Use of conventional wind turbines to harness solar energy using natural convection

Abstract

Wind turbines represent the most successful source to date of renewable energy ... but wind is unpredictable. Solar energy is the ideal source of renewable energy because of its abundance, availability and predictability. The author believes it should be possible to harness solar energy commercially using natural convection. A solar air collector and warm air store generate a flow of warm air. If this is required to flow through a venturi, some of its excess thermal energy is converted into kinetic energy. This can be harnessed by a turbine sited in the throat of the venturi.

These principles are used to devise a configuration that will supply a 100 m diameter turbine with air flow at 15 ms^{-1} at maximum insolation. The solar air collector suggested is cylindrical with a height of 50 m and diameter 360 m. The upper section is conical with the horizontal rotation turbine at the highest level of the configuration of overall height 70 m. Such a turbine would have output 15.6 MW at insolation 750 wm^{-2} and efficiency of over 20%. Output will rise and fall in line with insolation.

The author asks experts in wind and solar energy to consider and develop the proposal. The concept is of a commercial wind turbine that creates its own wind – from solar energy.

Introduction

Wind turbines represent the most successful source of renewable energy to date. Installed capacity worldwide reached 281,000 MW in 2012 and is growing at 20% annually. Germany now generates over 10% of its electricity from wind.

Commercial wind turbines have a blade diameter of about 100 m and are designed for a rated wind velocity of about 15 ms^{-1} (30 mph). The power output of the turbine increases as the wind increases to its rated velocity. The output then levels off above the rated velocity.

Solar energy is of course the ultimate ideal source of renewable energy if it could be harnessed efficiently and economically. There has been great progress in recent decades in the technologies for solar hot water, photovoltaics and concentrated solar power.

The author believes that it should be possible to harness solar energy using natural convection. The only significant example to date is the solar chimney [1]. A large area solar collector warms air which flows through a tall chimney. The height of the chimney and the excess temperature of the air create a buoyancy force that draws a continuous flow of ambient air through the configuration. This can be intercepted by a turbine generating electricity. It is an example of conversion of solar into wind energy. Unfortunately however a solar chimney of height 1000m provides only 2% efficiency.

If the air flow above is required to flow through a venturi, its velocity is multiplied and a much larger amount of flow kinetic energy can be made available. The extra kinetic energy comes from the internal energy of the warm air.

The present paper combines

- a solar air collector to absorb solar energy and provide a flow of warm air
- a warm air store whose height and excess temperature create buoyancy
- a venturi which multiplies air flow velocity
- a wind turbine which, sited in the throat of the venturi, intercepts the flow kinetic energy generating electricity.

The aim of this paper is to devise a configuration of suitable dimensions to provide a turbine of diameter 100 m with continuous air flow at 15 ms^{-1} at maximum insolation.

Theoretical Development

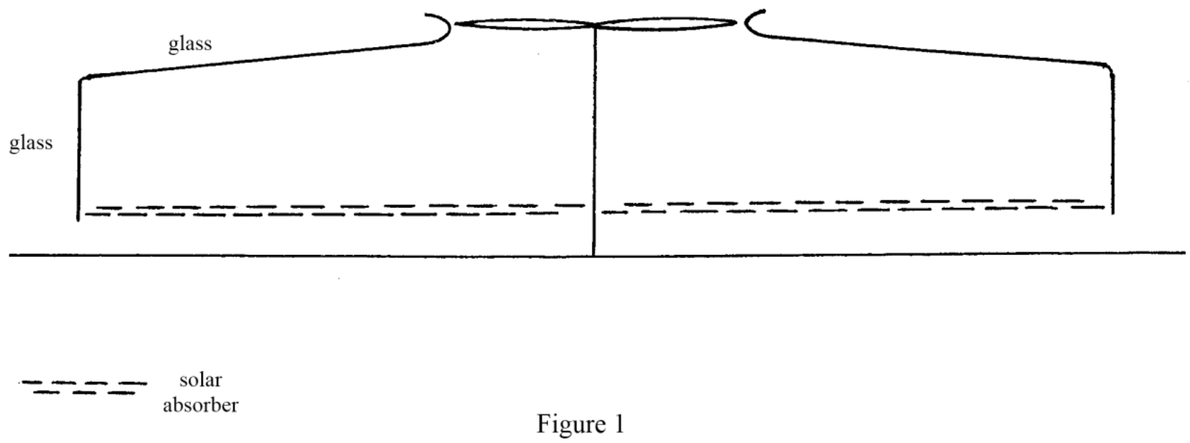

Figure 1

Consider the configuration shown in Figure 1. The main structure is a large cylindrical warm air store with a sloping roof built of glass or transparent plastic on a strong framework. There is a substantial gap between the bottom edge of the main structure and the ground to allow entry of ambient air. Immediately above the level of the bottom edge of the solar collector there is a multi layered solar absorber of height 1-2 m. The absorber is metallic with its upper surface coated with solar absorber paint. It is of very open structure allowing easy through flow of air and efficient heat transfer. A vertical axle, horizontal rotation wind turbine is housed at the centre of the configuration at its uppermost level.

During the day, as solar energy is taken up by the absorber it warms air in its immediate vicinity which rises because of its lower density drawing ambient air from beneath to replace. At constant insolation a steady state is established where there is a continuous flow of air through the configuration. As the rising air flow encounters the narrowing neck of the warm air store (the venturi) it must acquire higher velocity. Some of its excess thermal energy is converted into kinetic energy which can be harnessed by the wind turbine.

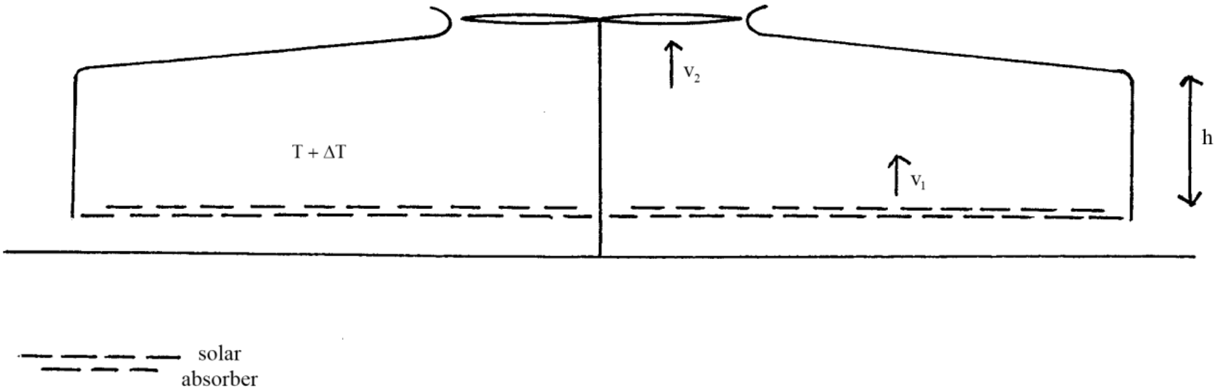

Figure 2

Consider that in Figure 2

A_1	cross-sectional area of the solar absorber and warm air store
h	height of warm air store
v_1	velocity of air flow through the solar absorber and warm air store
T	ambient temperature
ΔT	excess temperature (above ambient) of air in warm air store
A_2	cross-sectional area of turbine
v_2	velocity of air flow through turbine
$\Delta T'$	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 excess temperature of air in the warm air store creates a buoyancy force which draws ambient air through the configuration. The velocity of air flow through the solar absorber and warm air store is given by the solar chimney equation [1]

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

Constant mass flow requires that

mass flow through solar absorber = mass flow through turbine

$$A_1\, v_1\, \rho = A_2\, v_2\, \rho$$

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

When the rising air in the warm air store flows through the venturi, it must increase velocity from v_1 to v_2. The extra kinetic energy comes from its internal energy and its temperature falls by $\Delta T'$.

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

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

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

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

Solar energy is taken up by the absorber raising the temperature of the air flow by an amount $\Delta T + \Delta T'$ to provide the temperature rise that creates buoyancy and kinetic energy for the turbine. It should be noted that exit air leaves the turbine at a temperature $T + \Delta T$.

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

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

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

If we consider equations (1) to (4) collectively, they involve known constants T g C_p ρ and I and variables A_1 A_2 h v_1 v_2 ΔT and $\Delta T'$. There are 4 equations and 7 variables. If 3 of the variables are fixed, the other 4 can be calculated.

Cylindrical solar collector/warm air store with standard wind turbine

Consider the configuration in Figure 2 with a wind turbine installed of diameter 100 m (cross-sectional area 7850 m^2) and a warm air store of height 50 m. Consider further that dimensions are such that at maximum insolation there is an air flow velocity through the turbine of 15 ms^{-1}.

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

From equation (1)

$$v_1^{\,2} = 2 \frac{\Delta T}{300} \times 9.81 \times 50$$

$$v_1^{\,2} = 3.27\, \Delta T$$

From equation (3)

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

$$\Delta T' = 0.11194$$

From equation (4)

$$v_1 = \frac{750}{1.18 \times 1005\, (\Delta T + 0.11194)}$$

$$v_1 = \frac{0.63243}{\Delta T + 0.11194}$$

Thus

$$\left[\frac{0.63243}{\Delta T + 0.11194}\right]^2 = 3.27\, \Delta T$$

$$\Delta T\, (\Delta T + 0.11194)^2 = \frac{(0.63243)^2}{3.27}$$

$$\Delta T^3 + 0.22388 \Delta T^2 + 0.01253 \Delta T = 0.12231$$

$$\Delta T = 0.4247$$

$$v_1 = 1.178$$

From equation (2) $\quad A_1 = \frac{7850 \times 15}{1.178}$

$$A_1 = 99{,}920 \text{ m}^2$$

This gives a solar collector diameter of 356.8 m

The kinetic energy of the air flow to be harnessed by the turbine is

$$\text{kinetic energy} = \tfrac{1}{2} \rho A_2 v_2^{\,3}$$

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

$$= 15.63 \text{ MW}$$

This represents the kinetic energy available when insolation $I = 750$

$$\text{total solar energy absorbed} = I A_1$$

$$= 750 \times 99{,}920$$

$$= 74.94 \text{ MW}$$

This gives an efficiency of $\frac{15.63}{74.94} = 20.8\%$

$$\text{energy loss in exit air} = \rho A_1 v_1 Cp \Delta T$$

$$= 1.18 \times 99{,}920 \times 1.178 \times 1005 \times 0.4247$$

$$= 59.28 \text{ MW}$$

Thus to provide the 100 m diameter turbine with air flow at 15 ms^{-1} at insolation 750 wm^{-2} with a warm air store height 50 m requires a solar collector of diameter 356.8 m. The efficiency of conversion of solar energy into available kinetic energy is 20.8%. The remainder of the solar energy absorbed is lost in providing buoyancy and leaves the turbine at a temperature $T + 0.4247$.

Clearance under solar collector

Consider that the bottom edge of the solar collector is at a height x above the ground and that the velocity of air inflow is v_x. Constant mass flow requires that

$$\text{inflow at perimeter solar collector} = \text{outflow through turbine}$$

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

where D is the diameter of the solar collector. Consider further that $v_x = v_2$

$$x = \frac{7850}{3.14 \times 356.8}$$

$$= 7.0 \text{ m}$$

Thus the configuration requires a clearance of 7.0 m between the bottom edge of the collector and the ground to allow air inflow.

Overall height

A height of 50 m has been assumed for the warm air store. To this must be added the clearance under the solar collector of 7.0 m and 1-2 m for the height of the solar absorber. The warm air store has a conical upper section so that the rising air flow is accelerated smoothly into the turbine. These give an overall height of about 70 m.

Average output

The output calculated above is 15.6 MW at insolation 750 wm^{-2}. If built in a tropical climate with average annualised daily insolation of 6 kWh per m^2, output is 5.2 MW averaged over 24 hr/day and 365 days/year. If the configuration proposed was built in repeat units in a solar/wind farm, it would allow average output of 35 MW/km^2.

Energy storage

Schlaich et al. [1] describe the use of sealed water tubes at ground level to store peak daytime solar energy to be released for evening/night generation and suggest a height of 20 cm water for the daily cycle. There is abundant available volume at ground level beneath the solar absorber for such a facility.

Boundary wall

A boundary wall w is suggested of height 10 m at a distance of 10 m from the perimeter to the solar collector. This would impose downward flow of incoming air into the configuration minimising problems of airborne dust.

A sketch of the proposal is shown in Figure 3 (drawn to scale).

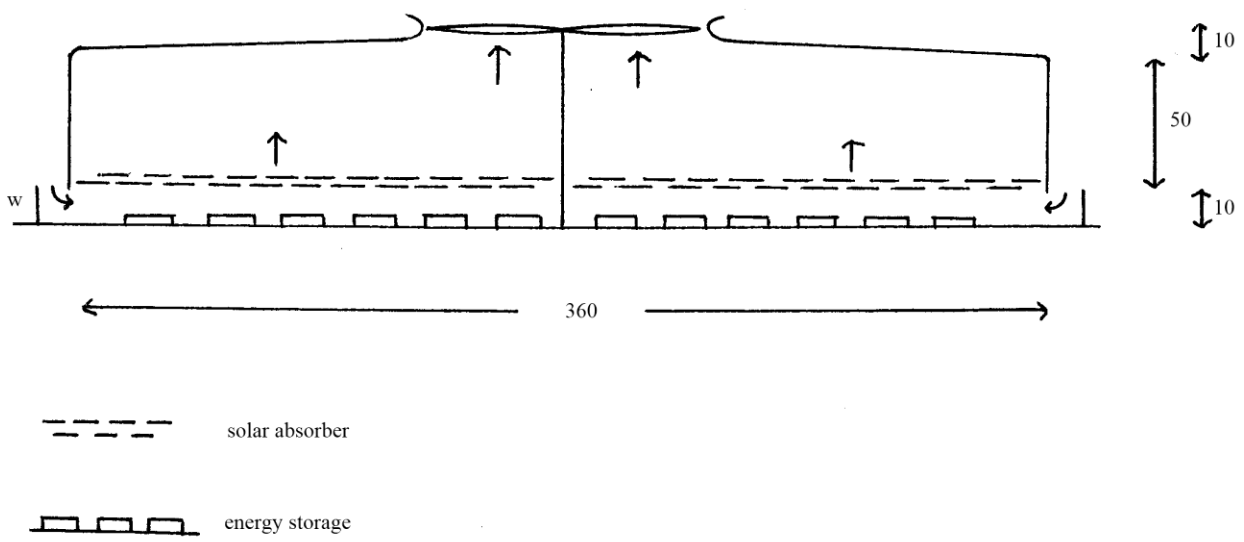

Figure 3

Advantages of solar generated wind energy

- The most unsatisfactory feature of wind energy is its unpredictability. Solar energy in contrast is reliable and predictable allowing continuous daytime production. The availability/load factor and output of the wind turbine in this proposal will be several times that of conventional wind turbines.

- Wind turbines have to be sited in the most exposed locations on hills or high plateau. The present proposal can be sited anywhere ... on plateau, hills or valley floors or poor land or desert. Solar energy is available everywhere.

Conclusion

The aim of this paper has been to devise a configuration for a wind turbine that creates its own wind from solar energy. Using the principles of the solar chimney and the venturi the proposal provides a conventional wind turbine with air flow at its rated velocity at maximum insolation.

The typical modern wind turbine has a diameter of 100 m and a rated velocity of 15 ms^{-1}. The air flow can be provided by natural convection from a cylindrical solar collector and warm air store of height 50 m and diameter 360 m. The configuration has a conical upper section (venturi) to accelerate the air flow and to house the horizontal rotation vertical axle turbine giving an overall height of 70 m. The efficiency of conversion of solar into kinetic energy is 20.8% and at insolation 750 wm^{-2} the output is 15.6 MW.

Wind energy is unpredictable. Solar energy in contrast is reliable, abundant and predictable. Load factor/availability and output for the wind turbine in this proposal will be several times that of a conventional wind turbine. To the proven technologies of wind energy is added the availability of solar energy.

The units involved in solar generated wind energy can be sited anywhere ... on plateau, valley floors, poor land or desert and in repeat patterns have an average output of 35 MW/km^2 in a warm climate.

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

References

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