. In the collector area, a large glass-covered area, wide-banded solar radiation heats the collector ground and consequently warms up the air inside the collector area, through the mechanism of natural convection. The buoyant air rises up into the chimney of the plant, thereby drawing in more air at the collector perimeter and thus initiating forced convection which heats the collector air more rapidly. The driving force or potential that causes air to flow through the solar tower is due to the pressure difference between the column of cold air outside and the column of hot air inside the chimney. The power conversion unit is at the foot of the tower. There, as the collector air flows across the turbines, the kinetic energy of the air turns the blades of the turbine which in turn drives the generators, so that the energy in the stream of warm air is transformed into electric power.

The production of energy is then based on the natural updraft of heated air, and the natural fuel of SUPPs – solar radiation – is inexhaustible and practically unlimited. Moreover, the building components of a SUPP are worldwide “usual” – concrete, glass and steel – which makes this technology interesting especially for developing countries. Its energy generation does not need water for cooling and is free of direct carbon dioxide emissions. If one incorporates all energies required for the plant construction in the evaluation of greenhouse gas emissions, one ends up with 70 to 170 g of CO_2–

equivalents per kWh of produced electricity, depending on the life duration and the installed capacity of the plant. Intended design aims are of 80 to 120 years, with long-period renewals of the turbo-generators and of the glass-roof.

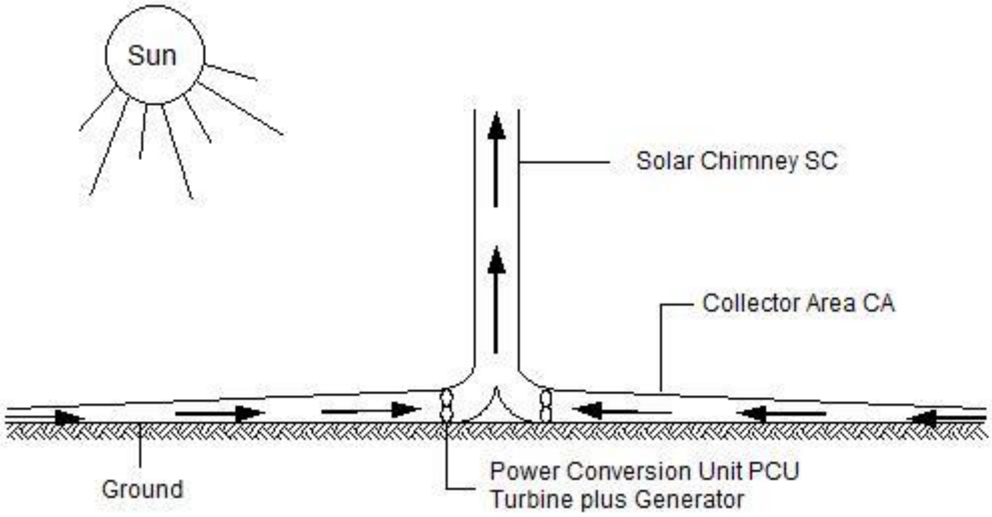
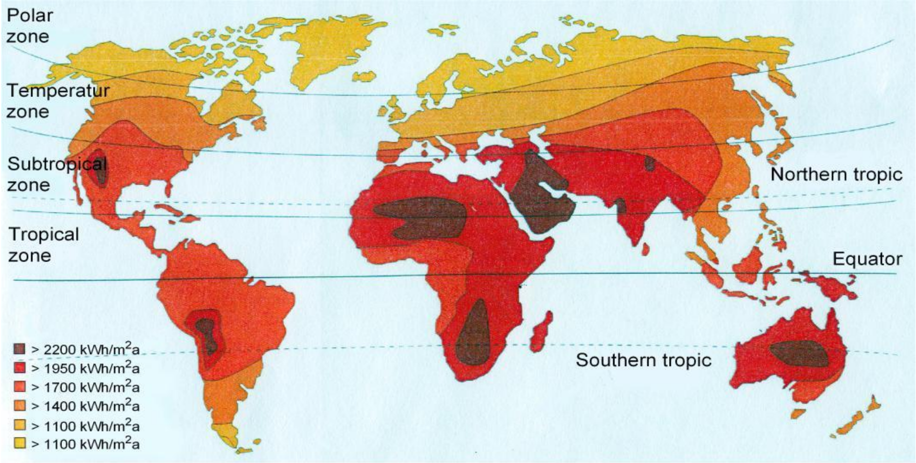


Figure 2. Solar Updraft Power Plants: the working principle (Schlaich, 1995)

However, such power station concepts will only deliver sufficient efficiency in areas with solar radiation input higher than 2.0-2.3 MWh/a, as it occurs in all great deserts up to ± 30° of latitude (north or south of the equator).

The distribution of yearly solar radiation is shown in Figure 3.



Nach M. Lorek: Green Tower im südl. Afrika
Berg. Universität Wupprttal

Figure 3. Distribution of yearly solar irradiation

The working principle is then simple, but what makes it interesting - a real challenge, in fact - is the huge dimension of the power plant. The tower has a height of more than 500 m and structures up to 1500 m are envisaged. The diameter of the collector is up to 7 km. Why such huge dimensions? The degree of efficiency of a SUPP depends primarily on the size of the collector area (it influences the temperature rise of air) and on the height of the tower (it determines the pressure gradient and guarantees a good updraft to the air). A plant with a collector area diameter of 7 km and with solar tower height of 1500m is estimated to deliver a max (peak) electricity power of 400 MW (Pretorius & Kröger 2006). This assumption has been recently assessed, experimentally as well as theoretically for a wide range of plant geometries, as a reasonable global assumption (Fluri 2008). In particular, the production of energy is proportional, in a non-linear manner, to the volume of the cylinder having the height of the tower and the diameter of the collector. It means that the power delivered by a small power plant is only a little, but a small increase in dimensions of sufficiently large power plant increases the output more than proportionally. A tower of 500 m in height can deliver about 50 MW of energy, but if its height is doubled (1000 m), the power can be four times more (200 MW), if a collector of 5 km in diameter is provided.

However, due to the huge dimensions of the power plant, the potentials of an unrivalled economical energy production can be achieved only through the highest degree of optimization of the structural behavior, the thermodynamic efficiency and the construction costs.

The high-risk of the project consists in the very narrow boundaries within which all SUPP design parameters must be defined correctly. This means, that all dominant factors (i.e. loads by natural hazards, static and stochastic dynamic response, thermo-fluid-dynamic profiling of the tower, construction technology, economic estimates) shall be determined with a high degree of accuracy, i.e. with very low tolerance for uncertainties. Only in this case, the industrial viability and acceptance by investors will be guaranteed.

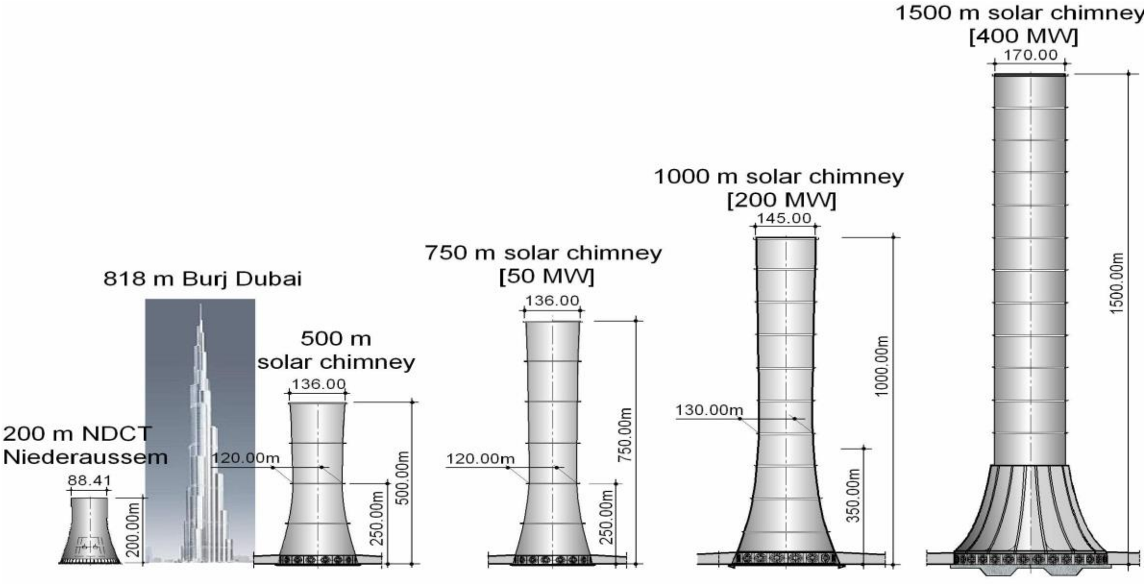


Figure 4. From the world-highest cooling tower to pre-designs of future SUPPs (Krätzig&Partner GmbH Bochum, Germany)

On the other hand, the high-win character consists in the definite affirmation and consequent diffusion of a new generation of renewable energy sources deployment, which could give a tremendous and positive impulse to the economic and environmental benefit of many developing areas and regions of the world.

In the following sections, the main issues concerning the production of energy and the structural design of Solar Updraft Power Plants are addressed.

Section 2 will briefly summarize the origins of the idea, which goes back to the early ‘900 (Cabanyes, 1903). It was re-evoked in 1931 (Günther, 1931), but the first modern feasibility studies have been carried out only since the early 80s (Schlaich, 1995).

In Section 3, several plant configurations will be investigated by the study of the airflow through the collector, the heat source analysis from solar radiation and the coupling with the chimney pressure.

Section 4 describes the enormous glass collector roof at the tower feet.

Then, in Section 5, all the actions involved in the structural designed are introduced. They are the self-weight, the wind load, the thermal action, shrinkage effects, seismic action, differential soil settlements, construction loads. However, from all these actions, the wind load plays the most important role and thus decides on the feasibility of solar towers.

The wind action and the wind-induced effects will be largely described in Section 6.

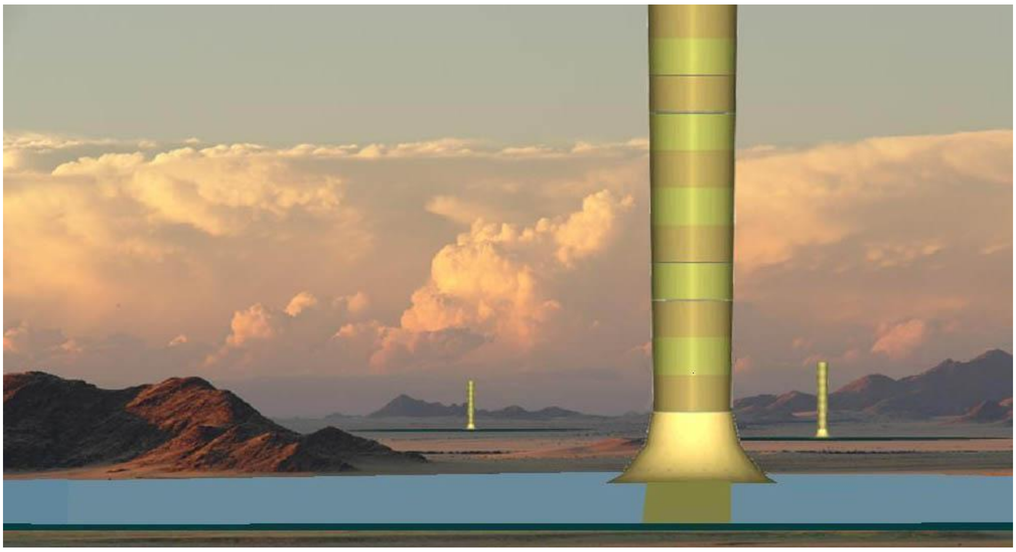


Figure 5. Solar Updraft Power Plants (http://www.greentower.net/)

Section 7 analyzes the structural behavior of solar towers, highlighting the peculiar beam-like behavior of such a high and slender structure. In fact, the ovalling deformations of the shell are prevented by some stiffening rings along the height and on top. The ring beams play a key-role in the structural design and are the most important parameter in the structural optimization of solar towers. Strategies of optimizations are presented in Section 8.

Last, but not least, Section 9 deals with the construction process. Indeed, it is a crucial key for a break-through to realization of Solar Updraft Power Plants.

Figure 6. Solar Updraft Power Plants (http://www.greentower.net/)

2. History of the Solar Updraft Power technology

The Solar Updraft Power generation was first proposed in 1903 by the Spanish Colonel Isidoro Cabanyes (Cabanyes, 1903). His apparatus consisted of an air-heater attached to a house with a chimney. Inside the house, there was a wind propeller for electricity production (Figure 7).

Another early description can be found in the work of the German author Hanns Günther (Günther, 1931). This name is just the pseudonym for Walter de Haas. In 1931, in his most important book (“In hundert Jahren - Die künftige Energieversorgung der Welt” – “In a hundred years: the world's future energy supply”) he wrote that the humanity would have run out of petrol and coal, so he went through other sources of energy. He wrote about some renewable energy technologies already existing at that time (e.g. geothermal power), and then he also mentioned the solar updraft tower. The idea of the author was a solar chimney on the slope of a mountain (Figure 8). The very high air speed could deliver an enormous amount of energy which could be extracted by means of wind turbines.

Around 1975, a series of patents were granted to the US engineer R.E. Lucier in countries with deserts suitable for SUPPs, like Australia, Canada, Israel and the US. These patents concerned: “Apparatus for converting Solar to Electrical Energy", "Utilization of Solar Energy", "System and Apparatus for Converting Solar Heat to Electrical Energy", "System for converting solar heat to electrical energy".

AÑO V.—Tomo 8. 25 de Agosto de 1903. Núm. 4

La Energía Eléctrica

REVISTA GENERAL DE ELECTRICIDAD Y SUS APLICACIONES

PUBLICACIÓN QUINCENAL ILUSTRADA

SUMARIO

Proyecto de motor solar (continuará), por Isidoro Cabanyes.—Algo de electricidad práctica.—Instalación eléctrica del tranvía de Bilbao á Durango y Arratia (continuación), por S. C.—¿Qué es el potencial? (continuará), por Nicolás de Ugarte.—Estaciones transportables para telegrafía sin conductores, sistema del profesor Braun y Siemens y Halske, y su empleo en el ejército alemán (continuará), por C. Ferrero. Teorías y explicaciones sobre el papel que en la propagación de las ondulaciones eléctricas, en la Telegrafía sin conductores, parecen desempeñar la tierra, la antena y la atmósfera (conclusión), por Carlos Dorrien.—*Crónica científica:* Radio-actividad del agua.—La resistencia eléctrica de los aceites.—*Información.*—*Ofertas y demandas.*—*Correspondencia particular.*

PROYECTO DE MOTOR SOLAR

CONCIBAMOS una gran caja de cristal herméticamente cerrada; bajo la caja transparente, otra de hierro pintada de negro, y dentro de esta última caja, aire ó agua, medios que, una vez elevados á alta temperatura pasen á cualquiera de las máquinas ya conocidas de aire caliente ó de vapor de agua y en ella funcionen; y todo ello, caja

Figure 7. Part of the article of Isidoro Cabanyes, published on “La Energia Electrica” (1903) and his “Proyecto de motor solar”. (De Los Archivos Históricos De La Energía Solar http://www.fotovoltaica.com/chimenea.pdf)

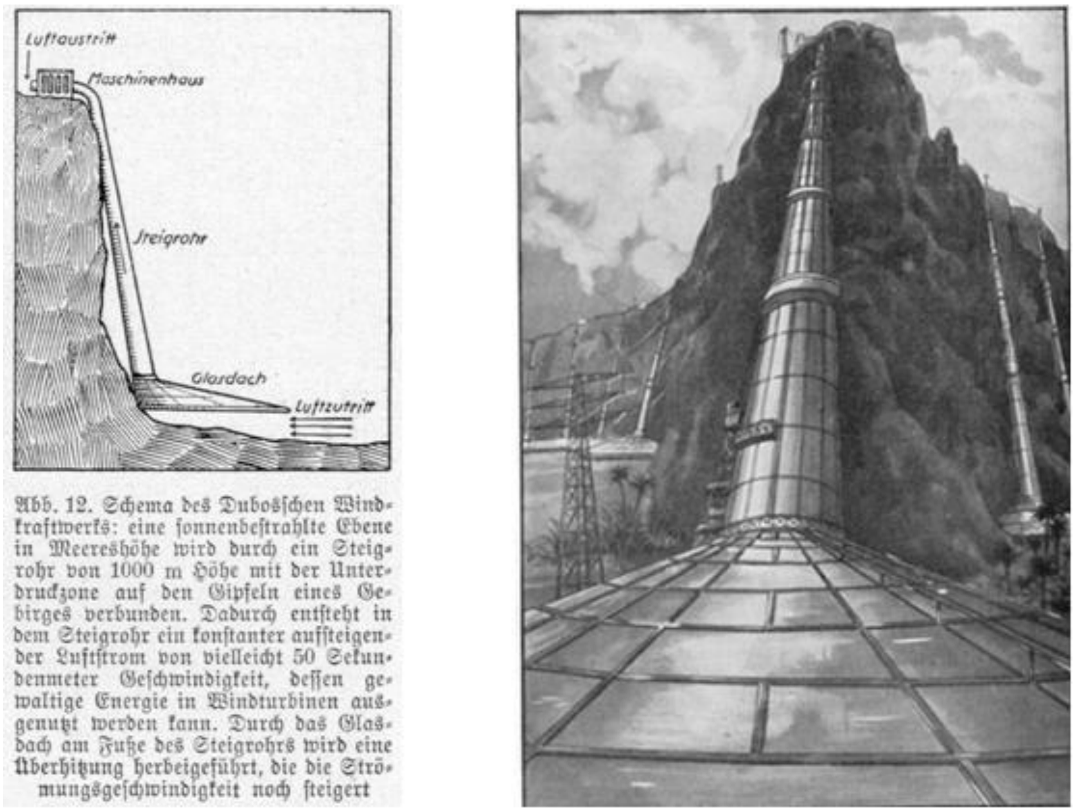


Abb. 12. Schema des Dubosſchen Windkraftwerks: eine ſonnenbeſtrahlte Ebene in Meereshöhe wird durch ein Steigrohr von 1000 m Höhe mit der Unterdruckzone auf den Gipfeln eines Gebirges verbunden. Dadurch entſteht in dem Steigrohr ein konſtanter aufſteigender Luftſtrom von vielleicht 50 Sekundenmeter Geſchwindigkeit, deſſen gewaltige Energie in Windturbinen ausgenutzt werden kann. Durch das Glasdach am Fuße des Steigrohrs wird eine Überhitzung herbeigeführt, die die Strömungsgeſchwindigkeit noch ſteigert

Figure 8. Proposal by Günther: a solar chimney on the slope of a high mountain. (Günther, 1931)

Starting in 1980, a team led by the German engineer Jörg Schlaich took the initiative and constructed a prototype in Manzanares (Spain) with 200 m high solar tower and a maximum power output of 50 kW. This plant operated successfully for more than six years (Schlaich, 1995). A more detailed description of the project is given in the following section.

In 1987, Pasumarthi and Sherif erected a small prototype installation in California and published the first thermo-mechanical plant model (Pasumarthi&Sherif, 1998).

Since those days, projects of SUPPs have been developed in arid zones all over the world. For example, in Spain there was a proposal for a 750 m Solar Tower with an expected production of 40 MW. Enviromission projects concerning Solar Updraft Tower were also proposed in Australia. In Namibia, the so-called Greentower (a name which combines, in its meaning, a greenhouse with a Solar Tower) is an innovating project proposal involving the construction of 1.5 km tower able to generate 400 MW of electricity. However, none of these projects has been brought to realization, up to now.

2.1. Solar Tower Prototype in Manzanares (Spain)

Jörg Schlaich, Rudolf Bergermann and their team have been very active in developing and spreading the Solar Updraft Power Technology. Thanks to them, a solar tower prototype was built in Manzanares (Spain), in order to test the new technology and confirm analytical results through experimental data.

Their first idea goes back to 1972, when they were invited by the power industry to develop a large scale cooling tower for dry cooling. Then, a new question soon arose, whether the natural updraft which is produced in such chimney tubes could not be utilized to produce electricity, provided an additional “fire” at the base of the chimney tube. And why not to use solar radiation and collect solar warm air by means of a large greenhouse roof? All of that resulted, in 1979, in what they called the “Solar Chimney”. (Schlaich, 2010)

The plan was built in 1980 in Manzanares (about 150 km south of Madrid) thanks to a grant by the German Ministry for Research and Technology. The prototype is represented in Figure 9. “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” (Schlaich, 1995). The prototype was only designed for experimental purposes, to collect measurements for a period of three years. It was intended to be removed without trace after that. Because of that, the chimney was made of a corrugated metal sheeting, whose thickness was only 1.25 mm and which could be used again after the experiment. This solution only made sense for the specific use it had been planned for, i.e. a temporary structure. It would not be reasonable for solar towers intended to have a long life-span, which should be reinforced concrete shells.

The chimney was a cylindrical tube of 195 m in height and 10 m in diameter. It was surrounded by a collector of 240 m in diameter. Since the type of collector roof primarily determines a solar chimney's performance costs, different building methods and materials for the collector roof were also tested in Manzanares. The 45000 m^2 of the prototype were covered with various plastic films and glass, to establish the optimum and cheapest material in the long term. Moreover, an experimental planting was also carried out under the roof, to investigate additional use of the collector as a greenhouse.

The original plan was to take measurements in 1981 and 1982 and dismantle the structure in 1983, after three years from the construction, since the grant did not permit regular corrosion protection especially for the stay-cables. Anyway, years passed away permitting them to take more measurements. However, corrosion was on the way and by spring 1989 the cables had rusted so badly that they broke in a storm and the chimney fell down. It was expected, but the chimney still lasted for eight years rather than the initially requested three and when it failed the necessary measurements had long been completed.

Experimental results were very promising, a detailed analysis can be found in (Schlaich, 1995).

Schlaich, Bergermann and their team developed this challenging idea on their own, and only at the end of the 1980s they got hold of the paper written in 1931 by Günther, describing the basic principle of the solar updraft tower. So they frankly admitted that they did not invent but "only" developed the solar updraft technology. However, such a fact makes this new technology even more promising.

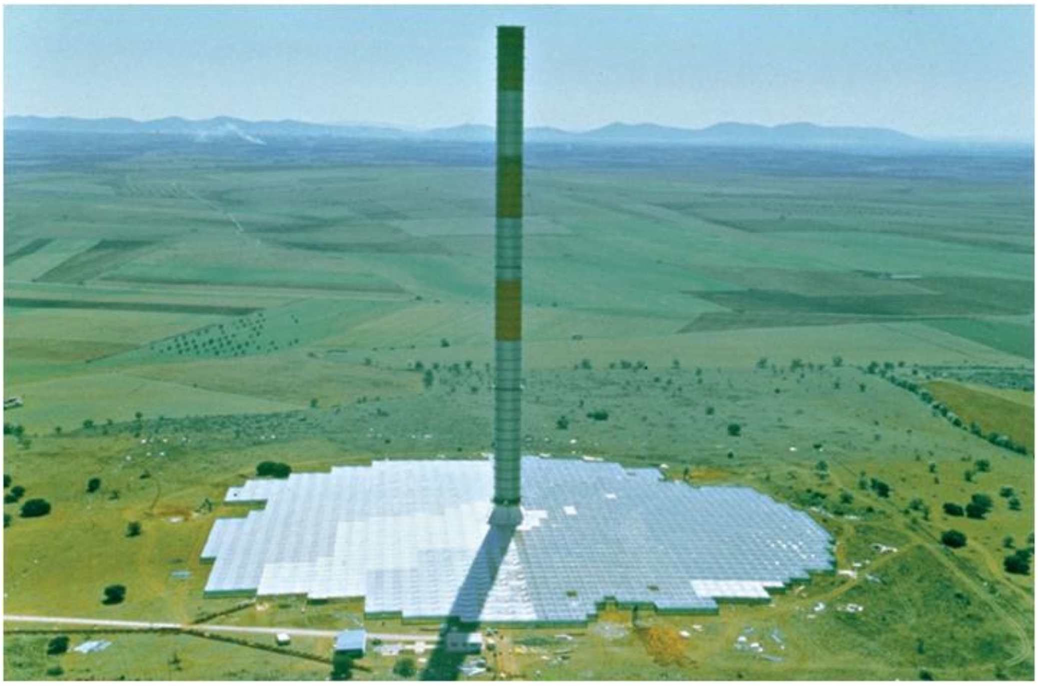


Figure 9. J. Schlaich's prototype SUPP in Manzanares/Spain (Schlaich, 1995)

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Biographical Sketches

Prof. Dr.-Ing. Claudio Borri is Full Professor of Structural Mechanics and Chair of Computational Mechanics and Wind Engineering at the University of Florence, School of Engineering. He studied in Florence, Bochum and Karlsruhe; he has received a CNR, a DAAD, and an A von Humboldt research fellowship and has served as Visiting Prof. in several European and USA Universities.

Prof. Borri is Author of approx. 220 scientific publications and 3 books; he is Editor of 5 volumes (conf. Proceedings). In 1994 he was awarded with the Max Planck research Prize (jointly awarded by the A. von Humboldt Foundation and M. Planck Gesellschaft) and, later on, he has received Honoris Causa (h. c.) degrees at UACEG Sofia, Bulgaria in 2000 and at TU-Tallin, Estonia in 2007.

Prof. Borri serves also as structural engineering consultant and proof engineer for statics; in 2010 he was appointed in Higher Scientific Advisory Board of the Stretto di Messina Soc. for the project of the 3,300m suspended bridge over the Strait of Messina (largest bridge ever designed).

Prof. Dr.-Ing. habil. Dr.-Ing. E.h. Wilfried B. Krätzig was born in 1932 and raised up in Hamburg/Germany. From 1952-1957 he studied Civil Engineering at the Technical University of Hannover, finishing this time with the degree of Diplomingenieur. After this studies he joined the German civil industry (Ed. Züblin AG) and worked there as a project engineer and site manager until the end of 1961. At the beginning of 1962 he returned back to the Technical University of Hannover to the Institute of Reinforced and Concrete Engineering (Professor Dr.-Ing. W. Zerna) as Senior Engineer (Oberingenieur) finishing his Dr.-Ing.-degree in 1965 and his habilitation (Dr.-Ing. habil.) in 1969.

From 1969-1970 he served as Associate Professor at the University of California in Berkeley/California/USA, returning to Germany at the end of 1970. From then on he stayed as Full Professor of Structural Engineering at the Ruhr-University Bochum/Germany, becoming Professor Emeritus in 1998. Professor Krätzig has published more than 320 publication in national and international journals as well as congress reports, on topics like theory of structures, analysis of structures, shell theory and dynamics of structures. He has given approximately the same number of scientific lectures.

Besides this he was working as Consulting Engineer, State-authorized Verification Engineer and State-authorized Expert for the Safety of Structures. He is a partner in the Engineering Consultant Office Krätzig & Partners, Bochum/Germany and in this position he was involved in the design and construction many important civil engineering structures. He was member of several National Standardizing Committees.

Professor Krätzig is member in many national and international scientific organizations, and has received a large number of academic as well as professional honors, e.g. the degree of Dr.-Ing. E.H. (honorary doctoral degree) of the Technical University of Dresden/Germany.

Dipl.-Ing. Francesca Lupi, born in 1984 in Prato (Italy), graduated "cum laude" in Civil Engineering at the University of Florence (Italy) in 2009. She prepared her Master Thesis, entitled "Structural behaviour, optimization and design of a solar chimney prototype under wind loading and other actions" at the Ruhr-University of Bochum (Germany), where she attended a training period at Niemann&Partner (February-May 2009).

From 2010, she is a PhD student in the International Graduate College "Mitigation of risk due to natural hazards on structures and infrastructures" jointly run by the University of Florence (Italy) and the Technical University of Braunschweig (Germany). Her research topic is structural wind engineering, focusing on the investigation of wind loading models for evaluation of local effects on Solar Updraft Towers.

Prof. Dr.-Ing. habil Hans-Jürgen Niemann, born 1935 in Lueneburg, Germany; studied Civil Engineering at the Universitaet Hannover, graduated as Diplomingenieur (corresponding to the master degree); worked as a design engineer in Bremen; worked as research assistant at the Universitaet Hannover and the then newly established Ruhr-Universitaet Bochum; graduated as Doctor of Civil Engineering and obtained the "authorization for lecturing" (Habilitation) in Structural Engineering from the Ruhr-Universitaet Bochum; was appointed Prof. of Wind Engineering and Fluid Mechanics; established the Boundary Layer Wind Tunnel Laboratory at the RUB.

Co-chairman of two Collaborative Research Centers funded by the German Science Foundation, namely "Structural Dynamics" (1982-1994) and "Life-time oriented Design Concepts" (1995-2001).

Dean of the Department of Civil Engineering, Ruhr-Universitaet Bochum from 1997-2001.

Published around 120 papers, editor and co-editor of several books. Chairman and co-chairman of several conferences in the fields of Wind Engineering, Cooling Tower Design, and Structural Dynamics.

Advisory Professor at the Shanghai-University of Technology since 1987; was awarded the Humboldt-South-Africa Research Award 1997.

Chairman of the code committee „Wind Actions on Structures" since 1993; member of 4 more code committees.

Founded the Engineering Company Niemann und Partner, Bochum, in 2001; Consulting Engineer for various national and international projects. Recent examples are the stadia in Bern, Hannover, Duisburg, Moscow; high-rise buildings in Doha, Katar; Rhine crossing Wesel, a cable-stayed steel bridge; numerous Natural Draught Cooling Towers in Germany, India, Poland; other structures in power plants.