FLOATING SOLAR CHIMNEY TECHNOLOGY SCALE ANALYSIS

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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 greenhouse, a tall cylinder in the center of the greenhouse named solar chimney and an air turbine inside the solar chimney, geared to appropriate electric generators. Floating Solar Chimney (FSC) is a low cost alternative of the concrete solar chimney. The Floating solar chimney, as a lighter than air structure, can be raised anywhere and its cost is as low as 2% of the cost of the respective concrete chimney.

Our approach includes a low cost greenhouse that can be used in FSC technology, which is also a low cost alternative to the usual glass roofed circular greenhouse related to the concrete chimney. This plastic covered low cost greenhouse could solve also the ingress of dust, which is a problem that could be a serious obstacle in desert installations of the FSC technology. Furthermore according to the construction cost and the electricity generation figures, we present a scale analysis of the FSC technology. Even with moderate height FSC structures of 650m, is possible the direct production cost to be approximately 45 USD/MWh.

The unused mid-latitude desert or semi desert lands of high solar radiation in many countries in all the continents can be used for large-scale application of Floating Solar Chimney technology securing sustainability and mitigating global warming effects.

KEY WORDS
Floating Solar Chimney scale effects

1. Introduction
The purpose of this paper is to present solar chimney technology scale effects. 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 (SAEPs).

In the previously mentioned web 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, under 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 Prof Papageorgiou in a series of papers see for example [6, 7]. Bernades M.A. dos S., Vob A., Weinbre G. introduced the first time varying thermal performance of solar chimney technology in [8]. Pretorius J.P., Kroger D.G [9] use a different mathematical approach for their solar chimney performance analysis. Johannes P. Pretorius in his PhD dissertation includes an excellent presentation for solar technology [10].


2. Floating Solar Chimney (FSC) technology operation
A Solar Chimney power plant is made of three basic parts:
• A large circular solar collector with a transparent glassed roof supported a few meters above the ground, open at its periphery (the Greenhouse).
• A tall concrete cylinder in the center of the solar collector (the 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 chimney, becomes warm by the solar irradiation and is also up drafting through the chimney, etc.

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, geared to electric generators that transform a
part of the thermodynamic energy of the moving air mass to electricity.
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 600-700 m. Due to its patented [11] construction the FSC is a free standing lighter construction than air structure and behaves like bending when external winds appear, as shown in the figure (1).

![Fig 1. Figure of the FSC](image1)

A small part of this cylinder is shown in the next figure. As shown in the figure the FSC is made of:
- A fabric core reinforced by very strong aramid belts.
- A set of successive non compressed lifting tubes made of HDPE or BOPET film filled with lighter than air gas
- A set of strong plastic (BOPET) supporting rings over pressed with ambient air in order to keep the rigidity of the fabric structure

The lifting and supporting tubes can be placed inside the fabric core.

![Fig 2. Sectional view of the fabric cylinder of the FSC.](image2)

The whole fabric cylinder cannot be deformed by external winds or by the operational sub pressure and can be a free standing lighter than air structure. The warm air of the greenhouse is up drafting through this free standing cylinder. When external winds appear, the structure is bending due to its inclining special patented heavy base. The up drafting operation is not interrupted by the inclining position of the structure. The external winds, for a properly dimensioned FSC, have a marginal effect on its average annual electricity generation.

The construction cost of a FSC can be calculated by the formula:

$$FSC_{cost} = 25 \cdot H \cdot d \text{ (USD)}$$

where H is the height in meters, and d is the external diameter in meters.

The concrete chimney cost up to 600m is 50 times more expensive, given by the formula:

$$Concrete\ Chimney_{cost} = 1250 \cdot H \cdot d \text{ (USD)}$$

The FSC fabric structure should be replaced every 6-8 years and the annual cost related to its replacement is \( \sim 0.15 \cdot FSC_{cost} \text{ USD/year} \).

### 3. A low cost greenhouse for FSC technology

The ordinary glassed roof circular greenhouse is a rather expensive structure with major problems by the dust in desert solar chimney applications. The estimated construction cost for double layered structure is not less than 10.0 USD/m². The proposed patented pending plastic layered, low cost alternative greenhouse [10] as shown in the next figures has a cost of not more than 2.5 USD/m².

This low cost alternative greenhouse, named desert solar collector, is a rectangular structure made by a set of parallel reversed U tunnels.

The presented greenhouse can solve the dust problem related with desert applications of FSC technology. The plastic covers should be replaced every 3-4 years and the annual cost related to the plastic replacement is \( \sim 0.25 \cdot A_c \text{ USD/year} \), where \( A_c \) is the active surface area of the greenhouse.

The tunnels are warming the air and lead it to a closed corridor of adequate dimensions connected to the base of the FSC as shown in the next figures.

### 4. Solar Aero Electric Power Plants (SAEPs) main characteristics

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

The annual efficiency, see J. Schlaigh in [1] and C. Papageorgiou in [8], can be estimating, as a product of three following efficiencies: The efficiency of the double layered greenhouse which is estimated to 50%, the efficiency of the air turbines and electric generators which is estimated to 80% and the efficiency of the FSC which is estimated to:

$$\eta_{FSC} = \frac{0.9 \cdot g \cdot H}{c_p \cdot T_0} \approx 3\%$$

Due to the ground thermal storage Bernades [12] and Pretorius [13] have shown that the SAEP can operate all year round 24 hours per day. A typical daily operation curve for an average day of the year is shown in the figure (5).

Figure (6) evident that the SAEP produce in daily average 100 units of electricity, in a power producing unit of rating power of 180 units. Furthermore, the typical annual horizontal irradiation curve has a 133% daily summer maximum in comparison to the daily maximum annual average. Thus in order to estimate the rating of the power producing air turbines and electric generators of the SAEP (that should be equal to the noon summer power
production of the SAEP) we should multiply, by a factor 1.80X1.33 ≈ 2.4 the average power of the SAEP. This average power is SAEP’s annual electricity production divided by the 8760 hours of the year. The rating of the air turbines and electric generators can be estimated by the annual electricity production in kWh divided by (8760/2.4) ≈ 3660 hours.

We should consider the correct evaluation of the inner diameter of the FSC in order the SAEP to operate properly. For a rough estimation of the proper FSC diameter an air speed inside the FSC of 8-10 m/sec should be assumed for the summer noon operation of the SAEP. The cost of the caged air turbine, gear box electric generator, electric transformer cabling and switchgears is estimated for FSC technology to 400 USD per rating kW of the SAEP.

In order to estimate the direct production cost of the electricity generated by the FSC SAEPs we will use the following formula:

\[ C_{el} = \frac{C_{inv} + C_{opm} + C_{plfa}}{E_{an}} \]

where:
- \( C_{el} \) is the production cost in USD/kWh
- \( C_{inv} \) is the total investment cost in USD
- \( C_{opm} \) is the operation and maintenance cost in USD
- \( C_{plfa} \) is the plastic and fabric replacement cost in USD
- \( E_{an} \) is the annual produced electricity in kWh

For an economic lifetime of 30 years and 6% interest rate the Investment cost is Investment x 7.265%. The Operation & Maintenance cost is approximately 1% on the Investment.

The annual electricity generation \( E_{an} \) by a FSC technology SAEP is approximately calculated by the formula:

\[ E_{an} = \frac{I_{an} \cdot A_c \cdot \eta_{av}}{100} \]

where:
- \( E_{an} \) is the annual electricity generation in MWh
- \( I_{an} \) is the Annual Horizontal Solar Irradiation in MWh/m²
- \( A_c \) is the greenhouse area in Acres
- \( \eta_{av} \) is the annual efficiency

The rating power of the SAEP in MW is calculated by the formula:

\[ P_R = \frac{E_{an}}{3660} \]

5. Scale Analysis of the FSC technology

Using the previous approximate relations we have calculated the geometric, operational and cost figures for SAEPs as functions of their rating power.
The FSC technology does not demand any water or fertile land fields. Using a small part (5%) of the existing desert or semi desert unused land fields in all continents we can generate 50% of their electricity demand securing their sustainable development and decreasing the CO₂ emissions below any safe threshold for our planet.

A small demo of 125 kW with a FSC of H=200m and diameter d=13.5 m (external 16 m) and Aₙ=100,000 m² should cost less than 1,000,000 USD and can prove the validity of the FSC technology.

6. Conclusion

The presented scale analysis proves that the FSC technology, even with moderate FSC heights, can become cheaper than all the rest electricity generation technologies, including renewables and non renewables. Furthermore, the daily power profile of the FSC technology is uninterrupted and close to the demand profile, thus the FSC technology can be considered as baseline electricity generation technology.

References