Solar Driven Wind Turbines

Abstract

Wind turbines are the most successful source of renewable energy but wind is unpredictable. Solar energy is predictable and thoroughly reliable. If solar energy could be used to provide the air flow for a wind turbine using natural convection, then wind turbines could have the availability of solar energy.

Using the principles of the solar air collector, the solar chimney and the venturi, a configuration has been devised and customised to provide air flow to a 100 m diameter wind turbine at its rated velocity 15 ms^{-1} at maximum insolation. It requires a chimney of 50 m height and 300 m diameter surrounded by a solar collector of diameter 560 m. The air flow generated passes through a convergent-divergent nozzle at the base of the chimney to multiply air flow velocity; the horizontal rotation turbine is sited in the throat of the nozzle. It is calculated that at insolation 750 wm^{-2} the solar driven wind turbine generates 15.6 MW with an efficiency of 11.6%.

The efficiency of conversion of air flow in a ducted turbine to electricity is much higher than for a turbine in the open air. This and the higher availability of solar energy mean that a 100 m diameter turbine used in this configuration will generate 5-10 times the output of its equivalent conventional turbine. If built in repeat patterns on desert or low value agricultural land, the solar driven wind turbine could generate an average 14 MW km^{-2} in tropical climates.

The author asks experts in solar and wind energy to consider, test and develop the proposal.

Introduction

Wind turbines are the most important source of renewable energy. World wind capacity is doubling every 3 years and increased 10 fold from 2000 to 2012 to a total of 270 GW. China has now overtaken the United States with a capacity of 62.3 GW and has a target of 200 GW by 2020. But wind is unpredictable, large scale energy storage is unavailable and there are problems of grid connection.

Solar energy is the ultimate source of all renewable energy and fossil fuels. If it was possible to harness just 0.001% of the solar energy intercepted by the earth, then that is the world energy problem solved. Solar energy is reliable, predictable and available everywhere.

If it was possible to use solar energy to drive wind turbines then it could provide wind energy with the availability and reliability of solar. The present paper is an attempt to devise air flow for a wind turbine powered by solar energy using natural convection. It involves the principles of the solar air collector, the solar chimney and the venturi and is a development of an earlier proposal [1]. Consider Figure 1

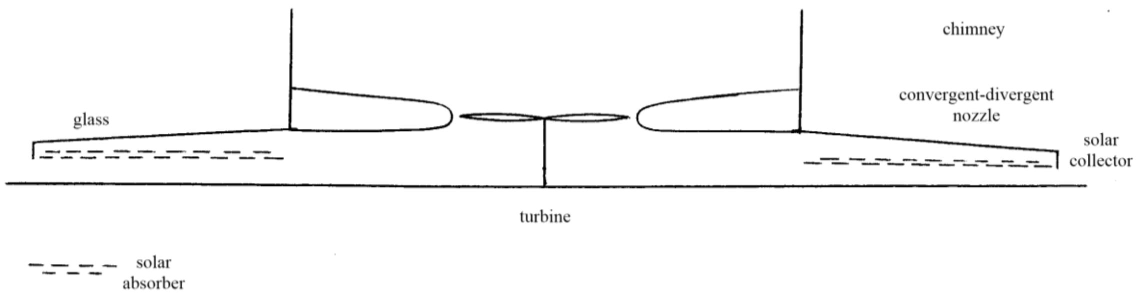

Figure 1

An absorber layer in the solar air collector takes up solar energy with high efficiency warming air in its vicinity which rises because of its lower density. A natural convection flow is established where heat from the solar absorber creates a moving reservoir of warm air in the chimney. The buoyancy effect of the latter draws ambient air from beneath the absorber and through the configuration. As the air flows through the nozzle, it must acquire higher velocity as it flows through the throat of the nozzle. A turbine sited in the throat of the nozzle can harness the kinetic energy of the air flow.

The aim of the present paper is to calculate the dimensions necessary to provide air flow for the typical wind turbine of today. This has a diameter of 100 m and a rated velocity of 15 ms^{-1} which should be met at maximum insolation.

A recent paper by Koonsrisuk and Chitsomboon

The ideas presented in this paper received remarkable confirmation in a recent paper by Koonsrisuk and Chitsomboon [2]. The authors considered a reference solar chimney (Figure 2a) where the collector has a diameter of 200 m and a height of 2 m, and it has a 100 m high chimney with a diameter of 8 m. This was compared with a solar chimney with a sloping collector and divergent-top (Figure 2b). This has the same collector area and chimney height but with a chimney base diameter 8 m and a chimney top diameter 32 m. Using CFD technology they found that the amount of kinetic energy in the air flow at the base of the chimney is multiplied "hundreds of times" in the divergent-top chimney. Indeed in their conclusion the authors state that, "The system with the sloping collector and divergent-top chimney of chimney area ratio 16 can produce power as much as 400 times that of the reference case."

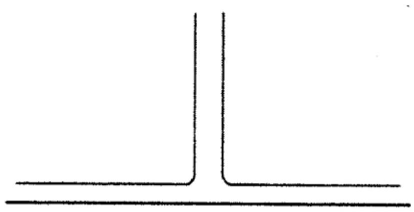

Figure 2a

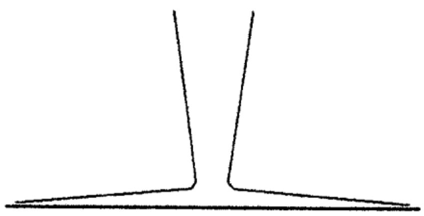

Figure 2b

It is the present author's belief that the narrow base of the chimney in Figure 2b multiplies air flow velocity by 16 and its available kinetic energy by $(16)^2 = 256$. Exactly the same principles are involved in the configuration in Figure 1.

The work of Koonsrisuk and Chitsomboon provides remarkable confirmation of the underlying principles in this proposal.

Theoretical Development

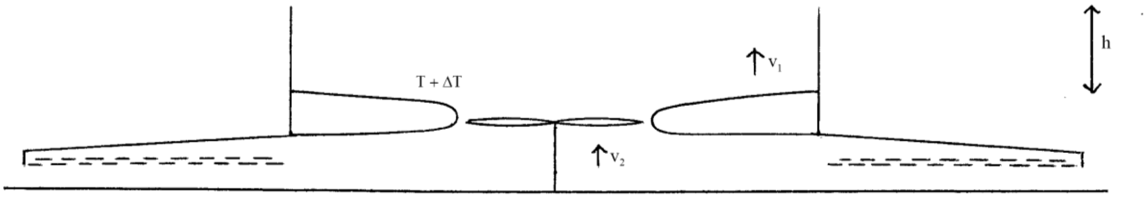

Figure 3

Consider the configuration shown in Figure 3.

The solar collector is circular in shape and has a roof made of glass or transparent polymer. Its perimeter has a rim of significant height. The roof slopes gently upwards from the perimeter towards the centre.

The solar absorber is of metal coated with absorber paint. It is multi layered and abundantly perforated to allow easy flow of air. The absorber is placed above the level of the bottom rim of the solar collector so that incoming air enters beneath the absorber and flows through the layers of absorber.

The chimney is an insulated open cylinder of robust framework to withstand cross-winds and whose outer surface is painted in harmony with the environment.

The convergent-divergent nozzle is built into the base of the chimney and whose height is a considerable fraction of that of the chimney.

The vertical axis horizontal rotation turbine is sited in the throat of the nozzle.

Consider that in Figure 3

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

At constant insolation, the configuration acquires a steady state with continuous air flow as shown. For an open cylinder of height h containing air at a temperature ΔT above ambient, the velocity of air flow generated by buoyancy [3] is given by

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

Constant mass flow requires that

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

The constriction caused by the convergent-divergent nozzle requires air flow to accelerate from v_1 to v_2. The additional flow kinetic energy comes from the internal energy of the air whose temperature falls by $\Delta T'$.

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

$$\frac{1}{2}\dot{m}\,v_2^{\,2} - \frac{1}{2}\dot{m}\,v_1^{\,2} = \dot{m}\,C_p\,\Delta T'$$

where $\dot{m}$ is the mass flow. Now consider $v_2 >> v_1$

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

As air flows through the solar absorber it must increase in temperature by $\Delta T + \Delta T'$; ΔT is required for its passage through the chimney and gives rise to buoyancy whilst $\Delta T'$ provides the kinetic energy for the turbine.

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

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

Equations (1) to (4) govern the air flow through the configuration. When we consider them collectively there are 8 variables h, A_1, A_2, A_3, v_1, v_2, ΔT, $\Delta T'$ and 5 constants T, g, C_p, ρ and I. We have 4 equations and 8 variables. If we fix 4 of the variables the algebra allows us to calculate the other 4.

Solar Driven Wind Turbine

Consider that in Figure 3 we have a turbine of diameter 100 m and that at maximum insolation there is air flow at its rated velocity 15 ms^{-1} through the turbine. Consider

h	=	50 m	T	=	300°	K
v_2	=	15 ms^{-1}	g	=	9.81	ms^{-2}
A_2	=	7850 m^2 (turbine diameter 100m)	C_p	=	1005	$j\,kg^{-1}\,K^{-1}$
A_1	=	9 x 7850 m^2 (chimney diameter 300m)	ρ	=	1.18	$kg\,m^{-3}$
			I	=	750	$w\,m^{-2}$

From equation (2)

$$v_1 = \frac{7850 \times 15}{9 \times 7850}$$

$$v_1 = 1.667\ ms^{-1}$$

From equation (1)

$$\Delta T = \frac{(1.667)^2 \times 300}{2 \times 9.81 \times 50}$$

$$\Delta T = 0.8495 \text{ K}$$

From equation (3)

$$\Delta T' = \frac{15 \times 15}{2 \times 1005}$$

$$\Delta T' = 0.1119 \text{ K}$$

From equation (4)

$$A_3 = \frac{1.18 \times 9 \times 7850 \times 1.667 \times 1005 \times 0.9614}{750}$$

$$A_3 = 179{,}000 \text{ m}^2$$

Total area of chimney + collector = 70,650 + 179,000

= 249,700

This gives a diameter for the entire configuration of 563.9 m.

The fall in temperature as air flows through the nozzle and turbine is 0.1119 K whilst exit air leaves the chimney at a temperature 0.8495 K above ambient. This gives an overall efficiency of

$$\frac{0.1119}{0.9614} = 11.6\%$$

<u>CHECK</u>

Maximum insolation = $I A_3$

= 750 x 179,000

= 134.3 MW

Maximum kinetic energy through the turbine = $\frac{1}{2} \rho A_2 v_2{}^3$

$= \frac{1.18}{2} \times 7850 \times (15)^3$

= 15.6 MW

This is the maximum output when insolation is 750 wm^{-2}.

Output will vary during the day in direct proportion to insolation.

Energy loss in air flow through chimney = $\rho A_1 v_1 C_p \Delta T$

= 1.18 x 9 x 7850 x 1.667 x 1005 x 0.8495

= 118.6 MW

This energy loss is unavoidable for it is the buoyancy created by this warm air that drives the convection flow.

Clearance under the solar collector

In the above proposal the amount of the temperature rise for air in the solar collector and chimney is exceptionally low at below 1 K. The corollary is that a very large volume of air has to be drawn into the solar collector to dissipate the solar energy absorbed. This in turn requires considerable height to be available beneath the solar collector for entry of incoming air. Consider that in Figure 3

x	distance from ground to bottom rim of collector
v_x	velocity of incoming air flow
D	diameter of solar collector

volume of air inflow = volume of air outflow

$$\pi D x v_x = v_2 A_2$$

Let us assume that it is desirable for $v_x = \frac{1}{3} v_2$

$$x = \frac{7850 \times 3}{3.14 \times 563.9}$$

$$x = 13.3 \text{ m}$$

Overall height for Solar Driven Wind Turbine

clearance beneath collector	15 m
height of rim and solar absorber	5
height of slope from rim to chimney	10
convergent-divergent nozzle	20
height of chimney above nozzle	50
	100 m

Turbine details

axle height	40 m
blade diameter	100 m
maximum velocity air flow	15 ms^{-1}
maximum power	15.6 MW

A sketch of the proposal (drawn to scale) is shown in Figure 4

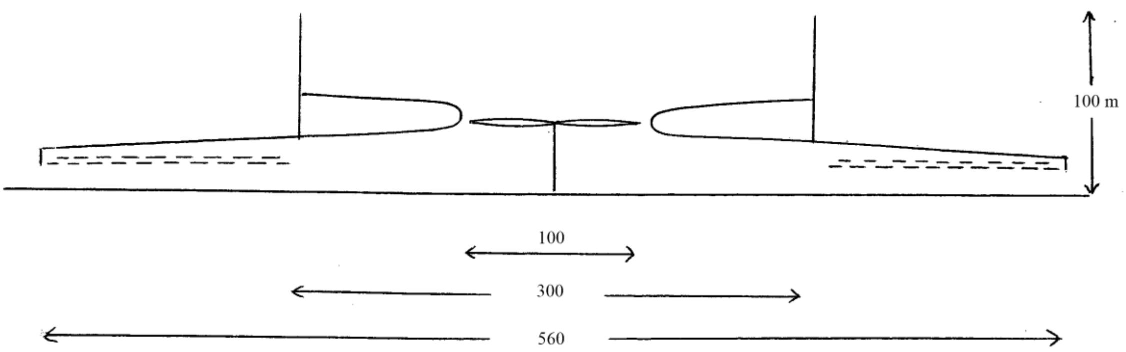

Figure 4

Further considerations

- The turbines needed in this proposal are for vertical air flow. All commercial wind turbines are of course for horizontal air flow. Though a problem, the author believes this is moderately soluble and is just a matter of developing the technology.

- The position of the turbine is extremely well-shielded and should suffer no turbulence from gusts of wind ... Further its workload will rise and fall very gently with daily variations in insolation. This should mean high performance under optimal working conditions.

- Energy storage can be easily added. Schlaich [3] suggests that water tubes of height 20 cm are sufficient to reduce daytime peak supply to provide evening and night generation. There is a height of over 10 m available underneath the solar collector allowing massive energy storage possibilities.

- Construction of the solar collector, chimney and nozzle should be straightforward and of moderate cost, perhaps comparable to the cost of the turbine if built on a large, repeat scale.

- The solar driven wind turbine described has a maximum output of 15 MW at insolation 750 wm^{-2}. If built in tropical climates with daily insolation 6 kWh m^{-2} it would give an output of 5 MW averaged over 24/365. In climates with lower insolation the area of the solar collector can be increased.

- The area of land needed for the central proposal outlined is less than 600 x 600 m equal to 0.36 km^2 to provide average output 5 MW. If built in repeat patterns the solar driven wind turbine could generate an average 14 MW km^{-2}.

- The proposal assumes maximum air flow velocity of 15 ms^{-1} which is the rated velocity of today's turbines. If turbines were to be developed to harness air flow velocity of 20 – 30 ms^{-1} then much higher output and efficiency become possible.

Advantages of Solar Driven Wind Turbines

- The overwhelming advantages are AVAILABILITY and RELIABILITY. Wind energy is unpredictable and erratic with an average load factor of about 30%. Solar energy is highly predictable and completely reliable allowing solar driven wind turbines to generate electricity in direct proportion to insolation during their 24 hour cycle. The availability/load factor of the wind turbine in this proposal is several times that of conventional wind turbines.

- Wind turbines in the open air are affected by turbulence and fluctuating wind direction and have an efficiency of only about 30%. In this proposal air flow is contained in an enclosed configuration and guided along a duct allowing turbine efficiency of over 80% [3].

- **These two factors mean that a 100 m diameter turbine used in this proposal will produce 5 – 10 times as much electricity as its equivalent in a conventional wind turbine.**

- Wind turbines have to be sited on hillsides, mountains or plateaus. The solar driven wind turbine can be sited anywhere – in the flat valley, on plateaus, on desert or low value agricultural land.

Conclusion

Wind turbines are the most successful source of renewable energy but wind is unpredictable. Solar energy is predictable and thoroughly reliable. If solar energy could be used to provide the air flow for a wind turbine using natural convection, then wind turbines could have the availability of solar energy.

Using the principles of the solar air collector, the solar chimney and the venturi, a configuration has been devised and customised to provide air flow to a 100 m diameter wind turbine at its rated velocity 15 ms^{-1} at maximum insolation. It requires a chimney of 50 m height and 300 m diameter surrounded by a solar collector of diameter 560 m. The air flow generated passes through a convergent-divergent nozzle at the base of the chimney to multiply air flow velocity; the horizontal rotation turbine is sited in the throat of the nozzle. It is calculated that at insolation 750 wm^{-2} the solar driven wind turbine generates 15.6 MW with an efficiency of 11.6%.

The efficiency of conversion of air flow in a ducted turbine to electricity is much higher than for a turbine in the open air. This and the higher availability of solar energy mean that a 100 m diameter turbine used in this configuration will generate 5-10 times the output of its equivalent conventional turbine. If built in repeat patterns on desert or low value agricultural land, the solar driven wind turbine could generate an average 14 MW km^{-2} in tropical climates.

The author asks experts in solar and wind energy to consider, test and develop the proposal.

References

[1] www.globalwarmingsolutions.co.uk, May 2012
The solar chimney – would a venturi multiply efficiency?

[2] A Koonsrisuk, T Chitsomboon. Effects of flow area changes on the potential of solar chimney power plants. Energy 2013, 51, 400-6.

[3] J Schlaich et al., Design of commercial solar updraft power systems, utilization of solar induced convective flows for power generation.
J. Sol. Energy Eng. 2005, 127, 117-24.