

FLOATING SOLAR CHIMNEY TECHNOLOGY FOR DESERTEC

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Abstract: - Solar chimney technology is a very promising solar thermal electricity generating technology. Solar chimney power plants have three major parts. A large circular greenhouse, a tall cylinder in the center of the greenhouse named solar chimney and a set of air turbines, around or in the solar chimney, geared to appropriate electric generators.

The technology is appropriate for desert or semi desert areas with high solar irradiation and limited strong winds or sand storms. The technology is cost competitive to any other solar technology (PVs or CSPs) and does not demand any water for its operation. Due to the ground thermal storage, the technology it is generating a continuous electric power output 24x365, thus can enter to the electric grid at least up to 50%.

All these benefits are making the FSC technology the most appropriate technology for the desertec project. The desertec project (www.DESERTEC.org) is proposing the construction of a HVDC electric grid, connecting Europe with MENA area. Solar electricity could be generating in MENA area and transmitted to Europe through the HVDC grid. The desertec project is supported by French president Nicolas Sarkozy political initiative for a closer cooperation of MENA countries and EU.

Key-Words: - Floating Solar Chimney Desertec project

1. Introduction

The purpose of this paper is to present the Floating solar chimney (FSC) technology and to give the important benefits of this technology that make it the proper candidate for the Desertec project. According to desertec the huge desert or semi desert areas of the Middle East and North Africa (MENA) countries can be used for solar electricity generation that could be transmitted to European countries through a HVDC grid. The desertec project is supported by

French president Nicolas Sarkozy political initiative for a closer cooperation of MENA countries and EU. The solar chimney power plants are usually referred as solar updraft power plants http://en.wikipedia.org/wiki/Solar_updraft_tower

and their proposed solar chimneys are reinforced concrete structures. A low cost alternative of the concrete solar chimney is the Floating Solar Chimney (FSC) www.floatingsolarchimney.gr. The solar chimney power plants, due to their similarity to hydroelectric power plants, were named by the author Solar Aero Electric Power Plants (SAEPPs).

In the previously mentioned sites there are a lot of references related to the solar chimney technology.

The solar chimney technology was experimentally tested in Manzanares of Spain, where a small prototype of 50 KW was built in 1982 and successfully tested for 6 years, by the team of Prof J. Schlaich. Part of the results by the operation of this small demo is appearing in the book [1] and in the reference [2].

A thermodynamic cycle analysis of the solar chimney power plant operation was given by Prof Backstrom and his associates in a series of papers [3,4, and 5].

Floating solar chimney technology was presented by the author in a series of papers [6,7,8, and 9]. Most recently the author presented a paper [10] for the application of the FSC technology in desert areas of China with adequate horizontal irradiation. Similar desert areas, even with higher solar irradiation, exist in USA, South America, Australia, south and North Africa and India.

It is estimating that with FSC technology, operating on 1% efficiency and using a 2-3% of the existing unused desert or semi desert areas, we can generate at least 50% of the world electricity demand.

In European countries there are places of adequate solar horizontal irradiation but the land is very expensive because there are no desert or semi desert areas. However in the nearby to Europe MENA countries there are huge unused desert or semi desert

areas with appropriate solar characteristics that can be used for solar electricity generation. This solar electricity can be transmitted to the European electric grid through an appropriate HVDC or UHVDC electric grid.

Floating Solar Chimney technology is the appropriate technology for the desertec project, the main reasons are:

a. The technology is cost competitive to any other solar technology. This means that FSC technology can generate electricity in much lower direct cost per produced KW in comparison to any other solar electricity generating technology.

b. The FSC technology is operating continuously (24x365) thus can replace fuel consuming base load power plants in the destination countries.

c. The technology demands no water for its operation, as for example demands the concentrating solar power plants (CSPs) for cleaning and cooling of their mirrors. Clean water is very valuable in desert or semi-desert areas of MENA.

2. Floating Solar Chimney (FSC) technology presentation

A Floating Solar Chimney (FSC) power plant is made of three basic parts:

- A large solar collector with a transparent roof supported a few meters above the ground, open at its perimeter (the greenhouse).
- A tall lighter than air cylinder in the center of the solar collector (the Floating Solar Chimney)
- A set of air turbines geared to appropriate electric generators placed in a circular path around the FSC (the turbo-generators)

The solar irradiation warms the ground below the roof of the greenhouse and consequently the air inside it. The warm air becomes lighter than the ambient air and tends to escape through the solar chimney, up drafting to the upper atmospheric layers. New ambient air is entering in the Greenhouse through its open periphery that, as is moving towards the FSC, becomes warm by the solar irradiation and is also up drafting through the FSC etc. Thus the first two parts of the FSC power plant form a huge passive thermodynamic machine circulating the air from the ground to the upper layers of the atmosphere. In the path of the airflow of the warm air are placed appropriate air turbines, with inlet guiding vanes, geared to electric

generators that transform to electricity a part of the thermodynamic energy of the moving air mass.

The floating in the air, lighter than air, "Floating Solar Chimney" (FSC) is a low cost alternative of the reinforced concrete solar chimney structure. The FSCs can easily be constructed to heights up to 1 Km. The figure (1) is representing the FSC power plant and its operation.

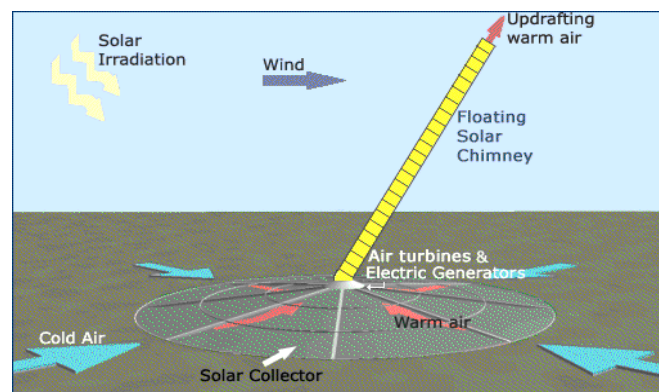


Figure1. Floating Solar Chimney Power Plant in operation

Due to its patented [11] construction the FSC as a free standing lighter than air structure is bending when external winds appear as shown in the figure(2).

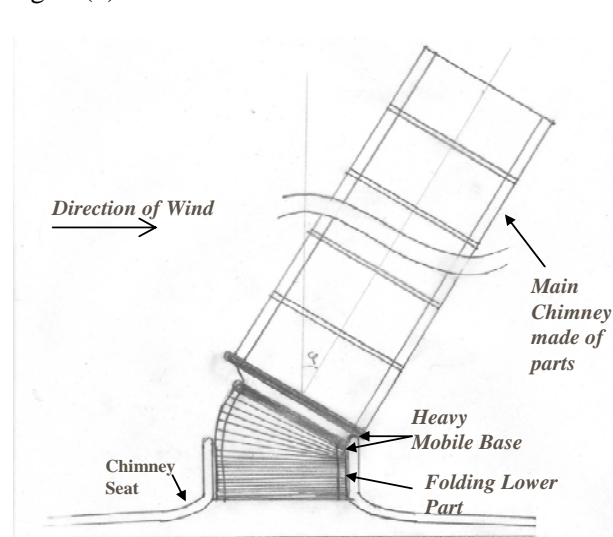


Fig 2. Schematic diagram of the FSC

A small part of this cylinder is shown in the next figure(3).

As shown in the figure the FSC is made by a series of successive tubular balloon rings made of fabric.

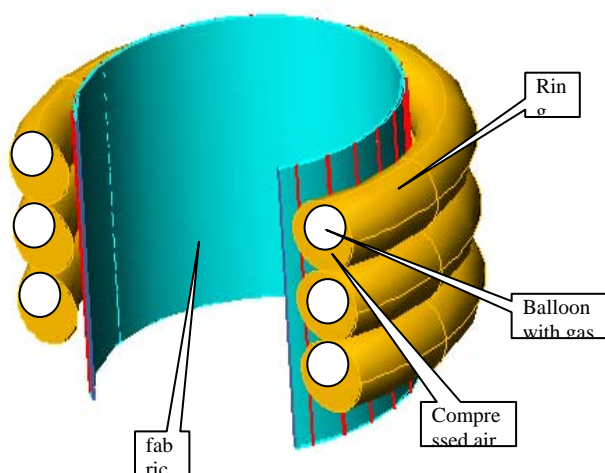


Fig 3. A small part of the fabric cylinder of the FSC

The polyester fabric of the tubular rings and the rest parts of the FSC, is similar to the polyester fabric already used for the construction of air balloons or airships. An extensive presentation of “light” structures is given by Prof Beukers in [11]. These tubular balloon rings can become lighter than air containing special balloons filled with lighter than air gas (He or NH_3). In order to keep the rigidity of the structure the balloon tubular rings should be over pressed with ambient air. Thus the whole fabric cylinder can not be deformed by external winds or by the operational sub pressure and can be a free standing lighter than air structure. Through this free standing cylinder the warm air of the greenhouse is up drafting. When external winds appear the structure is bending due to its inclining special patented heavy base. Of course its up drafting operation is not interrupted by the inclining position of the structure, however the operating height of the solar chimney it becomes smaller. The external winds, for a properly dimensioned FSC, have a marginal effect on its average annual operating height see ref [7].

3. Solar Aero Electric Power Plants (SAEPPs) main characteristics

The FSC power plants named by the author as Solar Aero Electric power plants (SAEPPs) are similar to hydroelectric power plants. In hydroelectric power plants the dynamic energy of the falling water, due to gravity, is partly transformed to electricity through water turbines geared to appropriate electric generators. In the SAEPPs the dynamic energy of the warm air, due to buoyancy, is partly transformed

to electricity through their air turbines geared to their appropriate electric generators. Furthermore both power plants efficiencies are proportional to their heights (falling water height or up drafting air height).

In fig. (4) The annual efficiency of a typical SAEPP is shown as function of its FSC height.

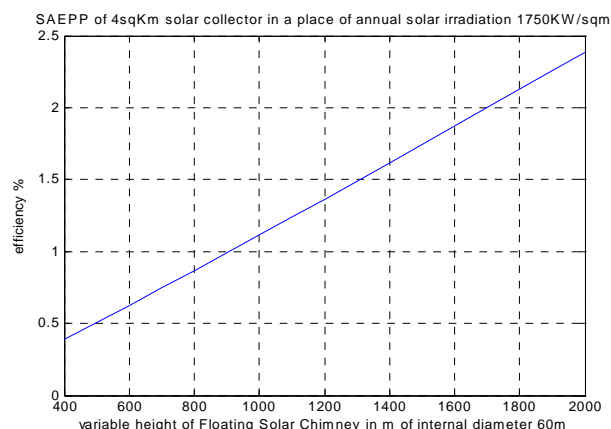


Figure 4. Annual efficiency of a typical SAEPP as function of its FSC height

The annual efficiency is defined as the ratio of the produced electricity in KWh to the annual solar irradiation arriving on the greenhouse roof. For example if in the place of a installation of a SAEPP the annual horizontal irradiation is 2000 KWh/m² and the greenhouse of the SAEPP has a roof of 4 Km² (4 million m²), 8000 GWh/year irradiation solar energy is arriving on its roof. If its FSC height is 900m than approximately by the diagram its efficiency is 1.0 % thus the annual electricity production is 80 GWh/year.

The annual efficiency, see J. Schlaigh in [1] and C. Papageorgiou in [8], can be estimating, as a product of three efficiencies, the efficiency of the greenhouse estimated to 55%, the efficiency of the Turbo generators estimated to 80% and the efficiency of the FSC estimated to 2.6% per Km height of the FSC. That is why the overall SAEPP efficiency for a Km FSC is about 1.15 %.

However by theoretical analysis, not yet published by the author, the greenhouse efficiency is achieved only if there is a double glazing roof. The inner glazing could be made of a thin crystal clear plastic sheet, hanged below the outer strong glazing of the roof. For single glazing roof, as calculated by the analysis of Bernades et al [12] the greenhouse efficiency is not more than 40%.

Due to the ground thermal storage Bernades [12] and Pretorius [13] have shown that the SAEPP can operate all year round 24 hours per day. Typical daily operation curves for an average day of the year is shown in the fig.(5), with and without artificial thermal storage

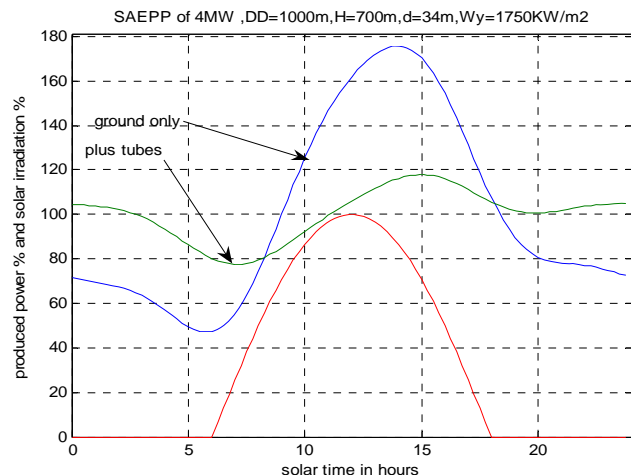


Figure 5. Typical daily production curves of the SAEPP

Care should be taken for the correct evaluation of the inner diameter of the FSC in order the SAEPP to operate properly. For a rough estimation of the proper FSC diameter an air speed inside the FSC of 10 m/sec should be assumed for the summer operation of the SAEPP.

In ref. [6] the author has proposed an algorithm through which the produced average electric power by the SAEPP can be calculated, as function of its mass flow, given the dimensions of the SAEPP and the annual solar irradiation of its place of installation. A short presentation of this analysis is appeared in Appendix I .

An optimal operation of the SAEPP, can be achieved by the proper control of the inlet guiding vanes blade pitch of its air turbines see ref. [5].

4. An optimized FSC technology power plant prototype for the desertec

By the previous description it is evident that the FSC technology power plants (SAEPPs) demands horizontal square lands of several Km² surface areas and floating solar chimneys of high height and proper internal diameters. Following the approximate analysis of appendix I and assuming an average annual solar irradiation of 2000 KWh/m² in

MENA area a cost optimal prototype SAEPP should have the following dimensions:

- A square solar collector of 2 Km side and surface area of 4 Km²
- A Floating Solar Chimney of ~900m height and of 64 m internal diameter (and ~70 m external diameter)
- A set of several air turbines, geared to appropriate electric generators of 20 MW overall rating power output

This SAEPP will generate more than 80 GWh of electricity yearly. The construction cost of this SAEPP will not be higher than 40-48 million EURO. Thus the construction cost per yearly produced KWh is approximately 0.5-0.6 EURO.

The onshore wind turbines they have a similar figure (0.5-0.6 EURO) for their investment cost per yearly produced KWh. Assuming that SAEPPs and onshore wind farms should have almost equal operation and maintenance costs, they should have an almost equal direct production cost per produced KWh. However the SAEPPs are prevailing of wind turbines because they are generating a continuous electric power profile while the wind turbines intermittent.

ACCIONA Energy will build two concentrating solar power plants (CSPs) of 50 MW capacity each, in Palma del Río (Córdoba, southern Spain) The facilities represent an investment close to 500 million EURO and their entry into service is planned for 2010. The CSP plants will produce 244 million KWh per annum. By the figures, the investment cost of the CSP plants is estimated to 2.0 EURO per yearly produced KWh. This means that CSPs will have a much higher direct KWh production cost in comparison to SAEPPs KWh. Furthermore the SAEPPs does not demand any water as the CSPs and are generating a continuous electric power profile while the CSPs intermittent. Thus the superiority of the SAEPPs in comparison to CSPs is obvious.

If the FSC heigh of the model SAEPP will be limited to 250 m, the rating power of the model SAEPP will become ~5 MW, its construction cost ~36 million EURO and its annual electricity generation ~18 GWh (leading to a construction cost of ~2.0 EURO per yearly produced KWh). Even in this case where the construction costs of the SAEPPs and CSPs are the same, the rest benefits of the SAEPPs (no water demand and continuous electric power profile) make SAEPPs superior to the CSPs for desertec and any other similar application.

In an area of 20 Km x 20 Km a farm of 100 similar model SAEPPs can be built generating yearly 8

TWh of electricity with a rating power of 2 GW, that will be available in summer noon.

For Greece, for example, a set of four such farms in appropriate areas, in one or two adjacent MENA countries, could generate and provide to the Greek electric grid, through a set of UHVDC lines, yearly up to 32 TWh (50% of its annual electricity demand) with a maximum power of 8 GW supplied in summer noon of high electricity demand.

However in order to prove the viability and the cost effectiveness of the FSC technology a demonstration SAEPP of 1 MW that could be installed in a south European country is necessary.

5. Initial dimensioning of a demonstration pilot SAEPP of 1MW

For a demo project SAEPP in a south European country the following objectives should be fulfilled:

- Its power rating should be at least one MW producing several million KWh per year in order to prove its importance as a renewable alternative technology.
- Its solar collector surface area should be $\sim 500000 \text{ m}^2$ (50 hectares), in order to prove its low construction cost and its ability to withstand any possible external adverse conditions (strong winds, rain, snow etc).
- Its Floating Solar Chimney should be $400 \text{ m} \div 500 \text{ m}$ high, in order to prove its ability to withstand any external conditions (winds, rain, possibly snow, thunderstorms etc) and its easy handling and maintenance.

Taking all these in consideration a pilot SAEPP should have the following dimensions:

- Solar collector area 0.5 Km^2
- Solar collector roof height minimum 2 m
- FSC height $\sim 450 \text{ m}$
- FSC internal diameter $\sim 24 \text{ m}$ (using lifting tubular balloons of 3 m diameter, its external diameter will be $\sim 30 \text{ m}$)

Assuming that in the area of installation of the demo SAEPP an annual solar irradiation of 1700 KWh/m^2 , an average irradiance $G_{av}=200 \text{ W/m}^2$ is used for the calculating procedure of the appendix I.

The output data of the calculating procedure of appendix I with the previous data are:

- Annual production by the SAEPP $\sim 4.0 \text{ GWh}$
- Rating power of the SAEPP $\sim 1 \text{ MW}$

The electricity production unit could be a set composed of:

- An air turbine of $\sim 22 \text{ m}$ diameter with a rotor of 12-16 blades and inlet guiding vanes (stator)
- A four pole induction generator of 1 MW
- A gear box to adjust the rotating frequency of the air turbine to the grid frequency of estimated transmission ratio $\sim 60 \text{ RPM}/1500 \text{ RPM}$
- An electric transformer of $\sim 1 \text{ MW}$ to adjust the output voltage of the generator to the grid voltage

The demo SAEPP will operate 24 hours per day 365 days per year. If necessary its continuous operation could be secured by a set of tubes filled with water placed on the ground of the inner part of the greenhouse (artificial thermal storage).

The model SAEPP output average daily electric power will be proportional to the daily horizontal solar irradiation in the area, while its daily power profile will have a minimum near the sun rise and a maximum after the noon.

6. Conclusion

In the paper a short presentation of the FSC technology and its respective power plants (SAEPPs) was given.

The SAEPPs demand no water for their operation and produce a continuous electric power profile 24×365 .

Their construction cost per yearly produced KWh is approximately 0.5-0.6 EURO.

In comparison the concentrating solar power plants (CSPs) they have a construction cost of $\sim 2.0 \text{ EURO}$ per yearly produced KWh (four times more expensive than SAEPPs). The CSPs demand water for cleaning and cooling their mirrors and produce a intermittent electric power profiles.

The desertec project is proposing the construction of a HVDC electric grid, connecting Europe with MENA area. Solar electricity could be generating in MENA area and transmitted to Europe through the HVDC grid. The desertec project is supported by French president Nicolas Sarkozy political initiative. By the comparison it is evident that the proper solar technology for desertec project is the FSC technology.

A model SAEPP of 20 MW for desertec and a pilot SAEPP of 1 MW are dimensioned.

The demo SAEPP has enough power output that is necessary in order to prove the cost effectiveness and the advantages of the FSC technology for its large-scale application. Taking into consideration

that there is an urgent demand for solar renewable energy in Europe in order to meet the demands of policies for greenhouse gases elimination, I hope that the proposal demo SAEPP project will be supported by the market and the states in the area.

Appendix I

An approximate procedure for the derivation of the equation describing the operation of the SAEPP i.e. the electric Power Output P as function of the moving air mass flow \dot{m} has been derived by the author in ref [6].

A short presentation of the results of this analysis is given below.

The derived equation is the following:

$$P = C_p \cdot \dot{m} \cdot (T_{03} - C_1 - T_4 - C_2 \cdot T_4^2)$$

Where T_{03} (in $^{\circ}\text{K}$) is the entrance stagnation air temperature in the air turbines and \dot{m} the warm air mass flow in Kg/sec . T_{03} is also the exit air temperature by the solar collector thus can be defined exclusively by the solar collector thermal analysis given the mass flow \dot{m} .

An approximate procedure for T_{03} calculation is given by Shlaigh in ref [1]. An approximate equation relating the exit solar collector air temperature T_{03} to its input air temperature T_{02} valid for the circular Solar Collector is given by:

$$ta \cdot G \cdot A_c = \dot{m} \cdot C_p \cdot (T_{03} - T_{02}) + \beta \cdot A_c \cdot (T_{03} - T_{02})$$

- β is the approximate thermal power losses coefficient of the Solar Collector (to the environment and ground) per m^2 and $^{\circ}\text{C}$ of the temperature difference ($T_{03} - T_{02}$). An average value for β is $\sim 3.8 \div 4 \text{ W}/\text{m}^2/^{\circ}\text{C}$ (for double glazing solar collectors).

- G is the horizontal irradiance on the surface of the solar collector. The average solar horizontal irradiance G_{av} is given by: G_{av} =annual horizontal irradiation in the place of installation of the SAEPP, (in KWh/m^2) divided by 8760 hours

- ta is the average of the product: {roof transmission coefficient for solar radiation X soil absorption coefficient for solar energy}. An average value for the coefficient ta for a double glazing roof is ~ 0.70 .

- A_c is the Solar Collector's surface area.

Thus an approximation for the function $T_{03}(\dot{m})$, is:

$$T_{03}(\dot{m}) = [ta \cdot G / (\beta + \dot{m} \cdot C_p / A_c)] - T_{02}$$

Where T_{02} is, approximately, equal to the ambient temperature T_0 (in $^{\circ}\text{K}$), plus 0.5 degrees (due to ground thermal storage around the Solar Collector).

T_4 is the appropriate root of the polynomial equation:

$$w_1 T_4^4 + w_2 T_4^3 + w_3 T_4^2 + w_4 T_4 + w_5 = 0, \text{ where } w_1, w_2, w_3, w_4, w_5 \text{ are given by the relations:}$$

$$w_1 = C_2^2 (1 - k)$$

$$w_2 = C_2 (2 - k - n_T C_2 T_4')$$

$$w_3 = C_2 C_3 (1 - k) + 1 - 2n_T C_2 T_4'$$

$$w_4 = C_3 - n_T T_4' (1 + C_1 C_2), \quad w_5 = -n_T T_4' C_1,$$

where:

$$C_1 = g \cdot H / C_p, \quad T_4' = T_{03} \cdot (1 - C_1 / T_0)$$

$$C_2 = a \cdot (R \cdot \dot{m} / (A_{ch} \cdot p_4))^2 / (2 \cdot C_p)$$

$$C_3 = T_{03} (n_T - 1) + C_1, \quad A_{ch} = \pi \cdot d^2 / 4$$

$$p_4 = p_0 (1 - C_1 / T_0)^{3.5} \text{ and:}$$

$$R = 287 \text{ J}/\text{Kg}^{\circ}\text{C}, \quad g = 9.81 \text{ m}/\text{sec}^2 \text{ and } C_p = 1005 \text{ J}/\text{Kg}^{\circ}\text{C}.$$

- p_0 is the ambient atmospheric pressure
- η_T is the overall efficiency of the air turbines and generators
- k is the FSC's friction loss coefficient and
- α kinetic energy correction coefficient.

Average values for T_0 and p_0 are $T_0 = 296^{\circ}\text{K}$ and $p_0 = 101300 \text{ Pa}$. A usual value for α is 1.1058.

An average value for η_T is 0.8, for a well-designed air turbine operating around its optimum point of operation.

An average value for k is given by the formula:

$$k = 0.25 + 0.012 \cdot H / d.$$

The necessary data for the calculation of the average Electric Power Output P_{av} as function of mass flow \dot{m} are the following figures:

The average annual solar horizontal irradiation W_y (in KWh/m^2)

And the dimensions:

H = FSC's height in m

d = FSC's internal diameter in m

D_c = Solar Collector's outer diameter in m.

The diameter of the Air Turbines is calculated approximately by the formula:

$$d_{rt} = d / \sqrt{N_{rt}} \text{ where } N_{rt} \text{ is the number of the air turbines around the bottom of the FSC.}$$

The entrance height in the outer diameter of the solar collector is $\sim 2 \text{ m}$ and the inner height of it is not less than d_{rt} . In an inner wall higher than d_{rt} the N_{rt} air turbines are placed with horizontal axis, geared to their respective induction generators, around the bottom of the Floating Solar Chimney. This inner

wall around the FSC should have a diameter bigger than $(d_{rt} \cdot N_{rt})/\pi$.

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