Solar Driven Wind Turbines – an alternative configuration for the solar chimney of modest height and high efficiency

Abstract

The solar chimney has a cylindrical chimney of about 1000 m height at the centre of a solar collector of area up to 20 km^2. Turbines at the base of the chimney harness the kinetic energy of air flow. The overall efficiency is 2 – 3%.

An alternative configuration is proposed with an annular (ring-shaped) chimney of modest height forming the outer circumference of the solar collector. This provides the chimney with a very large cross-sectional area. Turbines are symmetrically sited around the inner circumference of the solar collector to harness the kinetic energy of incoming air flow. The total area of cross-section of the turbines is severely restricted. In this way air flow velocity through the turbines is a considerable multiple of its velocity through the chimney. Efficiency is multiplied by the square of this multiple.

Calculations have been carried out for a range of dimensions from height 200 m down to height 3 m with maximum output ranging from 174 MW down to 3 KW. An experimental model is suggested of chimney height 10 m and outer diameter 25 m. This gives maximum output 127 KW with an efficiency of over 40%.

The author asks experts on the solar chimney to carry out a theoretical assessment of the proposals and to build, study and improve on the experimental model suggested. The configuration described could provide electricity from solar energy on a large scale with 40 – 50% efficiency.

Introduction

The solar chimney first developed by Schlaich et al. [1, 2] has been the subject of hundreds of papers over the last 40 years. It involves a solar collector of area up to 20 km^2 and a chimney height about 1000 m with turbines at its base to harness energy from the air flow. It is calculated that a solar chimney of such dimensions will generate up to 200 MW electricity with an efficiency of 2 – 3%. There are excellent recent reviews of the solar chimney by Al-Kayiem and Aja [3] and Guo et al. [4].

The present author has suggested an alternative configuration involving an annular (ring shaped) chimney sited on the outer circumference of the solar collector. Electricity generation is from incoming air flowing through wind turbines sited symmetrically on the inner circumference of the solar collector [5]. The annular chimney suggested allows a much larger chimney cross-sectional area. Also, by restricting the total area of cross-section of the turbines, the velocity of air flow through the turbines is multiplied. In this way the alternative configuration can achieve high efficiency (40 – 50%) with a much lower height of chimney (200 m).

The proposals elaborated in the previous paper were developed with large installations in mind to generate 100 – 1000 MW [5]. In this paper the size of the configurations considered is reduced in stages from height 200 m to height 3 m with maximum output reduced from 100 MW to 100 KW in the experimental model proposed. Dimensions have been devised with a target efficiency of 50% in each case.

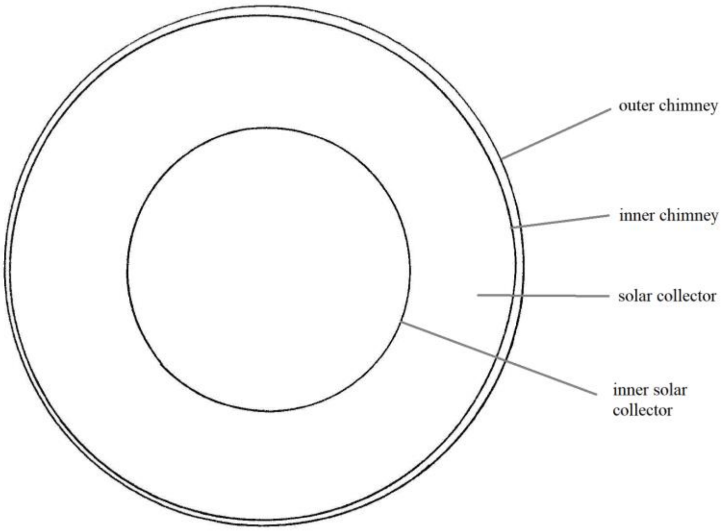

Figure 1 (aerial view)

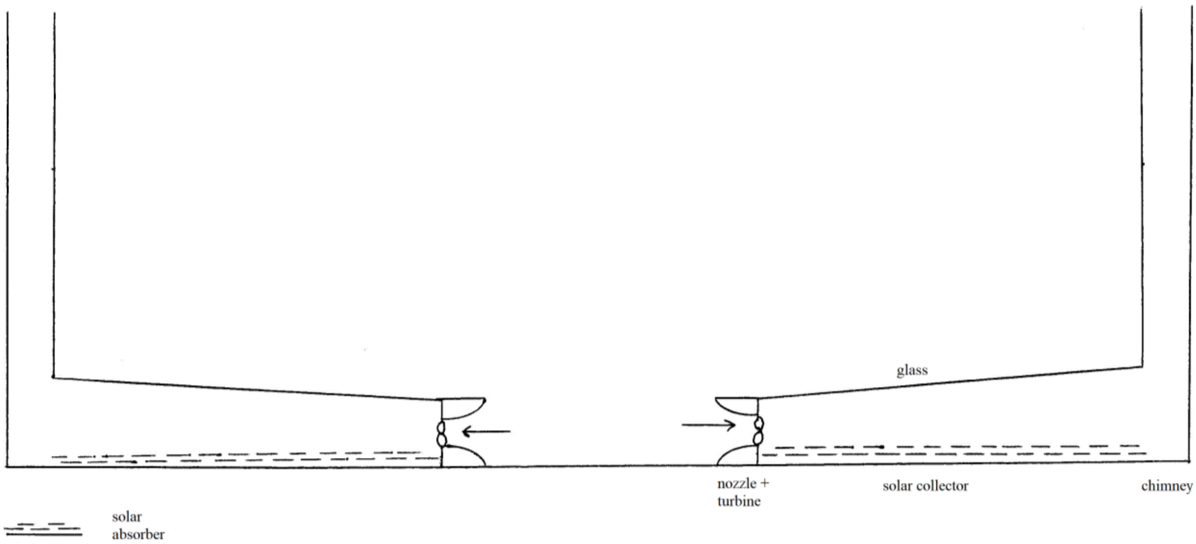

Figure 2 (transverse section)

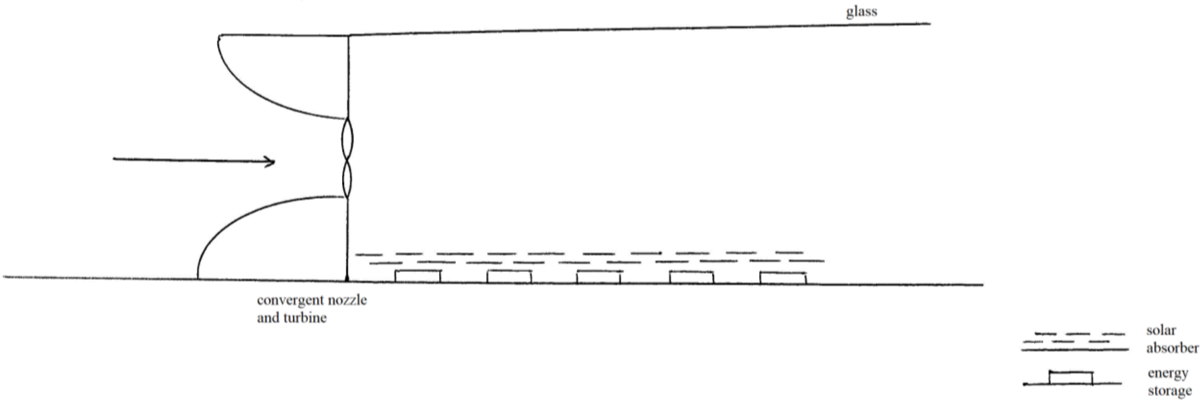

Figure 3 solar collector (entrance)

Alternative Configuration

The alternative configuration is elaborated in Figures 1 – 3. The overall structure has three concentric circles. The outer two circles form an annular chimney with the outer wall of strong construction and solid to ground level. The inner wall is of lighter structure with the bottom quarter standing on legs to allow air flow into the chimney. It is also secured by cables to the outer wall for support and stability.

The inner circle represents the entrance to the solar collector with wind turbines distributed symmetrically around the circumference. Each turbine is sited at the throat of a convergent nozzle which allows acceleration of incoming air to high velocity. It is suggested that the diameter of the mouth of the nozzle should be three times the diameter of the throat. This would mean that the velocity of air flow at the mouth of the nozzle is one ninth of its velocity through the turbine.

The area from the inner circle to the inner chimney forms the solar collector. It has a transparent roof, double glazed with high transmission glass and is air tight. The floor of the collector is covered with a solar absorber. This is metallic, coated with highly efficient absorber paint, multi-layered and of very open structure to allow easy through flow of air and rapid heat transfer.

The central area of the configuration is empty to allow access of ambient air from above to flow into the turbines. This area also provides space for electrical equipment and access to the turbines and solar collector for maintenance.

At night, when there is no solar energy, the configuration is inert. As the sun rises, the absorber takes up solar energy warming air in its neighbourhood, which rises. A convection current is established with warm air rising from the solar collector into the chimney drawing ambient air to replace through the wind turbines. The velocity of the air flow through the chimney depends on its excess temperature and on the height of the chimney. The velocity of air flow through the turbines is a multiple of the velocity through the chimney. This multiple is the ratio of the cross-sectional area of the chimney flow to the total area of the turbine flow.

Output of the turbines is directly proportional to insolation. From zero at night, output rises continually from dawn to a daytime peak and diminishes to zero from evening to night. All changes should be smooth and continuous. Energy storage can be added using water tubes at ground level underneath the solar absorber [2]. This allows daytime solar energy to be stored for electricity generation in the evening and at night.

Theoretical Development

Consider that in Figure 4

h	height of chimney
A_1	area cross-section of chimney
A_2	total area cross-section of turbines
A_3	area solar absorber
v_1	velocity of air flow through chimney
v_2	velocity of air flow through turbines
T	ambient temperature
ΔT	excess temperature (above ambient) of exit air
$\Delta T'$	fall in temperature as air flows through turbines
g	gravitational constant
ρ	density of air at atmospheric pressure and temperature T
C_p	heat capacity of air at constant pressure and temperature T
I	insolation

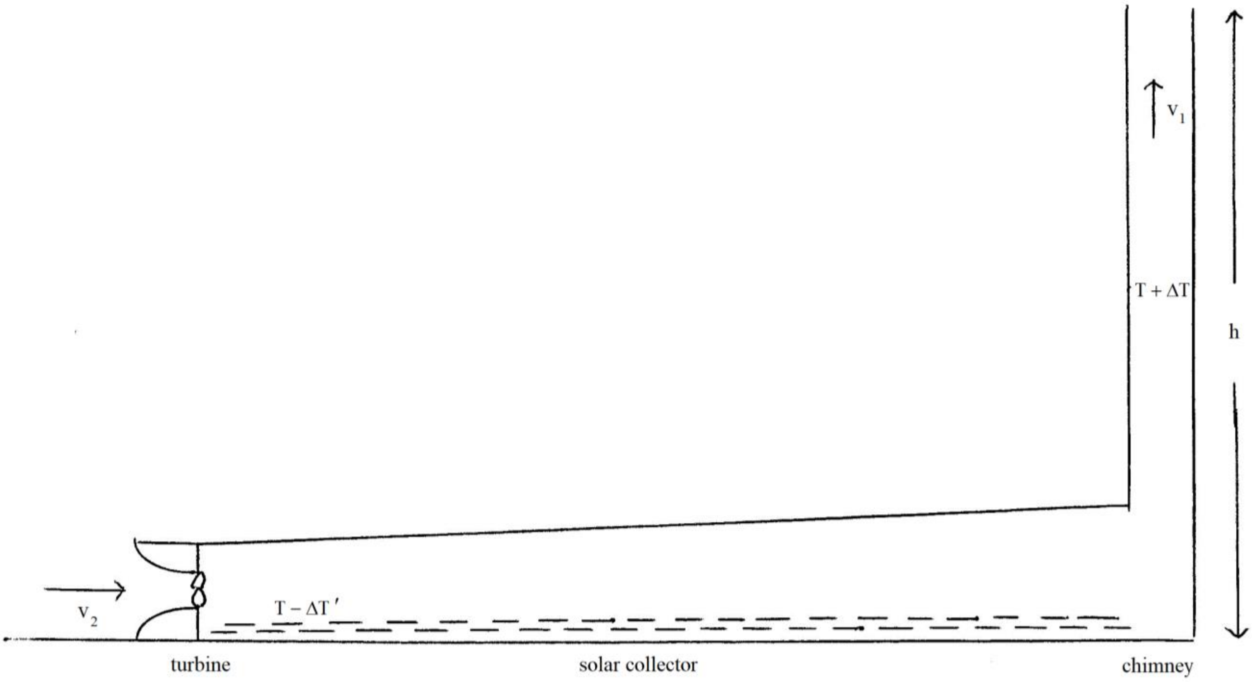

Figure 4 (radial section)

The velocity of air through the chimney is given by the solar chimney equation [1, 2]

$$v_1^{\,2} = 2\,\frac{\Delta T}{T}\,gh \qquad (1)$$

Assuming little change in density, constant mass flow requires that

volume flow rate through chimney = volume flow rate through turbines

$$A_1 v_1 = A_2 v_2 \qquad (2)$$

As incoming air is accelerated through the convergent nozzles the gain in flow kinetic energy is at the expense of internal energy and causes a fall in temperature $\Delta T'$

gain in kinetic energy = mass flow x heat capacity x fall in temperature

$$\tfrac{1}{2}\,\dot{m}\,v_2^{\,2} = \dot{m}\,C_p\,\Delta T'$$

where $\dot{m}$ is the mass flow. It is assumed that the turbines take up ALL of this kinetic energy.

$$v_2^{\,2} = 2\,C_p\,\Delta T' \qquad (3)$$

As incoming air flows through the solar collector, solar energy taken up by the absorber raises the temperature of the air flow from $\Delta T'$ below ambient to ΔT above ambient.

total solar energy absorbed = mass flow x heat capacity x temperature rise

$$I\,A_3 = \rho\,A_1\,v_1\,C_p\,(\Delta T + \Delta T') \qquad (4)$$

If we consider equations (1) – (4) they contain 8 variables h A_1 A_2 A_3 v_1 v_2 ΔT $\Delta T'$ and 5 constants T g ρ C_p I. If 4 of the variables are fixed the algebra is soluble. Thus any number of possible dimensions can be investigated.

A formula for good efficiency

Schlaich et al. [1, 2] find that the efficiency of a solar chimney is given by

$$\eta = \frac{gh}{C_p\, T}$$

Thus to achieve 100% efficiency with a cylindrical solar chimney requires a height of

$$\frac{1005 \times 300}{9.81} \sim 30{,}000 \text{ m}$$

This is in line with the prediction that a 1000 m height cylindrical solar chimney will have a maximum efficiency of about 3% [1, 2].

The present author [5] argues that when there is venturi multiplication between the cross-sectional area of the chimney (A_1) and the turbines (A_2) velocity through the turbines is multiplied by A_1/A_2 and efficiency by $(A_1/A_2)^2$.

Thus to achieve high efficiency with the present model requires

$$h\left(\frac{A_1}{A_2}\right)^2 \sim 30{,}000$$

This formula has been used as a guideline to help devise dimensions for good efficiency in the configurations considered in this paper.

Slenderness Ratio

Guo et al. [4] draw attention to the importance of the chimney slenderness ratio (SR) which is the ratio of the chimney height to its diameter to maintain good flow in a solar chimney. They suggest an optimum SR of 6 – 8. This guideline has also been followed.

Calculations for Model Configurations

Model configurations have been devised with chimney height ranging from 200 m for the largest, down to 3 m for the smallest experimental model. The diameter of the inner and outer solar collector and the chimney have been reduced in proportion and consistent with the guidelines above. The number of turbines, their diameter and the total cross-sectional area of the turbines have also been adjusted as best fit within the guidelines.

Calculations have been presented in full for the model of height 200 m in the earlier paper [5]. Calculations for the proposed experimental model of height 10 m are presented in the next section. The full results are presented in Tables 1 and 2.

chimney height	200	150	100	70	50 m
diameter outer chimney	1000	500	300	200	150 m
diameter inner chimney	960	470	280	188	142 m
diameter inner collector	600	200	100	80	70 m
turbine diameter	10	10	6	4	3 m
number of turbines	60	20	18	14	10
collector height	30-50	30-40	18-25	12-15	9-10 m
separation chimney walls	20	15	10	6	4 m
slenderness ratio	7.5	7.3	7.5	9.2	10
A_1 m^2	61,540	22,840	9,106	3,655	1,834
A_2 m^2	4,710	1,570	508.7	175.8	70.65
A_1/A_2	13.07	14.55	17.90	20.79	25.96
$h\ (A_1/A_2)^2$	34,150	31,760	32,050	30,240	33,680
A_3 m^2	440,900	142,000	53,690	22,720	11,980
v_1 ms^{-1}	3.039	2.667	2.286	2.086	1.861
v_2 ms^{-1}	39.71	38.80	40.91	43.35	48.31
ΔT °K	0.7061	0.7250	0.7988	0.9501	1.059
$\Delta T'$ °K	0.7846	0.7491	0.8327	0.9350	1.161
maximum output MW	174.0	54.12	20.55	8.452	4.699
efficiency %	52.64	50.82	51.03	49.60	52.29

Table 1 Results for large prototypes

chimney height	30	20	10	5	3	m
diameter outer chimney	100	50	25	10	5	m
diameter inner chimney	94	46	23	9	4.5	m
diameter inner collector	40	10	5	4	2	m
turbine diameter	2	1	0.5	0.2	0.12	m
number of turbines	10	10	8	6	4	
collector height	6-7	3-4	1.5-2	0.6-1.0	0.36-0.5	m
separation chimney walls	3	2	1	0.5	0.25	m
slenderness ratio	7.7	8	8	8	10	
A_1 m^2	913.7	301.4	75.36	14.92	3.729	
A_2 m^2	31.40	7.850	1.570	0.1884	0.04522	
A_1/A_2	29.40	38.40	48.00	79.17	82.47	
$h\,(A_1/A_2)^2$	25,400	29,490	23,040	31,340	20,400	
A_3 m^2	5,680	1,583	395.6	51.03	12.76	
v_1 ms^{-1}	1.616	1.304	1.075	0.7049	0.6342	
v_2 ms^{-1}	47.04	50.07	51.58	55.81	52.30	
ΔT °K	1.332	1.300	1.766	1.520	2.050	
$\Delta T'$ °K	1.101	1.247	1.324	1.549	1.361	
maximum output KW	1928	581.2	127.1	19.32	3.817	
efficiency %	45.25	48.97	42.85	50.49	39.90	

Table 2 Results for small experimental models

In reviewing the Tables, successively smaller configurations are presented from left to right. In each case, dimensions have been devised to give a target efficiency of 50%. The maximum output is given for each configuration when insolation is the UK summer maximum of 750 WM^{-2}. Maximum output ranges from 174.0 MW for the largest model down to 3.8 KW for the experimental model of chimney height 3 m.

The velocity of air flow through the turbines v_2 is about 40 – 50 ms^{-1} at maximum insolation. This compares with about 15 ms^{-1} as optimal velocity for conventional wind turbines. Specially built strong, efficient turbines will be needed. Air flow is accelerated smoothly to such high velocity as it flows through the nozzles. Turbine blades are very well shielded and air flow velocity will change slowly and smoothly during operation.

Note that ΔT and $\Delta T'$ are only about 1°C in each configuration. This implies that heat losses through the solar collector will be far lower than usually considered for the solar chimney.

Experimental Model Suggested

Consider the configuration shown in Figure 5 with the following dimensions

chimney height	10 m
diameter outer chimney	25 m
diameter inner chimney	23 m
diameter inner collector	5 m

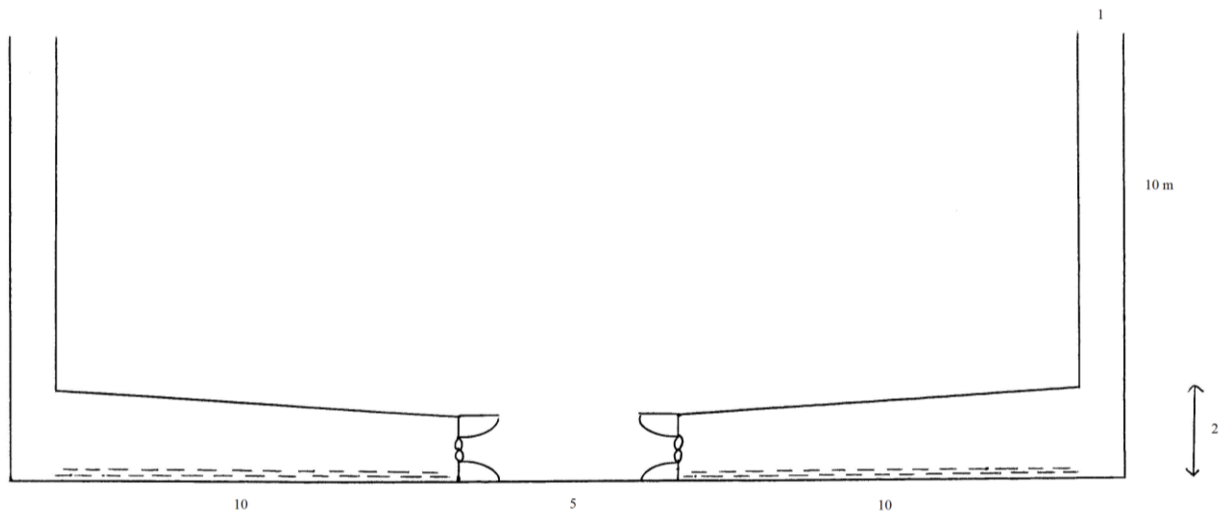

Figure 5 Experimental model for chimney height 10 m

The distance between the chimney walls is 1 m. The cross-sectional area of the chimney

$$A_1 = \pi (12.5)^2 - \pi (11.5)^2$$

$$= 24 \pi$$

$$= 75.36 \text{ m}^2$$

Consider that there are 8 turbines each of diameter 0.5 m arranged symmetrically around the inner circumference of the solar collector. The total cross-sectional area of the turbines

$$A_2 = 8\,(3.14)\,(0.25)^2$$

$$= 1.570 \text{ m}^2$$

This gives $\frac{A_1}{A_2} = 48$ and $h\left(\frac{A_1}{A_2}\right)^2 = 23{,}040$

This indicates an efficiency of somewhat below 50%.

The area of the solar collector in this configuration

$$A_3 = \pi\,(11.5)^2 - \pi\,(2.5)^2$$

$$= 126\,\pi$$

$$= 395.6 \text{ m}^2$$

The height of the solar collector rises from 3 x turbine diameter = 1.5 m at the inner circumference to 2 m as air enters the chimney.

$$\text{Slenderness ratio} = \frac{\text{height of chimney}}{\text{distance between walls}}$$

$$= \frac{10 - 2}{1} = 8$$

h	=	10	m	T	=	300	^{o}K
A_1	=	75.36	m^2	g	=	9.81	ms^{-2}
A_2	=	1.570	m^2	ρ	=	1.18	$kg\ m^{-3}$
A_3	=	395.6	km^2	C_p	=	1005	$j\ kg^{-1}\ K^{-1}$
				I	=	750	$w\ m^{-2}$

From equations (1) to (4)

(1) $$v_1^{\ 2} = 2\,\frac{\Delta T}{T}\,gh$$

$$v_1^{\ 2} = \frac{2\,\Delta T}{300} \times 9.81 \times 10$$

$$v_1^{\ 2} = 0.654\,\Delta T$$

(2) $$A_1 v_1 = A_2 v_2$$

$$75.36\,v_1 = 1.570\,v_2$$

$$v_2 = 48\,v_1$$

(3) $v_2^{\,2} = 2\, C_p\, \Delta T'$

$$v_2^{\,2} = 2 \times 1005\, \Delta T'$$

$$v_2^{\,2} = 2010\, \Delta T'$$

(4) $I\, A_3 = \rho\, A_1\, v_1\, C_p\, (\Delta T + \Delta T')$

$$750 \times 395.6 = 1.18 \times 75.36 \times 1005\, v_1\, (\Delta T + \Delta T')$$

From (1) (2) and (3) above

$$v_1 \left(\frac{v_1^{\,2}}{0.654} + \frac{2304}{2010}\, v_1^{\,2} \right) = \frac{296{,}700}{89{,}370}$$

$$v_1^{\,3}\, (2010 + 1507) = 3.320 \times 0.654 \times 2010$$

$$v_1^{\,3} = 1.241$$

$$v_1 = 1.075\ ms^{-1}$$

$$v_2 = 51.58\ ms^{-1}$$

$$\Delta T = 1.766\ °K$$

$$\Delta T' = 1.324\ °K$$

The velocity of air flow through the turbines at maximum insolation is 51.58 ms^{-1}. The temperature of air flow through the solar collector is 1.324 °K below ambient immediately post turbine rising uniformly to 1.766 °K above ambient as the air flow enters the chimney.

For the entire configuration, maximum insolation

$$I\ A_3 = 750 \times 395.6$$

$$= 296.7\ KW$$

Maximum kinetic energy of air flow through the turbines

$$\tfrac{1}{2}\, \rho\, A_2\, v_2^{\,3} = \frac{1.18}{2} \times 1.570\ (51.58)^3$$

$$= 127.1\ KW$$

This represents an efficiency of 42.85%.

The maximum output of the experimental model suggested is 127.1 KW. If built in a hot climate where average daily insolation is 6 KWH/m^2 it would have average daily output of 1000 KWH.

Pathway to Development

The author suggests that the experimental model above or similar be built, carefully studied and improved until there is good performance. Then a larger model as described in the Tables be built, investigated and enhanced … and so successively to ever larger dimensions. Economies of scale imply that as we progress to steadily larger models the cost of the electricity generated will fall continuously. Indeed the eventual challenge is to generate electricity on a large scale cheaper than from onshore wind or solar photovoltaics.

Energy Losses

The major energy loss in the proposal outlined is the heat energy lost in exit air which leaves the chimney at an elevated temperature. This amounts to about 50% of the solar energy absorbed. But this is inevitable as it is the excess temperature of exit air in the tall chimney that creates the buoyancy that drives the solar chimney.

There will also be energy losses from the solar collector and the turbines … No allowance has been made for these. The temperature of the air in the solar collector will be only about 1°C above or below ambient temperature thus minimizing possible heat losses. There will be some energy losses in the turbines and generators but these will be manifested as heat which will flow into the chimney and contribute to buoyancy. The latter are effectively recycled.

The eventual overall efficiency of 40 – 50% if achievable, is higher than from any other technology for generating electricity from solar energy.

Conclusion

An alternative configuration is proposed for the solar chimney involving three concentric circles. The outer circles form a tall, annular (ring-shaped) chimney through which exit air flows. The area between the inner circle and the chimney forms the solar collector. Air is drawn into the collector through wind turbines symmetrically placed around the circumference of the inner circle.

Calculations have been carried out for configurations with chimney heights from 200 m down to 3 m and with proportionately lower areas of solar collector and turbines. An experimental model is suggested for chimney height 10 m and outer diameter 25 m. Calculations show that it could generate up to 127.1 KW at maximum insolation with an efficiency of 42.85%.

The author asks experts in the field to consider the proposal, to carry out theoretical assessments and to build and test the experimental model suggested.

References

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