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A Generalized Overview of Solar Updraft Towers

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Abstract

The incessant depletion of fossil fuels means that there is an urgent need of new and emerging technologies that can provide clean, renewable and cheap energy to the masses. The generation of large scale solar thermal electricity is technically feasible and will soon become economically competitive, if more efforts to introduce it are made. Solar Updraft Tower is one such technology which is still to be harnessed to its full extent. This paper gives an overview of this technology and its potential.

Keywords : Solar Power, Solar Tower

I. INTRODUCTION

According to the International Energy Agency, 1.6 billion people have no access to electrical energy. This number is bound to increase as more and more people want and should be able to use electricity at an affordable rate. It will be short sighted to rely on conventional resources like coal or oil. Solar power, meanwhile, is clean, cheap and readily accessible source of power. In general there are three rather well known applications of solar energy use; direct use (lighting and drying), direct conversion into electricity (photovoltaic) and direct conversion into heat (hot water production). A fourth set of technologies is the Solar Thermal Power (STP) system, which converts solar energy use into electrical power. STP systems convert short wave direct sunlight radiation into long wave heat radiation. In the absence of direct sunlight, some of these technologies have the capability to use the earth's radiating heat. The heat is used to produce a gas flow, which is fed to a turbine. The turbines that produce the power in a STP plant are of the same kind as used in fossil fired power plants, hydro plants or windmills. This inherent flexibility in STP systems help it to manipulate the number of hours of power production and stretches them beyond the number of sunshine hours. STP systems can be divided into two distinct types – concentrating mirror technologies and temperature density technologies. In concentrating mirror technologies concentrate sunlight onto a central receiver using focusing mirrors. The temperature density technologies make use of air movements (convection currents) produced due presence of temperature difference. Power is produced by placing a turbine in the stream flow. Solar Updraft Tower (SUT) is a type of STP that is categorised as temperature density technology. Importance of SUTs lies in the fact that they can provide electricity at a cost comparable to conventional power plants. This reason is appealing enough to further develop this form of solar energy utilization to encompass large, economically viable units. In a future energy economy, SUTs could thus help assure the economic and environmentally benign provision of electricity in sunny regions. The three essential elements of a SUT are solar air collector, chimney/tower and wind turbines.

Fig 1: Artist view of Solar Updraft Tower

II. PRINCIPLE OF WORKING

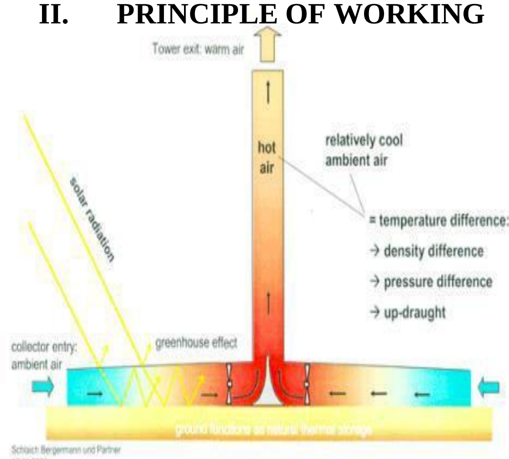


Fig 2: Operational Principle of Solar Updraft Tower

The working principle of a SUT is based on convection currents and green house effect. In a SUT, air is heated under a transparent (or translucent) roof, open at the periphery, by the use of solar radiation. This roof along with the ground below it forms the collector. The collector also operates as a green house cover, it lets the sunlight in (direct or diffused), but prevents heat from escaping. To accomplish this task, the collecting roof is generally made of single or double polyster material. This heat in turn heats up the air enclosed by the surrounding surface and ground. A vertical tower with large air inlets at its base is placed at the centre of the roof. The hot air roofed inside the collector rises through the tower while cold air from surrounding territory enters the collector area. Suction from the tower draws in further hot air and the process continues. For a continuous 24 hours process, large water filled bags or tubes can be placed below the roof. The water heats up during the day and releases its heat at night time. Thus solar radiation causes a continuous updraft in the tower. The energy contained in the updraft can be harnessed by first converting it into mechanical energy by using turbines and then into electrical energy by using coupled generators. The turbines are placed at the base of the tower.

A. *COLLECTOR*

The hot air required for the working of the solar updraft tower is generated under a large roof made up of glazed glass. For design and constructional flexibility, plastic glazing may also be used. The roof steadily inclines upwards as it approaches the tower placed in the middle. This feature is provided for the hot air to move towards the tower rapidly. The glazing works in similar fashion as that of a green house cover, letting in the direct short-wave solar radiation but preventing the longer re-radiation from escaping. This process leads to heating up of the ground which in turn heats up the air. The collector roof is suspended at a height of 2 to 20 m from the ground. Large collector area is required to increase the plant's capacity.

B. THERMAL STORAGE

To increase the thermal storage capacity of the plant, water filled bags or tubes are laid down under the soil. This adaptation reduces the peak power output round noon but makes power production after sunset possible. Water, stores up heat during day time and releases it at night, hence providing 24 hours of continuous operation. Since the heat capacity of water is about five times higher than that of soil, heat storage with water works more efficiently than with soil alone. No refilling is required for the water tubes and hence water requirement for the wholesome operation of plant is small. Addition of humidity in the updraft could increase the power output of the plant, but this method could prove costlier. The main reason is that the most suitable place to build a SUT is arid or semi-arid regions; hence water availability is one major concern.

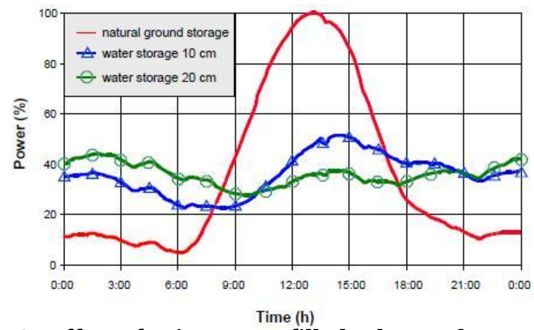


Fig 3: Effect of using water filled tubes under collector roof

C. *TOWER*

The tower is the actual generator of the power plant. The turbines are placed inside the tower and due to production of draught in the tower; the hot air updraft is created. In a SUT, the velocity of the updraft is directly proportional to the temperature difference between hot air in the collector and outside air. Since this temperature difference is no more than 35 K, the wind velocity inside the tower can reach (only) up to 15m/s. The relative low wind velocity obviates the use of any special constructional materials for the tower. Generally, steel or concrete is used in the construction of tower. The height of the tower directly affects the capacity of the plant.

D. TURBINE

Turbines convert the energy of the hot air updraft into mechanical form. Unlike a wind energy convertor, SUTs' turbines work in similar fashion as the turbines of a hydro electric power plant. In these turbines, static pressure is converted to rotational energy using casing. Air speed before and after the turbine is about the same. The output achieved is proportional to the product of the volume flow per time unit and the pressure differential over the turbine. With a view to maximum energy yield, the blade pitch is adjusted during operation to regulate the power output according to the changing 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% of the total pressure differential available.

III. PROTOTYPE

Fig 4: Aerial view of Manzanares SUT Plant

Theoretical research in the field of Solar Thermal Power Generation and advancements in wind tunnel experiments led to the installation of the first Solar Updraft Tower Prototype in Manzanares (Spain), 150 km south of Madrid in the year 1982. This plant was constructed by Schlaich Bergermann and Partner (SBP), a German engineering firm. The German Ministry of Research and Technology provided the necessary funding for this prototype while the land was made available by Spanish Utility Union Electrica Fenosa. The capacity of this experimental setup was 50 KW. The pilot plant was designed as a temporary structure that would last just three years, but it kept running until 1989. By then, however, its steel guy cables had rusted as they were not protected against corrosion, and it finally toppled in a strong windstorm. This SUT plant was made with a view to understand the future applications of the SUT technology and to collect experimental real time data that would benefit the future construction of higher capacity plants. . 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 2.5m/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 hours per day. In 1987 there were 3067 hours with a solar global horizontal irradiation of over 150 W/m² at the Manzanares site. Total operation time of the plant with net positive power to the grid was 3157 hours, including 244 hours of net positive power to the grid at night.

General Arrangement

Chimney Height	200 m
Collector Diameter	240 m
Turbine	50 KW
No. Of Turbine Blades	4
Chimney Diameter	10 m
Collector Height	2 m
Collector Area	45,000 m^2
Chimney Weight	125 ton
Collector Weight	5.5 kg/m^2
Roof segment size	9 * 9 m
10 membrane covered collector area	40,000 m^2
Glass covered collector area	5,000 m^2
Mean collector air	20 K

Table 1: Characteristics of SUT Plant in Manzanares, Spain

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 system, continuous operation throughout the day is possible, and for large systems even abrupt fluctuations in energy supply are effectively cushioned. The exploitation of single global radiation and the thermodynamic inertia is a characteristic feature of the system. Continuous operation throughout the day is possible and even abrupt fluctuation in energy supply is effectively cushioned, the plant operated continuously even on cloudy days, albeit at reduced output. Inexpensive materials were used in order to evaluate their performance. The solar tower was built of iron plating only 1.25 millimetres (0.049 in) thick. Various materials were used for testing, such as single or double glazing or plastic for the collector roof (which turned out not to be durable enough). One section was used as an actual greenhouse. During its operation, 180 sensors measured inside and outside temperature, while humidity and wind speed data was collected on a second-by-second basis. Another known working SUT plant is situated in Jinshawan in Inner Mongolia, China. This plant has a capacity of 200 KW and is privately owned.

A. OTHER SOLAR UPDRAFT TOWERS

A proposal to construct a SUT in Fuente el Frenso, Ciudad Real, Spain entitled Ciudad Real Torre Solar would be the first of its kind in the European Union and would stand 750 metres (2,460 ft) tall nearly twice as tall as the continent's tallest structure, the Belmont TV Mast – covering an area of 350 hectares (860 acres). It is expected to produce 40 MW. Enviro Mission, along with SBP was in the process of raising funds for a SUT plant in Western Australia when it was shelved. EnviroMission have plans for a similar plant in Arizona, and most recently (December 2013) in Texas, but there is no sign of 'breaking ground' in any of EnviroMission's proposals. SBP is currently working with an Australian Company, Hyperion Energy to build a 200 MW plant in Western Australia. This plant's tower will be 1 km tall, made of concrete and steel. Collector would be 10 km in diameter. Based on the need for plans for long-term energy strategies, Botswana's Ministry of Science and Technology designed and built a small scale research solar

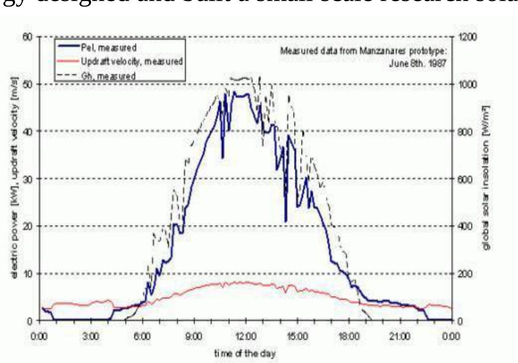
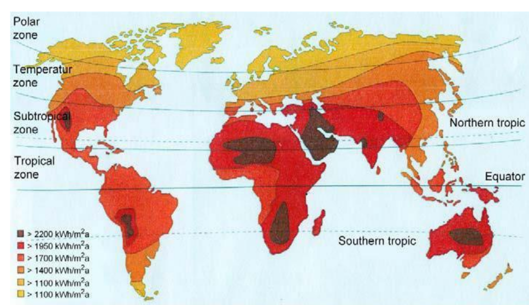


Fig 5: Measured Data from Manzanares Plant, June 8th, 1987

updraft power plant. The aim of this experiment was to decide upon the potential of updraft technology in Botswana. This experiment ran from 7 October 2005 to 22 November 2005. The tower had an inside diameter of 2 metres (6.6 ft) and a height of 22 metres (72 ft), manufactured from glass-reinforced polyester, with an area of approximately 160 square metres (1,700 sq ft). The roof was made of a 5 mm thick clear glass supported by a steel framework.

IV. GENERAL CHARACTERISTICS

Desert and Semi-Arid regions have a huge unfulfilled potential in the area of solar power. The major reason is that conventional technology used to harness the potential of sun, the Photo-voltaic method, does not provide power continuously for 24 hr period. Solar-Thermal technologies are an answer to this problem, but they require cooling water in their operation, which makes them unsuitable in dry region. Solar updraft technology overcomes the intermittency of solar power. A SUT does not need sunlight to function, it requires hot air. Sunlight just happens to be the cheapest and easiest way to heat up air. By storing this heat in large water filled tubes and bags, and then releasing it back automatically once sun goes down, helps a SUT plant to churn out power continuously. Also, a Solar Updraft Plant does not have any sort of cooling water requirement (The water employed in thermal storage is one time investment, it needs no



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

Fig 6: Distribution of yearly solar radiation

replacements). All the power plants using fossil fuels, as well as many Solar-Thermal Power Plants, require immense amount of water for cooling purposes. These reasons make Solar Updraft Towers an ideal source of cheap and green power generation in arid regions. Moreover, PV cells can lose much of their efficiency if they're covered by even a thin layer of dust. That's a problem in desert areas, which are not only dusty, but also very short of the water needed to keep solar panels clean. Solar towers need no water, and their canopies, which are less affected by grit, can be dusted clean without water. Another problem associated with solar power is that under cloudy conditions, solar power plants are either rendered useless or they work under efficiently. But the collector of a Solar Updraft Tower can use both direct and diffused sunlight. Thus a Solar Updraft Tower works well in cloudy conditions too. A Solar Updraft Power Plant is economically efficient in areas with solar radiation input of 1900 – 2300 KWh/m^2. This comprises almost all the deserts and semi-arid regions 30^o latitudes north and south of the equator. The simple and robust construction of a Solar Updraft Tower guarantees the requirement of minimal maintenance. Turbine and Generator – subjected to the air draft - are the only moving parts of the system. A lack of any combustible fuel means that the plant basically runs itself. A Solar Tower is very reliable and highly unlikely to break down.

V. 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 Qsolar multiplied by the respective efficiencies of collector, tower and turbine(s):

$$P = Q_{Solar} * \eta_{Coll} * \eta_{Tower} * \eta_{turbine}$$

$$= Q_{Solar} * \eta_{total}$$

The solar energy input Q& solar into the system can be written as the product of global horizontal radiation Gh and collector area Acoll.

$$Qsolar = Gh \ Acoll \qquad (2)$$

The Tower Chimney converts the heat-flows 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 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 ptot is produced between tower base (collector outlet) and the ambient.

$$\Delta p_{tot} = \int^{Htower} (\rho_a - \rho_{tower}) \cdot dH \qquad (3)$$

Thus Δptot increases with tower height. The pressure difference Δptot can be subdivided into a static and a dynamic component, neglecting friction losses:

$$\Delta p_{tot} = \Delta p_s + \Delta p_d \qquad (4)$$

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 the power $\Delta p_s = 0$, the power P_{tot} contained in the flow is now:

$$P_{tot} = \Delta p_{tot} \ v_{tower,max} \ A_{coll}$$

from which the efficiency of the tower established:

$$\eta = Q_{tower} / P_{tot}$$

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 $V_{tower,max}$ is achieved and the whole pressure difference is used to accelerate the air and is thus converted into kinetic energy:

$$P = 0.5 * m \,.\, V^2_{tower,max} \qquad (7)$$

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

$$V_{tower,max} = (2 \,.\, g \,.\, H_{tower} \,.\, \Delta T / T_0)^{0.5} \qquad (8)$$

where ΔT is the temperature rise between ambient and collector outlet (=tower inflow). Tower efficiency is given in equation 9:

$$\eta = g \,.\, H / c_p \,.\, T_0 \qquad (9)$$

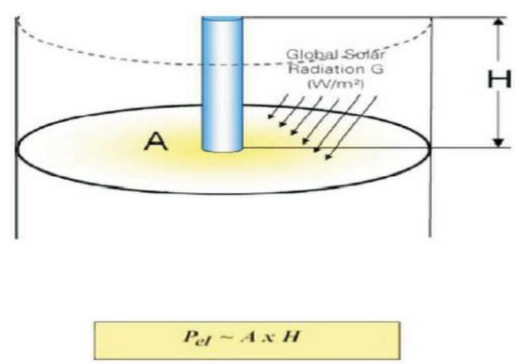


Fig 7

This simplified representation explains one of the basic characteristics of the solar tower, which is that the tower efficiency is fundamentally dependent only on its height. For heights of 1000m the deviation from the exact solution, caused by the Boussinesq approximation, is negligible. Using equations (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 figure 7. 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.

VI. FUTURE OF SOLAR UPDRAFT POWER PLANTS

Solar Updraft Towers contain humongous potential and could be the key of obtaining green and cheap electricity at a large scale. But presently, there are no large scale solar updraft power plants in working capacity anywhere in the world. Neither is one supposed to be constructed anywhere in the near future. There are some constraints with solar updraft towers. They require large acres of flat land and are unsuitable for earthquake prone zones. But these limitations are not the main reason for the lack of solar updraft towers. The foremost reason for this circumstance is purely economical. The capital cost of building a Solar Updraft Tower is gargantuan. A 200 MW updraft plant requires a funding of approximately $2 billion. The enormous price tag to build an industrial size power plant based on a technology that has never been tested at even half this scale puts off investors. But there is no point in building a smaller plant, as the upfront costs are very high. The efficiency of a solar updraft plant is 1 to 2 percent – compared to PV technologies that provide efficiency of 8 to 15 percent – but that doesn't matter. If built large enough, a Solar Updraft plat provides electricity at a cost per KWh competitive to conventional solar systems. Also, the operational and maintenance cost of a solar updraft plant are very low. Another challenge is the huge dimension of the power plant. For profitable production of power, plants as high as 1000 m and collector diameters as large as 7 km are envisioned. Such large constructions require civil engineering of peak quality. The solar updraft towers are to be build in such a fashion as to withstand all the challenges of a desert climate. Such large towers must also have a life expectancy of 60 to 75 years, if we want a return on our investment. Towers 1,000 m high are a challenge, but they can be built today. The Burj Khalifa is almost 800 m high and serious plans are being made for 1,500 m skyscrapers in earthquake-ridden Japan. The emergence of newer technologies to reduce the cost of constructing a Solar Updraft Tower has renewed interest in this field. In developing countries, with low labour costs and self sufficiency in terms of construction material and land, solar updraft technology become a viable prospect if there is a government backing to the project. The following table assumes annual global solar radiation of 2300 KWh/m2.

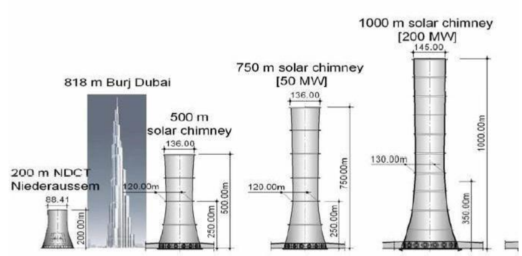


Fig 8: From the World's largest cooling tower to the future designs of Solar Updraft Towers

Capacity (MW)	**5**	**30**	**100**	**200**
Tower Height (m)	550	750	1000	1000
Tower Diameter (m)	45	70	110	120
Collector Diameter (km)	1.25	2.9	4.3	7.0
Electricity Output (GWh/a)	14	99	320	680

Table 2: Typical Dimensions and Electricity Output

VII. CONCLUSION

Generation of electricity using solar power is a viable concept which can replace conventional electricity generation plants like thermal or hydraulic power plants in near future. A solar updraft tower generates electricity using both direct and diffused solar radiation, and can provide 24 hours of continuous power. The physics of this technology is simple and well understood. But this technology is profitable only at a large scale, and as we increase the plant's capacity, its size increases in proportion. Large plants mean huge investment with lot of labour involved.

For a country like India, with huge areas of unused desert land, cheap labour and 9 months of sunshine, solar updraft technology could be a boon to the ever present energy crisis. Solar updraft towers reduce the dependency on environmentally hazardous fossil fuels for our power need. There is no harm to the ecosystem 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. In desert regions – with lots of sand and stone – solar towers can be considered to reproduce themselves.

VIII. NOMENCLATURE

Latin

A area [m²]
G global solar radiation [W m-2]

H height [m]

P power [W]

Q heat flux [W]

T temperature [K]
C_p specific heat at constant pressure [J kg-1 K-1]

m mass flow [kg s-1]

p pressure [N m-2]

v velocity [m s-1]

Greek

η efficiency [-]

Prefix

change in value

Subscript

0 at ground level

a ambient
coll collector

d dynamic

h horizontal
s static

tot total

max maximum

IX. BIOGRAPHY

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