# Floating Solar Chimney Technology Versus Coal Fired Electricity Generation

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ABSTRACT: Floating Solar Chimney (FSC) technology is a solar electricity generating technology. The technology is a low cost version of the solar chimney technology, due to the patented lighter than air solar chimney named Floating Solar Chimney.

The principle of operation of solar chimney power plants is very simple. The sun is warming the air below a large circular greenhouse (made of a transparent roof supported a few meters above the ground). The circular greenhouse is open at its periphery and in its center have a tall cylinder up drafting the warm air below the greenhouse to the upper layers of the atmosphere, while fresh ambient air is entering by its open periphery. Thus the structure is circulating the air as a passive solar machine. On the stream of the moving warm air, inside the greenhouse or the solar chimney, are placed several air turbines, geared to appropriate electric generators, generating electricity.

The FSC power plants are operating 24 hours per day (due to the ground thermal storage) for all the year. Due to this property the FSC power plants can replace coal fired power plants. In the proposed paper a construction, operation and maintenance cost comparison between the FSC power plants and coal fired power plants is presented.

Keywords: Solar Energy Floating Solar Chimney

## I. INTRODUCTION

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 related to the operation of this small demo was published by Prof J. Schlaich [1] -[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]-[ 5].

Floating solar chimney technology was presented by the author in a series of papers [6]-[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, Middle East and India.In south European countries there are places of adequate solar horizontal irradiation for this technology but there are no desert or semi desert areas.

The Floating Solar Chimney (FSC) technology power plants are operating continuously 24 hours per day for all the year. This property is exclusive for this solar technology due to the ground thermal storage below the greenhouses of the FSC power plants, reinforced when necessary by artificial thermal storage. The average daily electricity generation by the SAEPPs is proportional to the horizontal daily irradiation in the place of installation of these power plants.

## II. TECHNICAL INFORMATION

### A. Floating Solar Chimney (FSC) technology presentation

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

A large circular solar collector with a transparent roof supported a few meters above the ground, open at its periphery (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 Greenhouse warms the air inside it, due to the solar irradiation. The warm air becomes lighter than the ambient air and tends to escape though 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 and maintained to heights up to 1 Km.

The figure (1) is representing the FSC power plant and its operation.

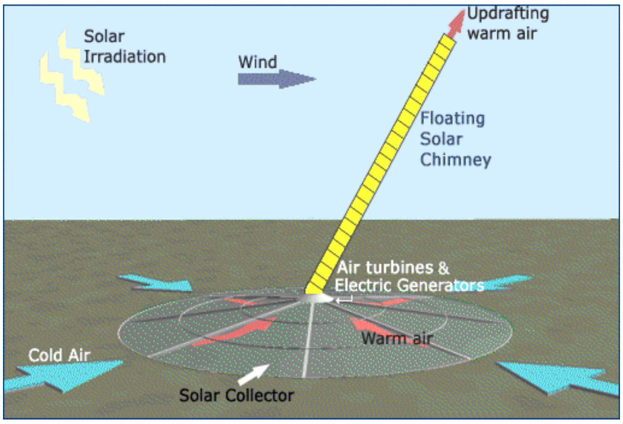


Figure1.Floating Solar Chimney Power Plant in operation

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).

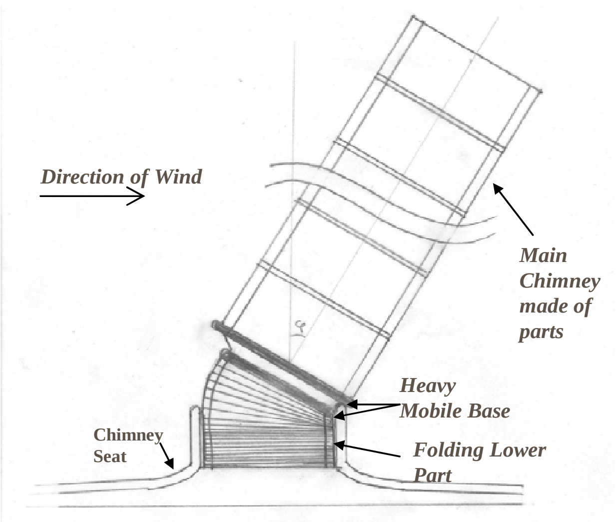


Fig 2. Schematic diagram of the FSC

A small part of this cylinder is shown in figure(3). As shown in this figure the FSC is made by a series of successive tubular balloon rings made of fabric. The polyester fabric of the tubular rings and of 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 [11]. These tubular balloon rings can become lighter than air containing special balloon buoyancy vessels filled with lighter than air gas. In order to keep the rigidity of the structure the balloon tubular rings should be over pressed with ambient air.

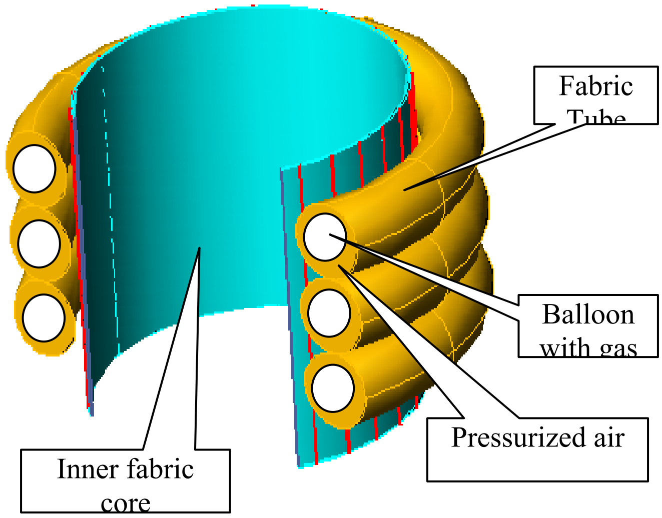


Fig 3. A small part of the fabric cylinder of the FSC

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. Its up drafting operation it 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 [7].

B. Floating Solar Chimney (FSC) power plants 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 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.

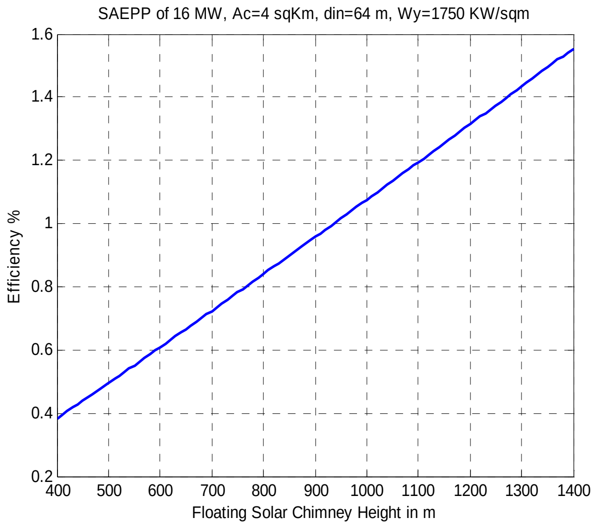


Figure 4. Annual efficiency of a typical SAEPP as function of its FSC height

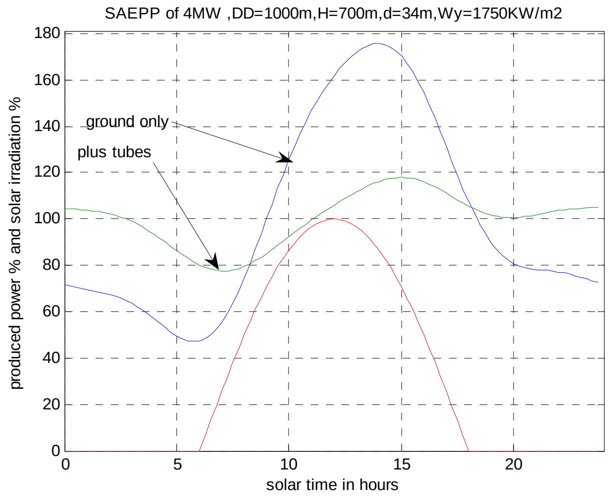


Figure 5. A typical daily production curve of the SAEPP

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 1750 KWh/$m^2$ and the Greenhouse of the SAEPP has a roof of 4 $Km^2$ (4 million $m^2$), 7000 GWh/year of irradiated solar energy are arriving on its roof. If its FSC height is 930m than approximately by the diagram its efficiency is 1.0 % thus the annual electricity production is 70 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 2.5% per Km height of the FSC. That is why the overall SAEPP efficiency for an 930 m FSC is about 1.0 %.

However by theoretical analysis, the Greenhouse efficiency of 55% 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.

Due to the ground thermal storage reinforced by artificial thermal storage in the form of closed tubes filled with water, 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 are shown in the fig.(5)

By the fig.(5) it is evident that the SAEPP with articial thermal storage, producing daily in average 100 units of electricity demands a power producing unit with a rating power of 120 units. Furthermore the typical annual horizontal irradiation curve of a south European country has a 155 % daily summer maximum in comparison to the annual daily average. Taking into consideration that the daily power production of the SAEPP is proportional to the horizontal irradiation, the summer daily average electricity production is 55% higher than the average annual production. Thus in order to estimate the rating of the power producing air turbines and electric generators of the SAEPP (that should be equal to the noon summer power production of the SAEPP) we should multiply, by a factor $1.2X1.55 \approx 1.86$ the average power of the SAEPP. The average power is SAEPP's annual electricity production divided by the 8760 hours of the year. Thus the rating of the air turbines and electric generators can be estimated by the annual electricity production in KWh divided by $(8760/1.86) \approx 4700$ hours. Equivalently this means a capacity factor of ~ 53%.

For the previous SAEPP producing 70 GWh/year, the rating power of its air turbines and electric generators are estimated to 70000MWh / 4700h < 16 MW, thus 16 Turbo-generators of 1MW, in circular path around the FSC can be used.

Care should also 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. For the SAEPP of 16 MW, an internal diameter of 64 m for the Floating Solar Chimney and diameters of 15m for the air turbines are appropriate.

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 [6].

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

C. Floating Solar Chimney (FSC) power plant KWh direct cost comparison to coal fired power plant.

The previously mentioned SAEPP of 16 MW can generate 70 GWh/year if is installed in Cyprus with annual horizontal solar irradiation of 1750 KWh/$m^2$ and should have the following dimensions:
A solar collector of 4 $Km^2$ surface area and a Floating Solar Chimney of height 930m and inner diameter 64m and outer diameter 70m, made of 310 fabric tubes with a small diameter 3m.
The construction cost of the solar collector made of glass it is not more than 32 million EURO (8 EURO/$m^2$), while if crystal clear plastic film is used the cost can be less than 12 million EURO (3 EURO/$m^2$). The plastic film however should be replaced every 4 years with an annual cost of 1 million EURO. The fabric Floating Solar Chimney will have a construction cost not more than 5 million EURO and the air turbines, electric generators, gear boxes etc. will cost approximately 5 million EURO.
Thus the construction cost of the SAEPP with plastic roof will be in the range of 22 million EURO. An array made of 3X3 such SAEPPs in an area of 6KmX6Km, will have an annual production ability of ~630 GWh with a maximum power output of 144 MW and an overall construction cost of ~200 million EURO. This array of SAEPPs it will be equivalent to a coal fired power plant of approximately 90 MW (with a reasonable capacity factor ~80%). Both power plants are generating approximately the same quantity of continuous electricity of ~630 GWh per year.
The annual operation and maintenance cost is estimated to 1.25 million EURO per SAEPP (of which 1 million EURO is the plastic cover replacement) or approximately 11.2 million EURO per year for the array of the 9 SAEPPs.
The average construction cost of a new generation coal fired power plant it is estimated to 135 million EURO (1500 EURO/KW).Thus the capital cost of the coal fired power plant is approximately 67% of the capital cost of the array cost of the 9 SAEPPs.
The coal fired maintenance and operation cost it is estimated to 15 % of the capital cost and its fuel cost it is estimated to 50% of the capital cost [14]. Thus the coal fired overall cost per produced KWh is equal to a capital cost of 165 % of 135 million EURO i.e. approximately the capital cost of 223 million EURO. Estimating the annual capital cost approximately equal to 15% of the capital i.e. 33.5 million EURO, the production direct cost of the coal fired power plant is 33.5 million EURO or ~5.3 cents of EURO per produced KWh.
While the production cost of the array is the capital cost of the 200 million EURO or ~4.7 cents of EURO per produced KWh plus the operation and maintenance cost of 11.2 million or 1.8 cents of EURO per produced KWh, i.e. a direct production cost per produced KWh equal to 6.5 cents of EURO. The land lease it is not included in the cost calculations, considering that most of the land below the greenhouses of the SAEPPs can be used for farming.
Thus the direct production cost per KWh by the array of SAEPPs is higher in comparison to the direct production cost per KWh by the coal fired power plant but the array of SAEPPs produces zero $CO_2$ emissions.
Estimating the $CO_2$ emissions cost, of KYOTO protocol, in 20 EURO/ ton of $CO_2$, the $CO_2$ emissions cost for a new technology coal fired power plant, is approximately 2 cents of EURO per produced KWh, thus the overall coal fired KWh direct cost is 7.3 cents of EURO, or 11 % higher than the direct cost of 6.5 cents of EURO of the array of SAEPPs.
The situation for a country with a higher solar horizontal irradiation (like Israel) is even better. The necessary area of the greenhouse for an annual horizontal solar irradiation of 2150 KWh/$m^2$, for the same annual production of 70 GWh is 3.25 $Km^2$, thus the construction cost of the equivalent power plant is 20 million EURO, the array cost is 180 million EURO and the direct production cost of the produced KWh is not more than 6 cents of EURO.
In case of a coal fired power plant with Carbon Capture and Storage [15] the capital, operation and maintenance costs are increased and its efficiency it is decreased. Thus the direct production cost of KWh is increased at least ~70%, reaching the value 9 cents of EURO per produced KWh This direct cost of KWh of a coal fired power plant with Carbon Capture and Storage is even higher than the direct production cost per KWh of the array of the SAEPPs.
By the previous calculations, a coal fired power plant with Carbon Capture and Storage will have the production cost per KWh of a $CO_2$ emitting coal fired power plant paying at least 40 EURO per ton of emitted $CO_2$ .

D. Conclusion

A comparison of the direct production cost of produced KWh by the Floating Solar Chimney power plants and coal fired power plants was given. Under reasonable estimations the Floating Solar Chimney power plants are cost competitive to coal fired power plants with or without Carbon Capture and Storage. Both technologies are generating continuous electricity and they can replace each other.
The FSC power plants are using more land, but this land partially can be used for farming. The FSC power plants are not demand any water for their operation and they are not producing any local environmental pollution.
Taking into consideration that coal electricity generation is the cheapest electricity generation technology, the FSC technology is a very interesting renewable proposal. However a demo FSC power plant at least of 1MW is necessary to be built, in order to prove that the technology is operating, its power plants are cost effective and the lighter than air fabric structure Floating Solar Chimney can encounter external winds.

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## IV. BIOGRAPHIES

Prof. Christos D. Papageorgiou (19/04//1943)
1. Studies
1961-1966 Electrical and Mechanical engineer of National Technical University of Athens (NTUA).
1976-1979 Obtained his PhD by the Imperial College of London University
2. Academic carrier
1970-1976 Professor in the Technological University of Piraeus
1979- Associate Prof in the School of Electrical and Computer Engineering of National Technical University of Athens
in "Electromechanical Systems of Thrust and Power".
3. Most Important Management activities
-In his professional carrier held several top managerial positions the most important of which were:

- 1981-1983 Deputy president of HELLENIC RAILWAYS (O.S.E.)
- 1983-1985 Chairman and president of OLYMPIC AIRWAYS
- 1986-1987 Chairman of PYRKAL (the major Greek defense industry)
- 1988-1989 Managing director of HELLENIC RAILWAYS (O.S.E.)
- 1994-1995 Chairman of "GENERAL WAREHOUSES" OF NATIONAL BANK OF GREECE
- 1996-1997 Chairman of HELLENIC RAILWAYS (O.S.E.)

4. Research and academic interests

- Inventor of the "Floating Solar Chimney" (Patented on 2003)
- Research on the Solar Chimney technology (www.floatingsolarchimney.gr )

- His academic interests are including:

- Renewable energy
- Electromagnetism and Quantum Mechanics