We are IntechOpen,
the world's leading publisher of
Open Access books
Built by scientists, for scientists

6,900
Open access books available

186,000
International authors and editors

200M
Downloads

Our authors are among the

154
Countries delivered to

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

New Developments in Large Scale Solar Energy Conversion

Amr Serag-Eldin
American University in Cairo
Egypt

1. Introduction

This chapter is dedicated to large scale electrical energy production from Solar energy. The scale considered here is that comparable with the output of conventional Thermal and Nuclear power plants, i.e. of the order of 50-1000 MW. The technology involved in such applications is generally significantly different than that encountered in low temperature, low capacity systems, such as domestic solar water heaters and charging of small appliance batteries.

It is an established fact that fossil fuels are not replaceable and are being depleted at an alarming rate; moreover their direct burning produces atmospheric pollutants and CO_2 which contribute to global warming. Nuclear energy may be a short term replacement for fossil fuels, however, nuclear fuel sources are also limited and problems with long term, safe and economic disposal of nuclear waste have not yet been solved. Thus many studies have indicated that solar energy is expected to be the prime source of energy fifty years from now. As early as 2025, it is projected that 10.7 % of total electrical energy production in the US would come from Solar energy sources alone, and that figure would rise to 69% by 2050, (Pernick and Wilder,2008); this is substantial energy capacity, considering that the US is the largest energy consumer in the world. The future forecast is that the cost of electricity generation from fuels such as coal, oil, natural gas, and even Nuclear energy will continue to rise, while solar technologies' cost will continue to decline. Already, solar power can compete in regions with high electricity rates and with favourable incentives. Most countries of the developed world and many of the developing ones, are currently promoting the use of renewable energy by introducing incentives and legislation; these policies are expected to accelerate the wide spread of renewable energy sources in the near future.

Solar energy is one of the most abundant sources of renewable energy. The incident solar energy on the Earth's surface is several orders of magnitude above current energy consumption. However the problem is the relatively low energy concentration, which is not an issue with low temperature applications such as solar water heaters, but poses a challenge to large scale or high temperature applications.

The present chapter will start by reviewing the technologies currently available or proposed for large scale solar energy generation; these can be broadly divided into concentrating and non-concentrating technologies. It will start by reviewing the former type then focus on a new application of the latter type, namely the solar updraft tower, for which the author believes there is a bright future in desert environments.

2. Concentrating Solar Power Systems

Concentrating solar power (CSP) systems first concentrate the sun's energy using reflective devices, then the resulting concentrated heat energy is transformed to a heat transfer medium, which is employed to power a conventional turbine to produce electricity. Concentrating systems make use of the direct radiation component only, and cannot benefit from the diffuse component of solar radiation. There are three main types of CSP systems: the parabolic trough system, the Heliostat solar tower system and the solar dish system. The first of these is a line concentrating system, whereas the latter two are point concentrating ones. Each type is now presented in turn.

2.1 Parabolic Troughs

Trough technology, is the simplest of the three concentration technologies and currently the most widely spread and developed(La Porta,2005). An example of such a system is the EuroTrough parabolic trough collector (Michael et al. , 2002). It basically consists of rows of cylindrical parabolic mirrors which collect solar radiation and focus it on a line, along which lies an absorber tube. A carrier fluid then flows within the tube receiving the heat and delivering it to the remainder of the cycle. A schematic of a solar electric generating system (SEGS) employing synthetic oil as heat transfer medium is displayed in Figure 1. The diagram also reveals a secondary oil heater cycle to operate the plant when solar radiation is inadequate, e.g. night time. Many existing SEGS plants display this dual mode feature.
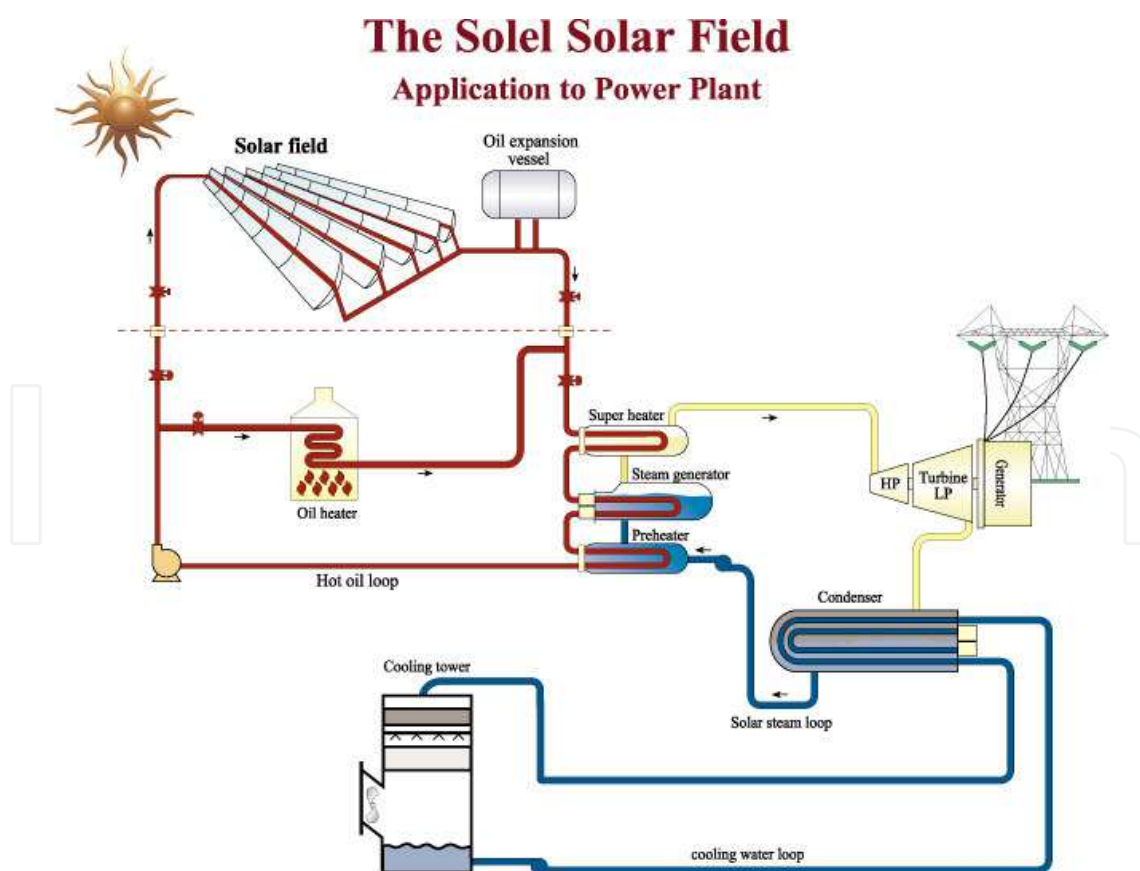

Fig. 1. Layout of a typical SEGS power plant, employing oil, (SOLEL, 2007)

The Californian company LUZ has built the largest solar energy generating system to date, boasting nine plants totalling 354 MW on a pure commercial basis, in the Mojave Desert, California. A picture of the parabolic trough collectors employed in this plant is displayed in Figure 2.

Fig. 2. SEGS plant in Mojave Desert, California , Solel(2007)

The collectors of the Parabolic trough plants use a computerized single-axis solar tracking system, that tracks the sun from sunrise to sunset(Solel,2007). Typical collector mirrors are formed of a glass layer covered on the back by a silver layer which is protected against oxidation by suitable resins; a 30 year operational lifetime is envisaged. The reflectivity of the mirrors is around 94% and their concentration ratios are typically 82 times to yield operation temperatures of about 400 ^{0}C. The absorbing tube is usually made of steel and covered by a highly selective metallic oxide-ceramic layer displaying an absorptivity of approximately 97%. To reduce losses, the absorbing tube is covered by a vacuum glass tube with a transmissivity of approximately 95%. Synthetic oil is a common working fluid (heat transfer medium); although some recent projects have used water for direct steam generation in order to reduce cost and improve operating performance, albeit introducing problems of controlling the two phase flow in horizontal tubes. A solar collector assembly based on the EuorTrough design, operating year round at a site with a 2300 kWh/m^2 annual direct radiation displayed a performance of 60% annual thermal collection efficiency, i.e. produced 1300 kWh thermal energy per year.

A modification of the parabolic trough system is the Fresnel trough system in which parabolic troughs are replaced by segmented mirrors operating according to the principle of Fresnel, Fig .3. The Belgium company Solarmundo operates a 2500 m^2 prototype in Liège, Belgium. The mirrors have a typical width of 0.5 m and are either perfectly flat or display a very small curvature achieved by mechanical bending. The collector comprises 48 rows of mirrors, resulting in a collector width of 24 m. On top of the absorber tube is a second stage cavity reflector designed to re-direct some of the reflected rays to the top of the absorber tube, thus enlarging the target for the Fresnel mirrors, and producing a more uniform heating of the tube over its cross-section. It also serves to reduce heat losses from the selectively coated absorber tube.
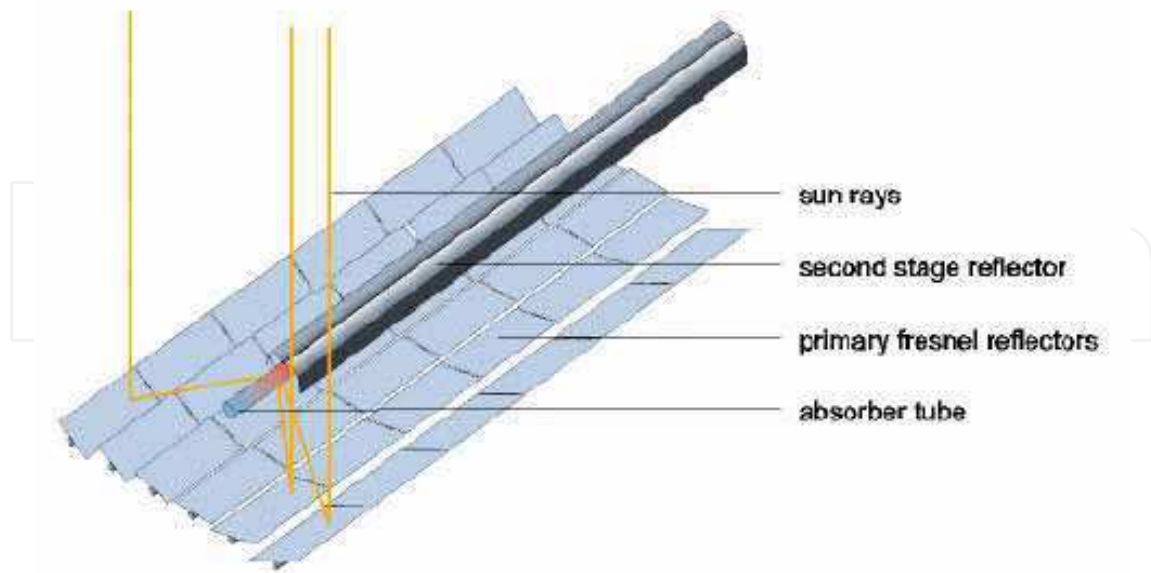
Fig. 3. Fresnel collector principle (Häberle et al,2002)

Fig. 4. Fresnel mirrors, absorber tube and secondary reflector(Häberle et al(2002).

Figure 4 shows a picture of such a system with the secondary reflector and absorber tube glowing brightly at the top of the frame, and the planar mirrors appearing at the bottom of the frame.

Compared to trough collectors, Fresnel collectors are slightly less efficient however the planar mirrors are much cheaper to manufacture and maintain, the tracking system is simpler and wind loads are considerably reduced. These advantages are expected to lead to a 50% reduction in cost over a comparable parabolic trough system(la Porta,2005).

Moreover, auxiliary benefits of this system have been suggested, among which are the use of the reflectors to act as a cover(roof) for large open car parks and exhibitions, and for a controlled greenhouse making use of the diffuse light and the light reflected from the back of mirrors. At the university of New South Wales, Australia, a model was developed in which more than one absorber line was employed and alternate mirrors pointed in alternate directions in such a way as to reduce shading between adjacent mirror lines.

2.2 Central Solar Tower

In this system an array of ground mirrors, called heliostats, reflect the solar radiation on to a target at the top of a tall central tower, as can be seen from Figure 5. This target is the receiver for the system while the heliostats are the collectors. The height of tower is determined by technical and economic optimization. Higher towers allow bigger and denser heliostat fields with lower shading losses. However, this is counteracted by need for higher tracking precision, and increased tower and piping construction costs, as well as pumping and heat losses. Common tower are 80-100 m tall, and are manufactured from either concrete or lattice structures.

Fig. 5. The 11 MW PS10 Solar Tower near Seville in Spain.

The heliostat field is composed of many single mirror facets, which are fixed on a steel structure and directed towards a focal point at the top of the tower, with the aid of a central processor. Each mirror has two degrees of freedom, rotating over both a horizontal and vertical axis, to closely track the sun's motion. Some new heliostats are manufactured from thin metallic membranes or plastic foils, which are tightened on a metallic frame and shaped into parabolic concave form, thus improving the accuracy of projection on the focal point. They are also cheaper to manufacture than conventional glass mirror heliostats but are less resistant to wind and sand erosion and more difficult to clean and maintain.

Compared to parabolic troughs, central tower systems are less efficient in using ground space, since a larger surface area is required to avoid single heliostats shadowing each other. The shape of the heliostat array is dictated by the receiver type; for example a symmetric, field covering the full 360^0 would be employed with an external receiver covering the entire periphery of the tower, while only a segment of this circle would be employed for a plain surface receiver, Figure 5 . Four different types of receivers at the top of the tower have been tested so far; they are:

i)   Cavity receiver

     this is a chamber tube receiver in which the heat transfer medium flows into the chamber inner walls, inside tubes which are bent into spirals and connected in parallel. The opening has a little surface which can be closed when direct solar radiation is poor. They are suitable for temperatures up to 600^0C.

ii) external receiver

     this is made of external heat transfer panels composed of many heat transfer tubes. A major problem is the freezing of the heat transfer medium(e.g. molten salts or sodium) when solar heating drops. Evacuation of tubes under such conditions becomes a necessity.

iii) volumetric receiver

     this type is used for higher temperatures. Concentrated solar radiation is incident on a volumetric absorber material consisting of steel wire or porous ceramics, displaying a large surface contact area for heat exchange. In open volumetric receivers, ambient air is sucked in by a blower and penetrates the radiated absorber material; the receiver operating essentially at atmospheric pressure. Alternatively, closed air receivers are pressurized up to 15 bars; this made possible by closing the aperture with a fused quartz window. The absorber is composed of several layers of porous material, which are heated by the oncoming radiation. Wire meshing of high-temperature resistant metal wire is used up to temperatures of 800 ^{0}C, while high-porosity ceramic foams are used at higher temperatures. Due to the penetration of radiation waves, a highly uniform internal temperature distribution is achieved.

iv) direct-absorption receiver

     here heat transfer is carried out by thin fluid films or by little particles which stream in an air-flow. These receivers are still in the experimental stages, but should be able to achieve peak temperatures of 2000^0C and heat densities of 2000 kW/m^2 (La Porta,2005).

Heat transfer mediums which are commonly employed include water/steam, salt metals, liquid sodium and air; whereas a mixture of solid particles and gas for direct radiation absorption is currently undergoing investigation.

Among new developments of the solar power tower is the introduction of beam-down optics in the Weizman Institute in Israel. In this a 70 m^2 hyperboloidal reflector is installed

up the tower with its upper focus coinciding with the heliostat field's target point. The reflector redirects the solar radiation from the heliostat field towards the lower focus of the hyperboloid, located near ground. Secondary concentrating non-imaging devices and receivers are installed below the lower focal point; magnification of the sun image by the hyperboloidal mirror is compensated by the ground secondary concentrator with a considerable net gain in concentration. Moreover, the placement of receivers and power block on the ground simplifies operation and reduces cost. Recent developments in non-imaging optics have yielded concentrations unheard off before, reaching 84,000 x ambient intensity of sunlight! Other developments include high-performance air receivers and solar-to-gas turbine interface (Solarpaces,2001).

2.3 Solar Dish Concentrators

As the name implies, the collector in this case is a parabolic shaped dish which concentrates the solar radiation on a receiver at its focal point. Two systems may be identified:

i) **Dish-Stirling systems**: a Stirling motor coupled to a generator is placed at the receiver end. In such systems the mirror, receiver, and motor-generator unit are rigidly connected and track the sun as one unit, Figure 6 .

ii) **Dish-farm systems**: Here a water/steam media flows through many dish-collectors collecting heat as it flows. The generated steam is then employed in a separate conventional Rankine cycle to generate electricity.

Fig. 6. A Dish – Stirling system, (Schiel, W. And Geyer,M. ,2007)

Dish-Stirling systems are relatively small power generation sets of typical capacities 5 -50 kW per unit; they are ideal for stand alone or other decentralized applications. However they may be connected in clusters with a capacity of 10 MW to meet moderate scale grid-

generation demands. The solar radiation is absorbed by the receiver heat exchanger to heat the working fluid(helium or hydrogen) of the Stirling engine to temperatures of about 650⁰C (Schelich Bergermann und Partner,2002). The engine is connected to a generator to produce electricity. The concentrator is mounted on a two-axis tracking system which tracks the sun continuously with the aid of servo-motors. The signal to the motor comes from either an instantaneous sun tracking sensor or from computer software which predicts the sun position.

The Sterling engine is ideally suited for the Dish-parabolic system. Not only does it follow the most efficient thermodynamic cycle, but it also employs an external heat source which allows it to operate with a hybrid heat receiver. Thus with an additionally installed burner, the heat source could be either the solar radiation or any other combustible fuel (e.g. bio-gas or natural gas) thus extending operation to cloudy periods and night time hours. Coupled with a digester producing bio-gas, the hybrid operated system could produce continuous electric output from renewable and environmentally friendly sources.

Since there is no internal combustion, combustion roar(noise) is absent and the "potential life-cycle of a Stirling engine is extraordinary high" (Schelich Bergermann und Partner,2002). Research is currently ongoing(Abdel-Rahman and Serag-Eldin,2008) to replace the Stirling engine with a corresponding Thermo-acoustic engine (Swift,2002) which features much of the advantages of the Stirling engine in addition to possessing no moving parts.

3. Solar Updraft Tower Plants

Solar updraft towers are non-concentrating solar energy plants designed for very large scale energy conversion, of the order of 200 MW; the larger the better. Because of lack of solar radiation concentration, the working fluid temperature rise within the plant is among the lowest in all large scale energy applications, and their conversion Carnot efficiencies are consequently very low. However, they compensate for their lower efficiencies with relatively low construction costs per kWh of electricity generated. Moreover, they possess several advantages which make them ideally suited for desert environments.

The original name for Solar Updraft towers was Solar Chimney Power plants; however due to the connotation with polluting chimneys, the name quickly fell out of favor and was replaced with the current one. As the original name signifies, the heart of the solar plant is a tall chimney stack, which is surrounded by a large conical collector, Figure 7. Pressure staged wind turbine-generator unit(s) extract the energy in the chimney draft to produce electrical power; their loation indicated by W.T. in Figure 7.
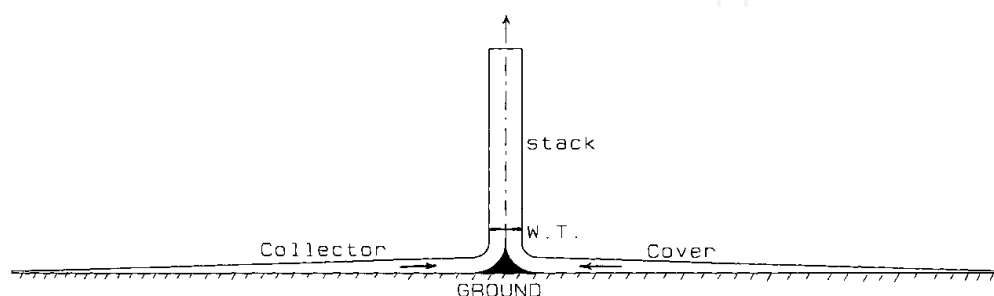

Fig. 7. Sketch of a Solar Updraft tower (Solar Chimney)

3.1 Concept

Solar updraft tower power plants are renewable energy devices which generate electrical power from solar energy after first converting it into wind (kinetic) energy. They comprise three main components, a central tall chimney stack (tower), a surrounding solar radiation collector, and turbine unit(s).

The collector comprises an elevated glass ceiling, covering a large area of ground acting as an absorber. The ground may also be partially covered with water tubes or shallow containers to improve its thermal storage properties. Solar radiation penetrates the collector ceiling to raise the temperature of the collector floor(ground), by virtue of the well known "green-house effect". The latter warms the air flowing immediately above it; and the hot air being lighter than the surrounding atmospheric air, rises up the chimney stack driven by buoyancy forces. This upward chimney draft is used to drive pressure-staged wind turbines. It also creates a partial vacuum at the bottom of the stack, which continuously sucks in fresh atmospheric air from the outer edges of the collector, and overcomes the internal flow resistance as the air flows inwards towards the stack, Figure 8.
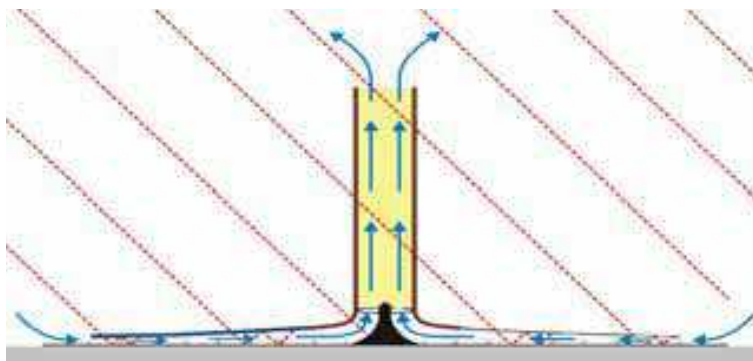

Fig. 8. Theory of operation of Solar Updraft tower

The Solar collector and stack cross-section are usually perfectly circular; thus the flow within the solar collector and chimney may generally be assumed to be axially symmetric. Indeed, if only conceptual design is required, the flow variations in the cross stream direction may be neglected and quasi-one dimensional models may be employed, e.g. Padki and Sherif(1999), Von Backstrom and Gannon(2000) and Pasumarthi and Sherif(1997). More detailed CFD models employing turbulence modeling and considering flow and property variations in all directions (Serag-Eldin,M.A. 2004a,b,2005a) are required for detailed geometric design and accurate performance calculations.

3.2 History and Current Status

In 1931, Hanns Gunther presented one of the earliest descriptions of a solar chimney power plant. As early as 1975, Robert Lucie applied for patents on a solar chimney electric power generator(Wikipedia,2007), yet to date there is not yet a single full scale commercial application. The cause is simple to explain; economically viable updraft towers need to be very large units, costing around $700 million, and potential investors are simply reluctant to risk this outlay on a technology which has not been field tested. However several starts have been made which are reported next.

In the late 1970's and early 1980's Professor Jorg Schlaich and his team at Schlaich Bergermann und Partner of Stuttgart, Germany developed a detailed proposal for a solar updraft tower, eventually gaining funding from the German Federal Ministry of Research and Technology to build an experimental pilot plant in Manzanares, Spain., Figure 9. The tower was 195 m tall and 10 m in diameter, with a collection area of 46000 m² (approx. 244 m diameter) producing a maximum output of 50 kW. The mean roof height was 1.85 m, and it possessed a single 4-blade axial turbine with a blade tip speed ratio of 10. The typical air temperature rise over ambient was 17 K. The majority of the collector was covered with plastic membranes(40000 m²) and the rest covered with glass(6000 m²). Vertical wind velocity in the stack reached a maximum of 12 m/s during turbine operations (Schlaich,2005).

Fig. 9. Picture of the 50 kW Solar Chimney plant at Manzanares, Spain.

The plant was highly instrumented with more than 180 sensors to record system behavior every second. It operated from 1982–1989, almost continuously with an availability exceeding 95%, until it was finally decommissioned due to structural problems. Plastic membrane covers were found cheaper than glass covers; however comparison between glass and plastic membrane endurance showed that glass resisted heavy storms for many years without harm and proved to be self-cleaning with occasional rains; whereas plastic membranes got brittle with time and tended to tear.

In 2000, the Australian company EnviroMission Ltd was founded, and became the exclusive holder of the Australian license to Solar Tower Technology (Thomas and

Davey,2004). The following year it unveiled a plan to build 200 MW solar updraft tower plants at a cost of approximately $700 million/plant, the first plant to commence construction in 2006, at Burronga Station, in the Riverland area of New South Wales. The stack height would be 1000 m tall and 120 m in diameter, whereas the collector diameter would be about 7000 m . Additional thermal storage would cover 25% of the total collector area and the plant was expected to operate 24 hrs. a day, at or close to nominal output in summer; albeit at significantly reduced output in winter. A total of 32 x 6.25 MW pressure-staged horizontal-axis turbines, symmetrically distributed on the ground close to the stack inlet would provide the necessary power. For large solar chimneys the air temperature in the collector is expected to be about 35 K, and the updraft velocity around 15 m/s.

However some time in 2006 the project was downscaled from 200 MWs to 50 MW (McLaren, 2006), because of the withdrawal of contractor and re-direction of some of the Australian government's funding. The reduced output plant should feature a 480 m tall tower of 78 m diameter, encircled by a 3300 m diameter collector. The height of collector at inlet will be 2.4 m and it will gradually slope up to 15 m at the tower's base. Unfortunately, the future of this project itself is still vague; the recent EnviroMission website states that "EnviroMission is now set to spearhead development and promotion of the Australian Solar Tower concept into markets outside Australia" and that "conditions in the USA support development ahead of Australia at this time".

Outside Australia several countries have also shown interest in building Solar updraft towers at some stage or other. Among these is Sri-Lanka's 200 MW project(Gluckman,2002), a 3x 200 MW project in the USA (Donovan,2004), the 200 MW plant in Rajasthan, India(2002) and a 200 MW plant in China (Woody,2006). A Spanish proposal for a 40 MW plant in Ciudad Real is also under consideration. In mid 2008 the Namibian government approved a proposal for the construction of a 400 MW solar chimney called the 'Greentower'. The tower is planned to be 1.5 km tall and 280 m in diameter, and the base will consist of a 37 km² greenhouse in which cash crops can be grown(Cloete,2008). It is difficult to know precisely the exact status of any of these projects right now, or how they will fare in the future; for up to date information it is recommended to visit the project's website, if it still exists!

3.3 Collector and Thermal Storage

The collector is basically a large green house. The cover is made from a transparent material such as glass which has high transmissivity for short wave solar radiation, and low transmissivity for reflected and emitted long wave radiation from the ground and surroundings. The net balance heats the ground of the collector, raising its temperature above that of the surroundings. The ground then warms the flowing air above it by forced convection. The collector uses all solar radiation, both direct and indirect; this is crucial for tropical countries where the sky is frequently overcast. The collector converts up to 70% of its irradiated solar energy into heat, a typical annual average being 50% (Schlaich,1995).

Solar radiation varies sharply throughout the day; however it is commonly assumed that the ground temperature does not vary appreciably due to its large thermal capacity.

Moreover since air temperature rise is the main factor affecting plant performance, and not ground temperature, the effect of cooler ground temperatures during night time on plant performance is partially offset by cooler external air temperatures. In desert environments, the difference between peak air daytime temperature and lowest night time temperature often exceeds 20 K.

Although the typical soil material forming the ground of the collector has high thermal capacity, its thermal diffusivity is low (it's also a good insulator) and thus the thermal penetration length during the day time hours is limited. Thus relatively large fluctuations in ground temperature would occur over the 24 hours, affecting uniformity of plant performance. Hence additional thermal storage is required in the form of shallow water cushions or tubes, which typically cover about 25% of the area of the collector foot print with an average depth of 5-20 cms. Although the thermal diffusivity of water is also low, its fluidity allows heat diffusion by natural convection which is orders of magnitude larger than molecular diffusion, thus increasing the effective thermal penetration depth. In the Manzanares test facility no additional thermal storage was added, and it was found that the output of the plant did vary appreciably throughout the day, confirming the need for additional thermal storage with high effective diffusivity.

The collector cover is inclined upwards with a small slope as it approaches the chimney stack. This slope is required in order to maintain a relatively constant flow velocity within the collector as the radius, and therefore flow area, decreases; as well as to change the flow direction smoothly as it enters the stack. The height of the collector cover at inlet should be sufficiently high to allow easy access of personal and maintenance equipment, and to produce low air flow velocities underneath collector cover so as to reduce flow losses. However, it should not be too high as this would increase construction costs, as well as negatively affect plant performance in presence of strong external atmospheric winds(Serag-Eldin,2004b). A height of 2.4 m is usually specified.

The results of the Manzanares test facility indicated that currently the preferred cover material is glass; however future material developments may lead to a superior and cheaper plastic membrane.

Close to the chimney stack, the temperature difference across the collector cover may exceed 30 K so that double glazing may be justified there, but not elsewhere. Near the inlet boundaries of the collector the air temperatures are favorable for plant growth, and this area may be exploited for growing or drying crop with negligible effect on performance, particularly since it is also the region with the minimum flow velocities. Indeed in Manzanares considerable wild plants were found to sprout underneath the collector cover, enjoying the green house effect.

3.4 Stack

The chimney stack is the plant's thermal engine. It is a pressure tube with low friction losses because of its very low surface/volume ratio. The efficiency of the Solar Chimney plant, is directly proportional to the height of the stack(Gannon and Backstrom,2000); thus the taller the stack the more efficient the cycle.

The chimney for the Manzanares test facility was constructed from sheet metal for economy purposes; however, full scale plants are expected to employ reinforced concrete structures and are expected to be around 1000 m tall. The life span of a reinforced concrete tower in a dry climate is at least 100 years. All the structural technology is already

available and tested in cooling towers and in building towers such as the 600 m tall television tower in Toronto, Canada. Alternatively, guy tubes, their skin made of corrugated metal sheet, cable-net with cladding or membranes are also possible.

The chimney is likely to be the most expensive component of the solar plant, and hence it is important to try to cut its cost down. Among ideas to reduce chimney cost is one that proposes a "Floating Chimney" (Papageorgiou,2004). Floating solar chimneys are lighter than air structures that can be as tall as 1.5 – 3 km. The wall sub pressure, acting on the main body cylinder of the chimney is handled by the supporting rings made of aluminum, or air inflated pressure tubes. The lifting force comes from a set of toridal tubes filled with lighter than air gas, such as He or NH3. Similar ideas have been proposed by others, e.g. use of vacuumized toroidal rings instead of gaz filled ones (Hamza Associates, 2008). However, questions pose themselves regarding the reliability and life time of such structures, as well as the increased resistance to internal flow when the stack walls are deformed by strong shear winds.

In an attempt to cut chimney stack costs considerably, it was proposed (Serag-eldin,2007) to search for special sites where favorably oriented steep mountains or cliffs may be found close to valleys, and thus the chimney stack would be replaced by a duct running up the mountain/cliff. Figure 10 displays such a geometry for a hypothetical case where the mountain on the right is inclined at 45^0 to a horizontal valley; the turbine(s) were distributed in a horizontal section at the bottle-neck displaying (W.T.). CFD simulation was employed to design the collector and updraft duct for this case as well as to predict plant performance. Notice the diverging duct cross-section in Figure 10 ; this recovers most of the kinetic energy head, thus raising cycle efficiencies. Also notice the shape of the collector which was developed to yield a smooth uniform velocity entry at the turbine. The latter is confirmed from Figure 11 which displays the velocity vectors in a horizontal section below the collector cover.
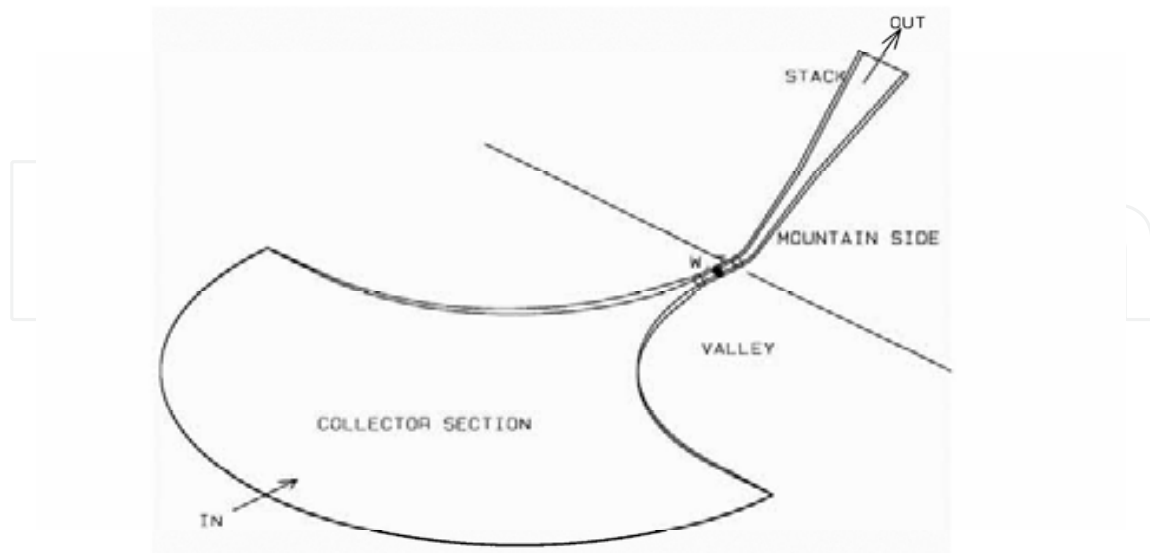

Fig. 10. Exploiting the height of a neighboring steep mountain(Serag-eldin,2007)
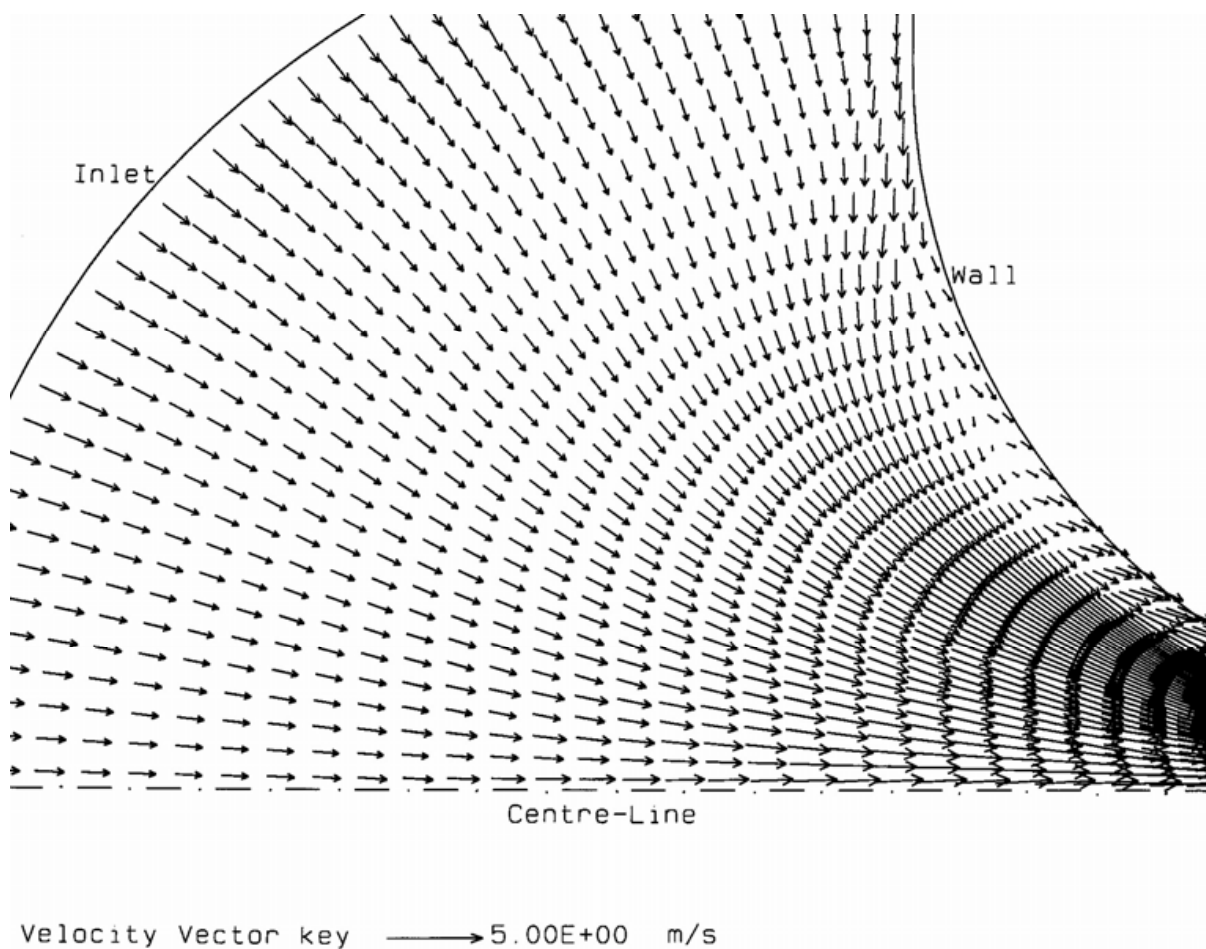
Fig. 11. Velocity vectors in one half of the collector(Serag-eldin,2007)

3.5 Turbine

The turbine(s) produce the mechanical output of the plant. They are pressure staged ones, considerably different than conventional wind-turbines, and more akin to Kaplan turbines employed in hydraulic power stations. Schematically, only a single turbine is always displayed, which is located a short distance up the chimney stack. This is probably for historical reasons, since it was the case for the 50 kW Manzanares plant, because it had relatively low output. However, because of the large dimensions of a full scale 100 – 200 MW plant, it is not possible nor practical to have a single axial turbine of such large diameter (of the order of 100 m).

Thus full scale plants are expected to adopt one of two configurations:

i)   several small vertical axis turbines covering the cross-section of the stack and at a small vertical distance from its base. They would however be independently supported on the ground to avoid structural loads on the stack and vibration problems. Figure 12 displays such an arrangement.

ii)   a ground level array of horizontal axis turbines positioned at equal spacing, along a circle of diameter slightly larger than stack's diameter, as sketched in Figure 13
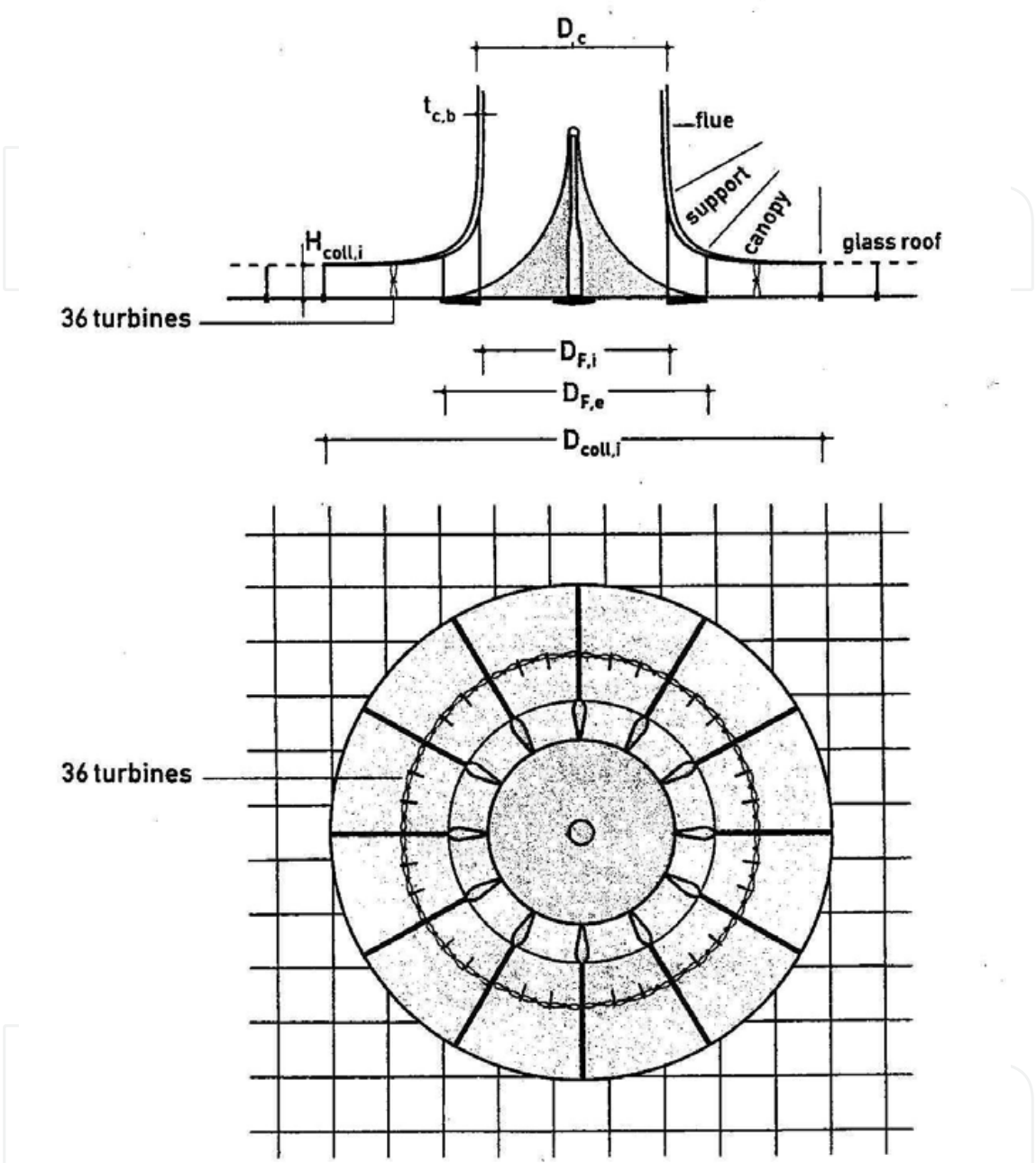
Fig. 12. The 6 vertical axes turbines on a C.S. plane near base of stack(Schlaich, 1995)
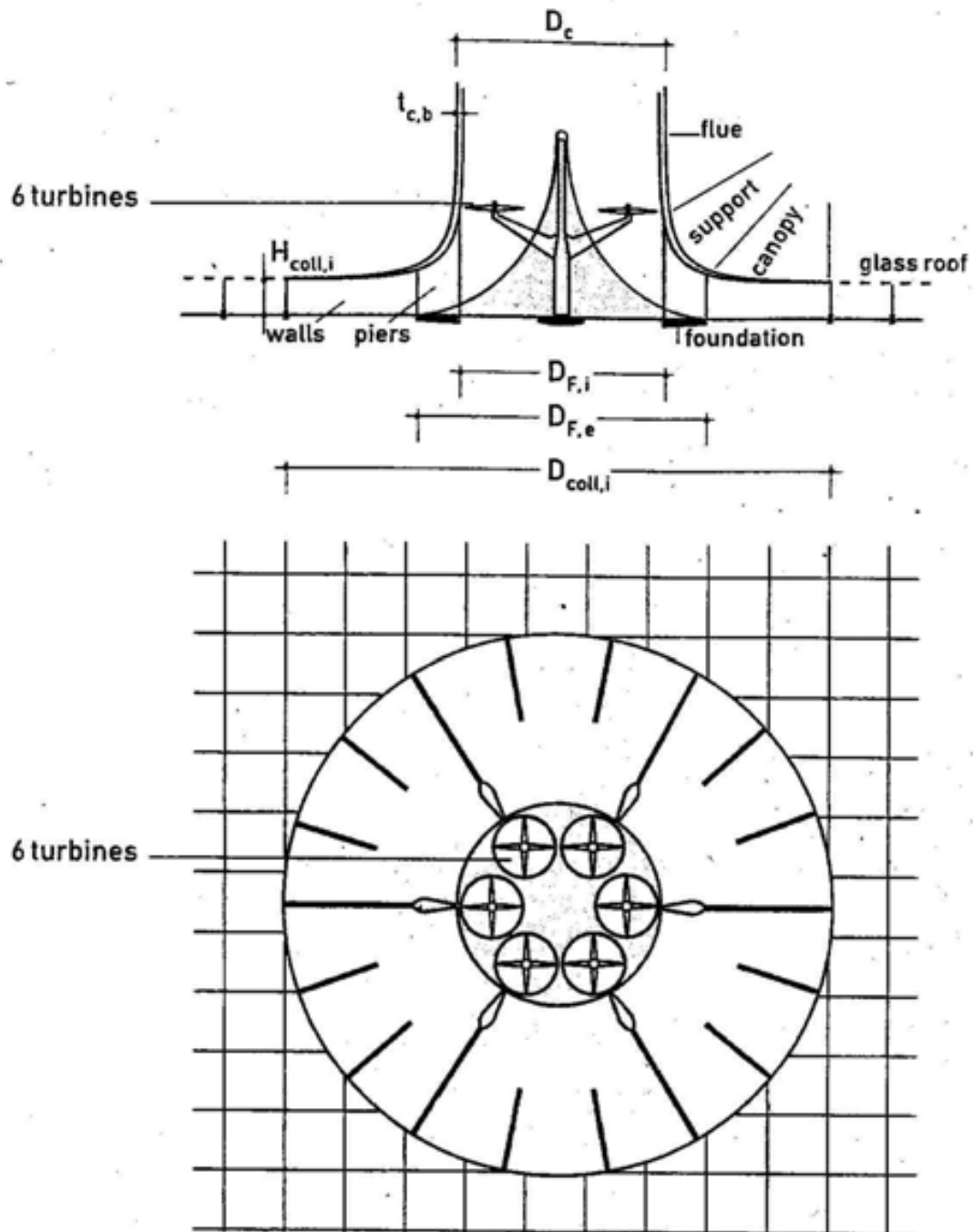
Fig. 13. Arrangement of 36 horizontal axes turbines on the ground(Schlaich, 1995)

The output of each turbine is proportional to product of the volumetric-flow-rate passing through it and the pressure drop across it. Therefore to maximize the output this quantity needs to be maximized. This may be achieved for an installed turbine by regulating the inlet guide vane angles, simultaneously with propeller pitch angle. The exact output of the turbine will depend on the matching of the turbine characteristics with the characteristics of the collector and stack.

The wind turbine characteristics have a strong bearing on the performance of a given solar chimney plant. For example, selecting a turbine with a lower specific-speed results in turbine characteristics with higher head across the turbine for a given flow rate. When this turbine is installed in a given solar plant installation, it will reduce the induced air flow rate because less head will be available to overcome system losses. However, since the power output from the turbine is proportional to the product of the head across the turbine times the volumetric flow rate, the net product may be either greater or lower than that of a higher specific-speed turbine, i.e. one displaying lower head across the system for a given flow rate. Moreover, as the induced air flow rate through the system is decreased, the absorber temperature and air temperature will rise for a given solar intensity. The latter affects system heat losses and pressure head across the stack; both of which will affect the performance of the plant. Thus to obtain the maximum performance from a given solar chimney plant (maximum power output) it is necessary to select the optimum turbine characteristic for a given solar plant characteristics and operating conditions.

As a rule of thumb, the output is maximized if the pressure drop across the turbine is approximately two thirds the total pressure differential available; however for accurate estimates it is necessary to solve the flow equations within the collector and stack coupled with the turbine pressure drop dictated by the turbine characteristics, retaining the full two way coupling between the turbine characteristic and the characteristics of the rest of the system. The results of such a study(Serag-Eldin, 2005b) is presented in Figure 14 which displays the computed variation of velocity in stack, Vstack, plant Output and exit stack temperature, Tstack, for a given system characteristic and solar radiation, and for 9 different turbine characteristics, each result corresponding to a different turbine characteristic. It is clear that the Output curve reveals a maxima, indicating that one of the characteristics is more suitable than others.
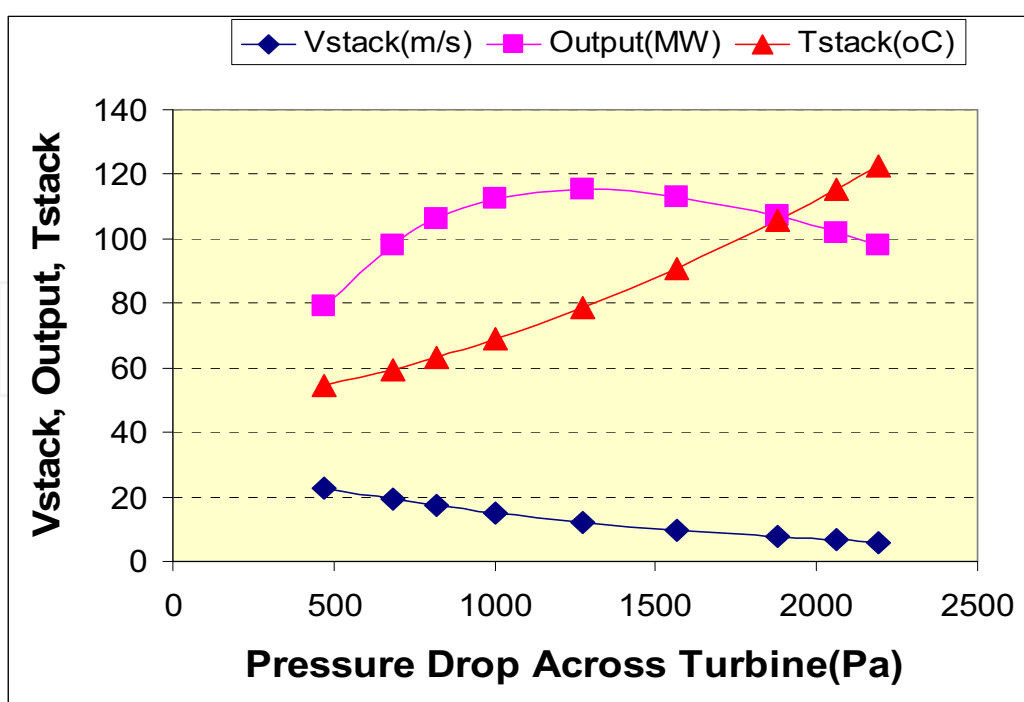

Fig. 14. Effect of turbine characteristic on performance of plant(Serag-Eldin, 2005b).

Some researchers have proposed replacing the array of wind turbines with a circular track carrying carriages supporting individual vertical aerofoil blades of uniform cross-section, spanning the entire height of the collector. The cascade of aerofoil blades rotate as one unit around the chimney center line, producing the plant useful work(Valentine,2008). Independently, others (Menoufy and Serag-eldin,2009) have been designing a somewhat similar wind turbine system with the aerofoil blades replaced by cylinders rotating about their axis. The lift force in this case is derived by the Magnus effect, and can be easily controlled by regulating the cylinder rotational speed. Their system is expected to be much cheaper and easier to build and maintain than conventional propeller turbines.

Turbines inserted in Solar Updraft towers are not subject to gusts, high turbulence, highly fluctuating and non-uniform winds such as wind turbines, nor cavitations such as hydraulic turbines; hence their life span is expected to be longer than both.

3.6 Shape and Size effect, Cost

A CFD computation of a typical solar updraft tower plant (Serag-Eldin,2005a) was conducted to investigate the effect of different geometric ratios on plant performance(Output), velocity in the stack, Vstack, and stack exit temperature, Tstack. The results showed minor influence of the geometric ratios, with the exception of the ratio of stack-height to collector-radius, Hstack/Rcollector, Figure 15 . It was found that the output of the plant increased almost linearly with stack height, all other parameters remaining the same. Increase of stack height also increased Vstack and reduced Tstack.
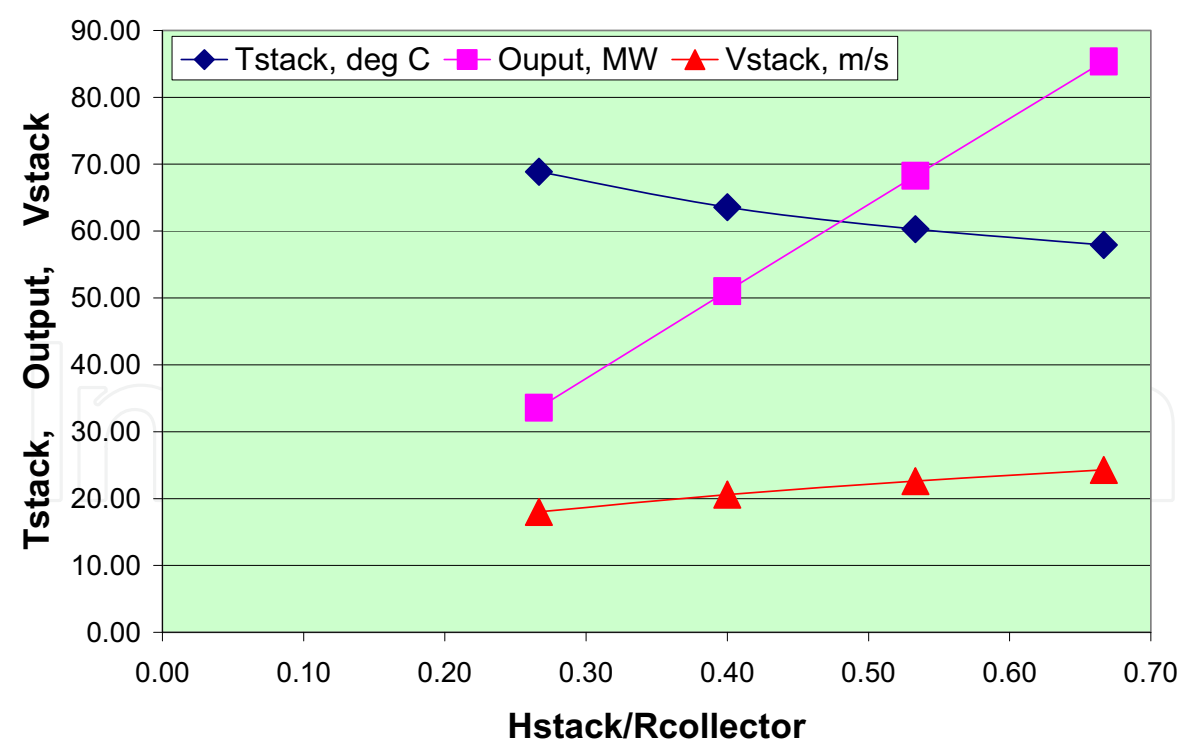

Fig. 15. Effect of stack height on plant performance(Serag-Eldin,2005a)

Investigation of effect of plant size on the Output, Vstack and Tstack was then conducted, retaining same geometric ratios throughout, but increasing the individual dimensions to scale. The results are displayed in Figure 16 with the collector outer radius dimension representing the plant size. It was revealed that the increase in power output with size was at a rate slightly faster than the cube of the size. No wonder economically viable plants need to be of large capacity!
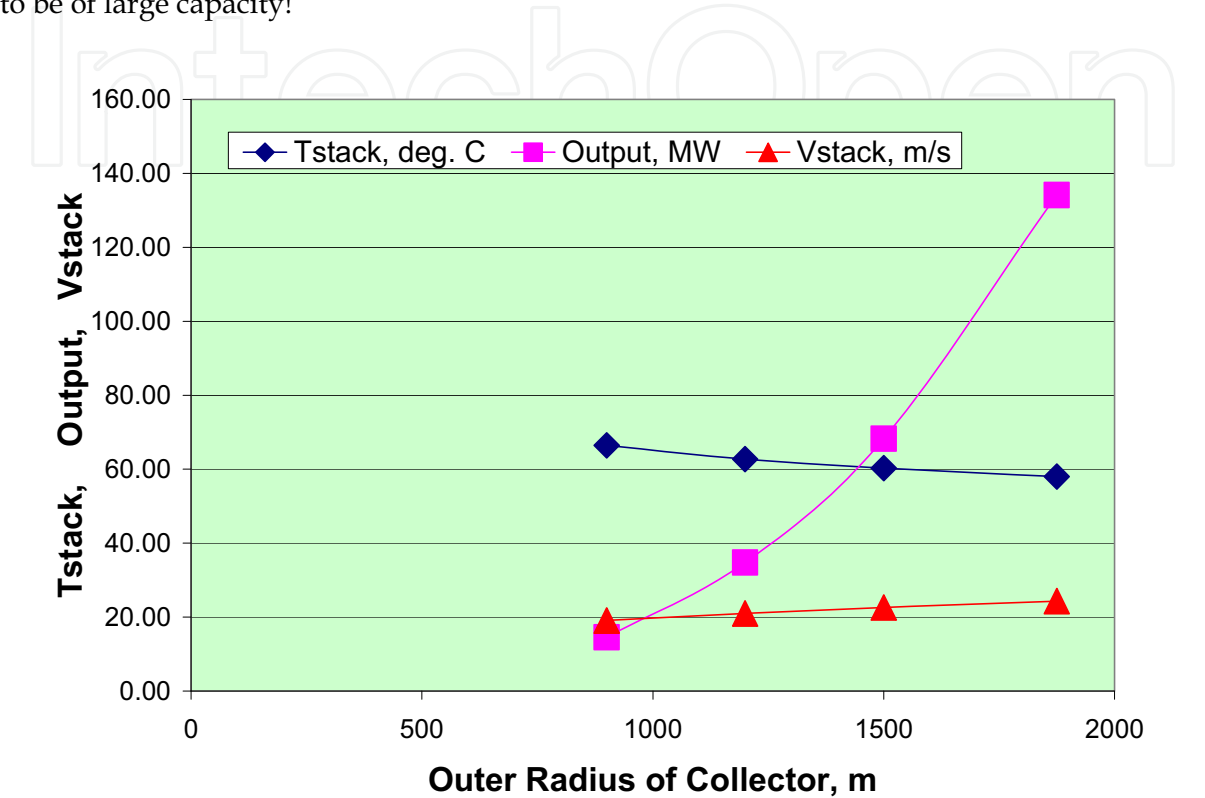

Fig. 16. Effect of Plant size on performance(Serag-Eldin,2005a)

The optimum geometric ratios of a solar updraft tower at a particular site will also depend largely on the relative cost of construction of the collector and chimney stack at this site. This cost may vary appreciably from one site to another; however, just as a global, rough guide, recommended dimensions are presented in Table 1.

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 annual global solar radiation of 2300 kWh/(m²a)					

Table 1. Typical dimensions and electricity output, Schlaich(2005)

In absence of a track record, estimates of electricity generation costs from this technology vary widely; e.g. Schlaich et al(2005) estimate a cost of 7 – 21 € per kWh, while others (Zaslavsky,2006) believe it would be no cheaper than 25-36 cents per kWh. The following

Table is thus useful mainly for comparing relative component costs and trends, and should be accepted with reservation:

Capacity	MW	5	30	100	200
Tower cost	(in million €)	19	49	156	170
Collector cost[A]	(in million €)	10	48	107	261
Turbine cost	(in million €)	8	32	75	133
Engineering, tests, misc.	(in million €)	5	16	40	42
total	**(in million €)**	**42**	**145**	**378**	**606**
Annuity on investment	(million €/a)	2.7	10.2	27.1	43.7
Annual operation & maintenance cost	(million €/a)	0.2	0.6	1.7	2.8
Levelized elelectricity cost (LEC)[B]	**(€/kWh)**	**0.21**	**0.11**	**0.09**	**0.07**
[A] cost for unskilled labor assumed 5 €/h; [B] at an interest rate of 6 % and 30 yrs depreciation					

Table 2. Investment cost and LEC, Schlaich et al (2005).

Table 2 reveals the rapid drop in LEC as plant size increases. It also reveals that the major cost is the tower cost, the only exception being for the 200 MW plant, since it employs the same tower height as the 100 MW plant but a much larger collector area. It is noticed that the source assumed a rate of 5 €/h for unskilled labor; however for many developing countries the cost is substantially lower, whereas the cost of constructing the tower and importing and installing the turbines may be higher, thus shifting the cost distribution.

3.7 Strength and Weakness

Solar updraft towers possess the following strengths:

(a) make use of both direct and indirect solar radiation

(b) possess a large built in thermal storage in the form of the ground underneath the collector. Extending this with a thin layer of scattered water tubes or cushions enhances the ability of the plant to operate at almost constant output 24/7. Thus standalone operation is possible for remote areas not connected to a central electrical grid.

(c) do not need any cooling water to operate

(d) their simplicity makes them particularly reliable and hard wearing, and not prone to sudden shut down

(e) most of the plant is built on the desert site itself employing local labor; thus providing job opportunities in under-developed countries.

(f) requires very few personal to operate

(g) maintenance cost is minimal and should endure the harsh desert environment better than most other technologies.

However, solar updraft towers suffer the following weaknesses:

(a) very low efficiency means it requires a large area of land for collectors

(b) frequent desert storms coupled with long dry spells may reduce efficiency of collectors.

(c) plant may suffer from effect of exceptionally strong external winds, both at ground level and above(Serag-Eldin, 2004b).

(d) tall slender stack is particularly vulnerable to Seismic actions; hence conventional rigid stacks may not be suitable for regions displaying strong seismic activity.

(e) very tall towers may impose construction challenges.

4. Comparison between the solar technologies

The upper limit for the conversion-efficiency of solar-energy into mechanical-energy by all the solar-power-systems, is restricted by Carnot's efficiency, η_c , defined by

$$\eta_c = 1 - T_{sink}/T_{source}$$

where T_{source} and T_{sink} refer to the heat source and sink temperatures, respectively. Carnot's efficiency is only a theoretical maximum. In practice, attainable efficiencies are always considerably less due to system losses and irreversibility effects; however Carnot's efficiency serves to indicate the maximum potential of each system and to give an indication of the relative true efficiencies of real systems. In our applications the heat source temperature is the maximum temperature in the cycle, which is the temperature at the receiver end of CSP systems, and the temperature at the exit from the collector and inlet to stack in the solar updraft tower system. The heat sink temperature is invariably the atmospheric temperature. Therefore it is clear that systems which produce highest concentration of solar energy, and therefore highest heat source temperatures, are the most efficient in converting solar energy into mechanical energy, and vice versa. Table 3 summarizes the typical source temperatures, concentration ratios, C, tracking system type and η_c , for each of the systems presented earlier. The concentration ratio is defined as the ratio between the optically active surface of the collector and the irradiated absorber's surface.

Technology	T_{source} (°C)	C	Tracking	η_c
Solar updraft tower	20-80	1	-	17%
Parabolic trough	260-400	8-80	One axis	56%
Fresnel reflector	260-400	8-80	One axis	56%
Heliostat field w/central receiver	500-800	600-1000	Two-axis	73%
Dish concentrators	500-1200	800-8000	Two-axis	80%

Table 3. Typical Source temperatures, concentration ratios and η_c for solar systems

It is apparent that the solar updraft tower has the least conversion efficiency because it does not provide any concentration what-so-ever; however it is also the simplest system because it does not need any tracking system. The Heliostat and Dish concentrator systems have the highest Carnot efficiencies, but are also the most complicated since they require to track the sun continuously in two planes(2-axis tracking). Fresnel and trough systems require tracking in only one direction and hence both their complication levels and efficiencies lie between the other two categories.

However, since solar energy is free and abundant, efficiency should not be used as the basis for selecting a system. Its impact should be confined to its role in reducing the total cost of solar energy conversion. Thus a less efficient but cheaper system may be the logical choice if its total cost of production of 1 kWh of electricity is lower. The cost of kWh is usually the prime criterion for selection of a system, but other important criteria include environmental impact, sustainability, reliability, durability, ease of maintenance, social returns, creation of local job opportunities, technology transfer, national energy strategy, and whatever other benefits or costs to the society that may result from the particular technology selected.

5. Summary and Conclusion

The review serves to demonstrate that solar energy technologies in the power sector are developing rapidly in several fronts, all of which strive to reduce the cost of energy conversion. This, together with economy of scale when solar energy technologies have spread widely, should pave the way for solar energy plants to gradually replace conventional and nuclear plants whose technologies have already matured so that further improvements are limited, and whose total construction and running costs are escalating.

One major difference between conventional and renewable energy technologies in general and solar in particular, is that the latter are very site specific, whereas the former are not. Thus a desert site may be ideal for a particular type of solar energy technology and totally unsuitable for another. Also the degree of sophistication required to operate and maintain some types of solar technologies is much higher than others, and some technologies are only suited to very large scale applications while others are not; some have built in thermal storage while others require external storage; some are more suitable for standalone mode than others. For each solar energy application we have several options, but it makes a very big difference to the success of the project that the most appropriate technology is the one selected for the given site and environment.

Currently parabolic trough-collectors are the most commonly used and are already cost effective in many parts of the world; the Fresnel mirror adaptation may further cut their conversion costs. However it is the Heliostat towers that are attracting most attention with their promise to yield very high concentrations with the beam-down optics, and ground steam generation.

The solar updraft tower is, at least on paper, a very viable candidate for the desert environment. However it is severely handicapped by the need to start big(minimum 200 MB), costing at least $700 million to be viable. Several projects have started but have either slowed down or stalled. A new project approved in Namibia in mid 2008 to build the largest ever contemplated solar updraft tower (400 MB) will hopefully see the light of day. If this project is implemented and succeeds, the solar updraft tower may turn out to be the black horse for desert environments. Furthermore, for certain favorable sites, the stack cost may be reduced considerably by following one of the suggestions presented here, so that the plant may be viable for plant sizes as small as 50-100 MB.

Finally, when comparing between Solar and conventional energy for electricity generation, it is prudent not to base the decision based on the cost of the kWh produced alone, but to include other important factors such as environmental impact, sustainability, reliability and social benefits.

6. References

Abdel Rahman, E. and Serag-Eldin, M. A. (2009). Energy component of the IDBT project at AUC, 1rst KAUST project Report, January 2009, project coordinator Haroun, M.

Cloete, R (2008). Solar tower sheds light on little-used technology. Engineering News Online. http://www.engineeringnews.co.za/.

Donovan, K. (2004). Hinkley could get world's tallest towers. http://www. solarmissiontechnologies.com/publications/VictorvilleDailyPress

Häberle, A., Zahler, C., Lerchenmuller, H, Mertuis, M., Wittwer, C., Trieb, F., Derch, J. (2002). The Solarmundo line focusing Fresnel collector Optical and thermal performance and cost calculations. http://www.solarpaces.org/CSP_technology/docs/solar paces_fresnel_9_2002.pdf

Gannon, A. J and Von Backstrom, T. W. (2000). Solar Chimney Cycle Analysis with System Loss and Solar Collector Performance. *J.Solar Energy Engineering*, 122,3, pp.133-137.

Gluckman, R. (2002). Smokestacks to the sky. http://www.gluckman.com/SolarChimney/

La Porta, F. (2005). Technical and economical analysis of future perspectives of solar thermal power plants. *Institut für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart*, IER thesis-report, 2005.

Lovegrove, K. And Dennis, M. (2006). Solar thermal energy systems in Australia. *Int. J. of Env. Studies*, Vol. 63, No. 6 , pp. 791-802.

McLaren, W. (2006). Solar Tower Project Pipped at the Post. *http://www.treehugger.com/ files/2006/11/solar_tower_pro.php*

Menoufi, M. and Serag-Eldin, M. A. (2009). Designing Magnus Effect turbines for Solar Chimney Plants. *MSc thesis, AUC,EGYPT;* expected thesis defence October,2009.

Michael, G., Eckhard,L., Osuna,R., Esteban, A., Schiel, W., Schweitzer, A. Eduardo,Z., Nava,P., Langenkamp, J. and Mandelberg, E. (2002). EuroTrough – Parabolic Torough Collector Developed for Cost Efficient Solar Power Generation. *Proceedings of the 11th Int. Symposium on Concentrating Solar Power and Chemical Energy Technologies*, Zurich, Switzerland, Sept 4-6, 2002.

Padki, M. M. and Sherif, S. A. (1999). On a Simple Analytical Model for Solar Chimneys. *Int. J. Energy Research*, **23**, 1999, pp. 345-349.

Papageorgiou, C. (2004). Solar Turbine Power Stations with Floating Solar Chimneys. *IASTED Proceedings of Power and Energy Systems, EuroPES 2004, Conference*, Rhodes Greece July 2004 pp, 151-158.

Pasumarthi, N. and Sherif, S. A. (1997). Performance of a Demonstration Solar Chimney Model for Power Generation. *Proceedings of 35th Heat Transfer and Fluid Mechanics Institute, ed,* Sacremento, Ca, May 29-30, 1997.

Pernick,R. And Wilder, C. (2008). Utility Solar Assessment (USA) Study: Reaching Ten Percent Solar by 2025. *Publisher Clean Edge, Inc. and Co-op American Foundation*, http://www.statesadvancingsolar.org/resource-center/clean-edge-utility-solar-assessment-study.

Schlaich, J. (1995). *The Solar Chimney: Electricity from the Sun* , Axel Menges, ISBN 3-930698-69-2, Stuttgart, Germany.

Schlaich,J. and Schiel, W. (2001). Solar Chimneys, In: *Encyclopedia of Physical Science and Technology*, 3rd edition, Academic press, London.

Schelich Bergermann und Partner. (2002). EuroDish – Stirling System Description: A New decentralized Solar Power Technology. *http://www.1000friendsofflorida.org/Solar /Eurodish -System-Description.*

Schlaich, J., Bergermann, R., Schiel, W. and Weinrebe, G. (2005) Design of Commercial Solar Updraft Tower Systems – Utilization of Solar Induced Convective Flows for Power Generation. *J. of Solar Energy Eng.*, 127, (1), February 2005, pp 117 -124.

Schiel, W. And Geyer, M. (2007). Dish Sterling Activities at Schlaich Bergermann und Partner, *2007 Solar Power Tower, Dish Stirling and Linear Fresnel Technologies Workshop at NREL*, Golden, Colorado, USA, March 7, 2007.

Serag-Eldin, M. A. (2004a). Mitigating Adverse Wind Effects on Flow in Solar Chimney Plants, *Proceedings of 4th International Engineering Conference*, Sharm El Sheikh, Egypt, April 20-22, 2004.

Serag-Eldin, M. A. (2004b). Computing Flow in a Solar Chimney Plant Subject to Atmospheric Winds, *Proceedings of 2004 ASME Heat Transfer/Fluids Engineering Summer Conference,* paper # HT-FED 2004-56651, Charlotte, N.C., July 11-15, 2004.

Serag-Eldin, M. A. (2005a). Analysis of Effect of Geometric Parameters on Performance of Solar Chimney Plants, *Proceedings of 2005 ASME Summer Heat Transfer Conference,* paper #HT2005-72340, San Francisco, Ca, USA, July 17-22,2005.

Serag-Eldin, M. A. (2005b). Analysis of Effect of Turbine Characteristics on Performance of Solar Chimney Plants, *Proceedings of 2005 ASME Summer Heat Transfer Conference,* paper #HT2005-72835, San Francisco, Ca, USA, July 17-22,2005.

Serag-Eldin, M. A. (2006). Analysis of a New Solar Chimney Plant Design for Mountainous Regions. *Advanced Computational Methods in Heat Transfer IX*, ed. Sundén,B. and Brebbia, C. A., WIT press, 2006.

Solel (2007). *http://www.solel.com/products/pgeneration/*

Thomas, M. H. and Davey, R. C. (2004). The Solar Tower: Large Scale Renewable Energy Power Station Development, *Proceedings of 19th World Energy Congress,* Sydney, Australia, Sept. 5-9, 2004.

Swift, G. W. (2002). *Thermoacoustics: A unifying Perspective for Some Engines and Refrigerators* . Publisher Acoustical Society of America .

Valentine, H. (2008). Combining Wind Power with Solar Chimneys. *http://www. energypulse.net/centers/article/*

Von Backström, T. W. and Gannon, A. J. (2000). Compressible Flow Through Solar Power Plant Chimneys. *ASME J. of Solar Energy Engineering*, Vol.122, No.3, pp.138-145.

Wikipedia (2007). Solar UpDraft Tower. *http://en.wikipedia.org/wiki/Solar_ updraft_ tower*

Woody, T. (2006). How Australia got hot for solar power. CNNMoney. *http://money.cnn.com /2006/08/01/technology/*

Zaslavsky, D. (2006). Energy Towers. *PhysicaPlus – Online magazine of the Israel Physical Society*, 7, 2006.

New Trends in Technologies

Edited by Blandna ramov

ISBN 978-953-7619-62-6

Hard cover, 242 pages

Publisher InTech

Published online 01, January, 2010

Published in print edition January, 2010

This book provides an overview of subjects in various fields of life. Authors solve current topics that present high methodical level. This book consists of 13 chapters and collects original and innovative research studies.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Amr Serag-Eldin (2010). New Developments in Large Scale Solar Energy Conversion, New Trends in Technologies, Blandna ramov (Ed.), ISBN: 978-953-7619-62-6, InTech, Available from: http://www.intechopen.com/books/new-trends-in-technologies/new-developments-in-large-scale-solar-energy-conversion

INTECH
open science | open minds