Use of hyperbolic solar collector to drive a conventional wind turbine

Abstract

Wind turbines represent the most successful source of renewable energy to date – but wind power is unpredictable. Solar energy is completely reliable and predictable. The principles of the solar air collector, the solar chimney and the venturi are used to devise a configuration that converts solar energy into wind energy with moderate efficiency. Suitable dimensions are devised for a hyperbolic shaped solar collector to provide the air flow to drive a horizontal rotation, vertical axis wind turbine. To provide air flow for a turbine of diameter 100 m at its rated velocity 15 ms^{-1} at insolation 750 wm^{-2} requires a solar collector of height 50 m and diameter 460 m. This gives an output of 15.6 MW with an efficiency of 12.6%.

The author asks experts in wind and solar energy to consider the proposal, to carry out assessments using computational fluid dynamics and other approaches and to develop the ideas.

Introduction

Wind turbines represent the most successful source of renewable energy to date. Global capacity has grown from 18 GW at the end of 2000 to 282 GW at end 2012. Wind power now generates 3% of the world's electricity and for Germany around 9% but wind energy is unpredictable.

There is no question that the ideal source of renewable energy is solar if only it could be harnessed efficiently and economically. There has been enormous progress for solar hot water and concentrated solar power and spectacular growth for photovoltaics in recent years.

The author believes that it should be possible to harness solar energy using natural convection. The solar chimney [1] converts solar energy absorbed into wind energy which is then intercepted by a turbine. Efficiency is low however (about 2%) even with a 1000 m height chimney. The author believes that the velocity of air flow can be multiplied if it is required to flow through a venturi. The amount of available kinetic energy can be multiplied by a large factor for a wind turbine sited in the throat of the venturi.

The aim of the present paper is to describe a configuration that absorbs solar energy and converts it into an air flow customised for a standard wind turbine. It is to devise suitable dimensions for a solar collector and <u>wind turbine that creates its own wind</u> from solar energy and with moderate efficiency. In this way it could provide <u>wind energy with the availability and predictability of solar energy</u>.

Choice of hyperbolic shape

The author has developed several proposals based on the above principles [2]. A recent paper titled "Use of conventional wind turbine to harness solar energy using natural convection" considered use of a cylindrical solar collector.

The use of a conical shaped solar collector has also been considered. It would have only one third of the volume of the cylindrical collector of the same height and one third of the buoyancy force. It is felt however that as air flows through the venturi, it requires high acceleration and would impose great stress on the glass containment in the throat of the venturi.

For collectors for the solar chimney, Krätzig [3] states that, "All plant designs in the last 15 years show a hyperbolic increase of the roof height (with varying exponents), from e.g. 5 m at the rim to 12 m close to the machinery." It is evident that a hyperbolic shape offers far better aerodynamics for the air flow. Ambient air is drawn in beneath the perimeter of the solar collector. As it is warmed by the solar absorber it acquires a vertical velocity. As the cross-section narrows in the venturi air flow is multiplied but there is less mechanical stress on the containment. The configuration suggested is shown in Figure 1.

Theoretical development

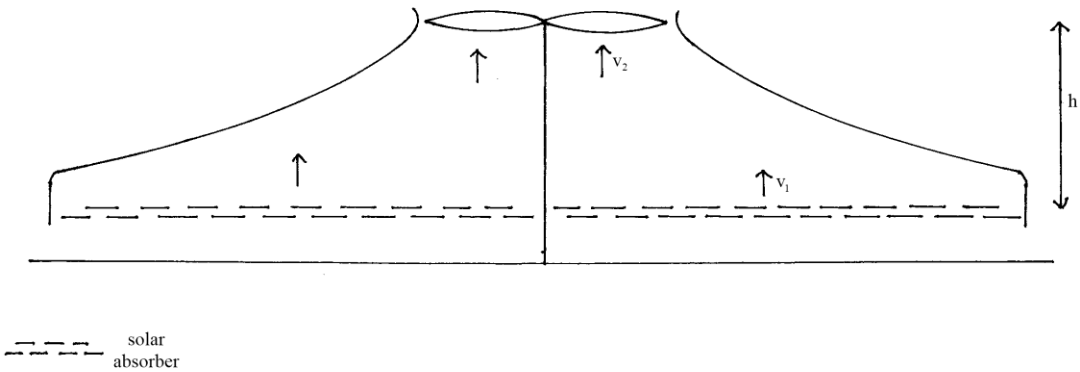

Figure 1

Consider that in Figure 1

h	height from solar absorber to turbine
A_1	area of solar absorber
A_2	cross-sectional area of turbine
v_1	velocity of air flow through solar absorber
v_2	velocity of air flow through turbine
T	ambient temperature
ΔT	excess temperature (above ambient) of air in solar collector
$\Delta T'$	fall in temperature as air flows through venturi
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

The main structure of the solar collector is built of glass or transparent polymer and could be double glazed. The vertical axis horizontal rotation turbine is sited in the throat of the venturi.

The solar absorber of metal coated with absorber paint is multi layered and designed to allow easy upward air flow. It is placed above the level of the bottom rim of the collector.

Solar energy is taken up by the absorber warming air in its neighbourhood which rises because of its lower density and draws incoming ambient air from beneath. At constant insolation a steady state is reached with air temperature above the absorber ΔT above ambient with incoming air drawn through the absorber with velocity v_1.

For an open cylinder of height h containing air at a temperature ΔT above ambient, the velocity of air flow [1] is given by

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

In this case however the solar collector is hyperbolic. The author suggests that it is designed so that the volume of air contained above the absorber is one fifth that of a cylinder of height h. In that case the buoyancy force will be one fifth that of the cylinder above and

$$v_1^{\,2} = \frac{2}{5} \frac{\Delta T}{T} gh \qquad (1)$$

Constant mass flow requires that

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

As air flows through the venturi, the narrowing cross-section requires its vertical velocity to increase from v_1 to v_2. This increase in kinetic energy of air flow comes from the internal energy of the rising 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 $v_2 \gg v_1$

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

Solar energy taken up by the absorber raises the temperature of the air flow by an amount ΔT which gives rise to buoyancy and by an amount $\Delta T'$ which provides kinetic energy of air flow through the venturi.

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

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

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

Equations (1) to (4) govern the air flow through the configuration. If we consider them collectively we have 7 variables h A_1 A_2 v_1 v_2 ΔT $\Delta T'$ and 5 constants T g C_p ρ and I. We have 4 equations and 7 variables. If we fix 3 of the variables the algebra allows us to calculate the other 4. In this way we can devise any number of proposals and consider if they are practical.

Central proposal

The above model can be used to assess the feasibility of providing air flow to today's standard wind turbine from solar energy. A typical wind turbine has blade diameter 100 m and rated wind velocity 15 ms^{-1}. Consider that at UK maximum insolation 750 wm^{-2} the rated wind velocity is achieved. Consider

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

From equation (1)

$$v_1^{\ 2} = \frac{2}{5} \cdot \frac{\Delta T}{300} \text{ x } 9.81 \text{ x } 50$$

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

From equation (3)

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

$$\Delta T' = 0.1119$$

From equation (4)

$$750 = 1.18 \text{ x } 1005\ v_1\ (\Delta T + 0.1119)$$

$$v_1 = \frac{0.6324}{\Delta T + 0.1119}$$

Thus

$$\left[\frac{0.6324}{\Delta T + 0.1119}\right]^2 = 0.654\ \Delta T$$

$$\Delta T\ (\Delta T + 0.1119)^{\ 2} = \frac{(0.6324)^{\ 2}}{0.654}$$

$$\Delta T^3 + 0.2238\Delta T^2 + 0.01253\Delta T = 0.6116$$

$$\Delta T = 0.7759\ °K$$

$$v_1 = 0.7123\ ms^{-1}$$

From equation (2)

$$A_1 = \frac{7850 \text{ x } 15}{0.7123}$$

$$= 165{,}300\ m^2$$

Thus a solar collector area is needed of 165,300 m^2. If it is circular in shape it means a diameter of 458.9 m. At maximum insolation the amount of solar energy taken up by the absorber is 165,300 x 750 watts = 124 MW. The amount of kinetic energy made available to the turbine is

$$\frac{1}{2}\rho A_2 v_2^{\,3} = \frac{1.18}{2} \times 7850 \times (15)^3$$

$$= 15.63 \text{ MW}$$

This gives a maximum efficiency of $\frac{15.63}{124.0} = 12.6\%$

The remaining energy is lost in exit air which leaves the turbine at a temperature 0.7759°K above ambient. This loss is unavoidable for it is the buoyancy created by this warm air that drives the air flow.

Clearance under solar collector

In the above proposal the amount of the excess temperature for air in the solar collector 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 an unusually large distance from the ground to the bottom rim of the solar collector to allow entry of incoming air at moderate velocity. Consider that in Figure 1

x distance from ground to bottom rim of collector
v_x velocity of incoming air flow beneath the collector
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 $v_x = ½ v_2$

Then $x = \frac{7850 \times 2}{3.14 \times 458.9} = 10.9$ m

Thus a clearance of about 11 m is needed beneath the solar collector. This gives the entire configuration an overall height of 60–65 m.

Though incoming air enters the solar collector with a horizontal velocity $½ v_2$ once inside the collector a headroom of eventually 50 m becomes available. Thus the horizontal velocity rapidly falls inside the collector. Incoming air does however acquire a vertical velocity of v_1 as it passes through the absorber but accelerating to v_2 as it approaches the venturi and turbine.

A sketch of the proposal drawn to scale is shown in Figure 2

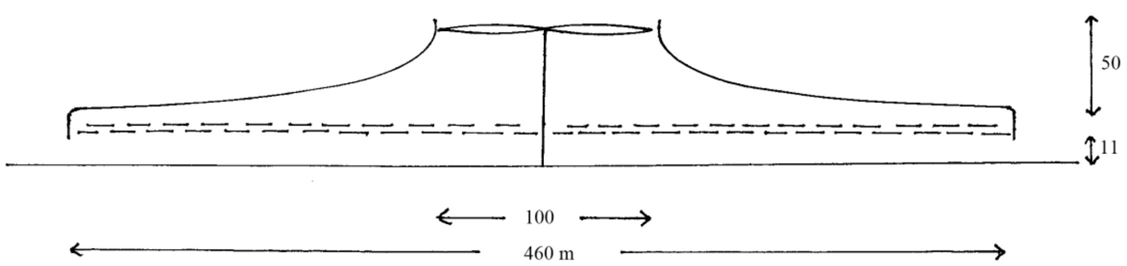

Figure 2

Further considerations

- The solar absorber is NOT at ground level. It is considered that the level of the solar absorber needs to be ABOVE the level of the bottom rim of the solar collector. In this way it is certain that all solar energy taken up by the absorber is transferred to incoming air and contributes to the buoyancy driven flow.
- All conventional wind turbines are vertical axis vertical rotation. The turbines required for this proposal are horizontal rotation. Though a problem, the author believes this is moderately soluble and is just a matter of developing the technology.
- Energy storage can be easily added. Schlaich et al. [1] suggest 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 absorber allowing massive energy storage possibilities.
- In low insolation countries the area of the solar collector can be increased. In normal use there could be advantage in having a detachable outer solar collector area that is used in winter but removed in summer.
- The hyperbolic shape of the solar collector gives excellent resilience against cross-winds. The aerodynamic shape will steer air flow from external winds along the upper surface.
- The proposal outlined gives a maximum output of 15 MW at insolation 750 wm^{-2}. If built in tropical climates with annualised average insolation of 6 $kWh/m^2/day$ it means an average output of 5 MW averaged over 24 hours/day and 365 days/year. Repeat units could be built in a large development at a density of 4 $units/km^2$ giving an AVERAGE output of 20 MW/km^2.
- The proposal assumes maximum wind velocity of 15 ms^{-1}. If turbines were to be developed to harness air flow velocity of 20-30 ms^{-1} then much higher output and efficiency becomes possible.

Advantages of solar generated wind energy

- The overwhelming advantages are AVAILABILITY and RELIABILITY. Wind energy is unpredictable and erratic. Solar energy is highly predictable and completely reliable. The availability/load factor of the wind turbine in this proposal is several times that of conventional wind turbines.
- The efficiency of wind turbines in the open air in converting the kinetic energy of air flow at 15 ms^{-1} into electricity is about 30%. In this proposal air flow is contained in an enclosed configuration and guided along a duct allowing turbine efficiency of over 80% [1].
- **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 in prominent positions 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

The principles of the solar air collector, the solar chimney and the venturi have been used to devise a configuration to convert solar energy into the kinetic energy of air flow with moderate efficiency. Dimensions have been customised to supply a 100 m diameter vertical axis horizontal rotation wind turbine with air flow at 15 ms^{-1} at maximum insolation. The solar collector suggested is hyperbolic in shape, has a ground level diameter of 458.9 m and an overall height of 60-65 m. It has a maximum output of 15 MW and a conversion efficiency of solar to wind energy of 12.6%.

Solar energy has much greater availability and reliability than wind energy. The ducted wind turbine also has much higher efficiency than wind turbines in the open air. Both these factors mean that a 100 m diameter turbine used in the configuration proposed 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 20 MW/km^2 in tropical climates.

The author asks experts on wind and solar energy in university departments, energy research institutes or wind power companies to consider the proposal, to verify using computational fluid dynamics and other approaches and to develop the ideas.

References

[1] J Schlaich et al., Journal of Solar Energy Engineering, 127 (2005), 117-124

[2] www.globalwarmingsolutions.co.uk

[3] W B Krätzig, Private communication, 4 July 2013.

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